SSC-360

USE OF FIBER REINFORCED PLASTICS IN THE MARINE INDUSTRY

SHIP STRUCTURE COMMITTEE

1990

Member Agencies:

United States Coast Guard
Naval Sea Systems Command
Maritime Administration
American Bureau of Shipping
Military Sealift Command

Ship Structure Committee

An Interagency Advisory Committee
Dedicated to the Improvement of Marine Structures

Address Correspondence to:

Secretary, Ship Structure Committee
U.S. Coast Guard (G-MTH)
2100 Second Street S.W.
Washington, D.C. 20593-0001
PH: (202) 267-0003
FAX: (202) 267-0025

September 6, 1990

SSC-360
SR-1328

USE OF FIBER REINFORCED PLASTICS
IN MARINE STRUCTURES

Fiber reinforced plastics (FRP) have been used extensively in the recreational boating industry for more than 30 years. We are now beginning to see applications for more widespread uses of FRP in larger marine structures. Many traditional naval architects and design engineers are not familiar with the processes used in the fabrication of FRP structures nor with the terminology associated with these processes. Although fundamental design considerations for FRP and steel structures are quite similar, the design of structural details varies drastically and must not be overlooked.

This report is the most comprehensive study to date on the state of the marine composites industry and should for many years serve as an excellent reference and source book for designers and builders of FRP structures. Over 200 manufacturers provided information concerning current building practices and material uses. Numerous charts, illustrations, and graphs are included and help to explain many of the concepts in the report.

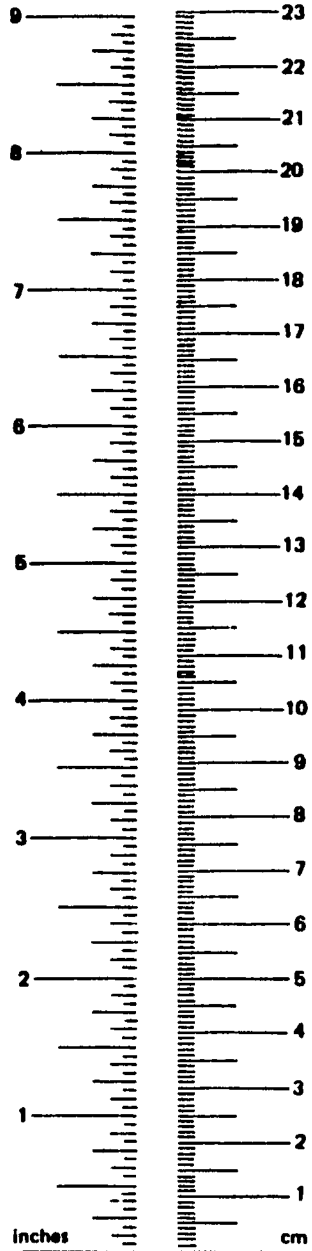
J. D. SIPES
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

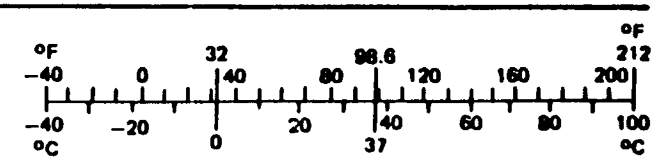
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Technical Report Documentation Page

1. Report No.
SSC 360

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
MARINE COMPOSITES
Investigation of Fiberglass Reinforced Plastics in Marine Structures

5. Report Date
June, 1990

6. Performing Organization Code

7. Author(s)
Eric Greene

8. Performing Organization Report No.
SR 1328

9. Performing Organization Name and Address
Eric Greene Associates, Inc.
18 Cushing Avenue
Annapolis, Maryland 21403

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTCG23-89-C-20015

12. Sponsoring Agency Name and Address
Ship Structure Committee
U. S. Coast Guard
2100 Second Street
Washington, DC 20593-001

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
G-M

15. Supplementary Notes

16. Abstract

The use of Fiberglass Reinforced Plastic (FRP) has increased recently in marine structures with a minimum of engineering analysis and design evolution. Although fiberglass has been used for many years in small recreational and high-performance boats, a range of new composite materials are now being utilized for various applications. The objective of this document is to examine the use of FRP and other composite materials in marine construction; determine important considerations in past design; review developments in related industries; predict areas for future marine applications; and recommend future research needs.

Reference information for this project included investigations of previous researchers, materials manufacturers' data and marine industry survey results. The publication is organized into the following chapters:

- Applications
- Materials
- Design
- Performance
- Fabrication
- Testing
- Reference

17. Key Words
Fiberglass Reinforced Plastic (FRP)
Composites, Hull Structure, Reinforcement
Material, Resin, Sandwich Construction

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, VA 22161 and the Marine Technical Information Facility, National Maritime Research Center, Kings Point, NY 10024-1699

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	284	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Naval architecture; Marine engineering; Marine hulls; Hulls structure; Fiberglass/reinforced plastics; Fiber reinforced composites; Sandwich construction; Loads forces/hydrodynamics; Ship design. (MM)

Preface

The use of Fiberglass Reinforced Plastic (FRP) has increased recently in marine structures with a minimum of engineering analysis and design evolution. Although fiberglass has been used for many years in small recreational and high-performance boats, a range of new composite materials are now being utilized for various applications. The objective of this document is to examine the use of FRP and other composite materials in marine construction; determine important considerations in past design; review developments in related industries; predict areas for future marine applications; and recommend future research needs.

This publication has been developed for use by designers and builders in the FRP marine industry. Most of the materials and applications were drawn from current practice in the United States. All data is presented in English units, although an extensive set of conversion tables is included in Chapter Seven.

The FRP marine industry in this country is market driven with very little structure. Consequently, little formal engineering guidance is available. This document attempts to summarize the works of investigators over the past thirty years who have studied both the theoretical and experimental performance of FRP in a marine environment.

An industry survey was performed as part of this project to provide input regarding the building practices and materials in use today. The responses from over 200 manufacturers are included in the report in graphic form.

Although formulas are presented to give the reader some insight into the variables that influence the behavior of a composite structure, current state-of-the-art does not satisfactorily predict the exact strength of laminates found in marine construction. The behavior of sandwich panels under extreme dynamic load is only recently being understood. In addition, a database of tested physical properties for the myriad of materials presented and possible orientations has yet to be established. This sort of comprehensive test program is needed by the industry to support the rule-based design guidance developed by classification organizations.

Contents

Chapter One APPLICATIONS

Chapter Two MATERIALS

Chapter Three DESIGN

Chapter Four PERFORMANCE

Chapter Five FABRICATION

Chapter Six TESTING

Chapter Seven REFERENCE

This page intentionally left blank

Recreational Marine Industry

Over 30 years of FRP boat building experience stands behind today's pleasure boats. Complex configurations and the advantages of seamless hulls were the driving factors in the development of FRP boats. FRP materials have gained unilateral acceptance in pleasure craft because of light weight, vibration damping, corrosion resistance, impact resistance, low construction costs and ease of fabrication, maintenance and repair.

Fiberglass construction has been the mainstay of the recreational boating industry since the mid 1960's. After about 20 years of development work, manufacturers seized the opportunity to mass produce easily maintained hulls with a minimum number of assembled parts. Much of the early FRP structural design work relied on trial and error, which may have also led to the high attrition rate of start-up builders. Current leading edge manufacturing technologies are driven by racing vessels, both power and sail.

Racing Powerboats

The structural components of a powerboat called the *Aramid Arrow* are an aramid prepreg and honeycomb sandwich composite. The boat weighs 3300 pounds, consumes 11 gallons of fuel per hour at 32 knots, and has a top cruising speed of 42 knots. [1-1]

The winner of the 1984 "Round Britain Powerboat Race" was *White Iveco*, which averaged as high as 69 knots on one leg of the race. The hull is constructed in a sandwich configuration with glass mat/aramid over 0.8 inch Contourkore® (bottom), 0.4 inch Contourkore® (sides), and 0.5 inch core (deck). The 36 foot hull and deck structure weighs 4600 pounds. [1-2]

Racing boats employ advanced and hybrid composites for a higher performance craft and driver safety. Fothergill Composites Inc., Bennington, VT, has designed, tested and manufactured a safety cell cockpit for the racing boat driver. The safety cell is constructed of carbon and aramid fibers with aramid honeycomb core. This structure can withstand a 100 foot drop test without significant damage. During the Sacramento Grand Prix, three drivers in safety cell equipped boats survived injury from accidents. The performance advantage of advanced composites was clearly demonstrated in 1978 in the Offshore Racing circuit, where boats constructed using aramid fiber reinforcement won 8 of the 10 races, including the U.S. and the World Championships. [1-3]

Racing Sailboats

Over the past ten years, the American Bureau of Shipping (ABS) has reviewed over 400 different design plans for racing yachts. Designers used the "ABS Guide for Building and Classing Offshore Racing Yachts" [1-4] for scantling development. Some of these vessels have successfully endured very heavy weather for long periods in events such as the "Whitbread Round the World Race" and the "Sydney Hobart Race."

The 77 foot carbon-glass-foam sandwich ketch *Great Britain II*, launched in 1973, won the 1975-1976 "Financial Times Clipper Race" and set a record of 134.5 days for the 1977-1978 "Whitbread Round the World Race." *British Oxygen*, a 70 foot GRP ocean racing catamaran launched in 1974, won the "Round Britain Race" that year. Launched in 1978, the *Great Britain IV* was a carbon-glass hybrid composite ocean racing trimaran which won its first event, the 1978 "Round Britain Race." The *Brittany Ferries GB*, a 65 foot carbon-aramid-foam sandwich composite trimaran, won the 1981 Two-Handed TransAtlantic Race. The *Elf Aquitaine II* was a 60 foot catamaran and, at the time, the largest structure built in carbon fiber. The *Formule TAG* was the world's largest racing catamaran when it was launched in September 1983. The hulls are aramid-epoxy prepreg and measure 80 x 42 feet, and the sailing weight is 20,000 pounds. This is possibly the fastest sailing yacht in the world, having covered 524 nautical miles in 24 hours and averaging 21.8 knots. One of the lightest racing hulls built was the 35 foot *Summer Wine*, a contender for the British Admirals Cup, which weighed 580 pounds just out of the mold. Her construction was Divinycell sandwich with unidirectional carbon fibers. A carbon fiber rudder was also used. The 60 foot carbon framed trimaran *Apricot* won the 1985 "City of Plymouth Round Britain and Ireland Race," the 1985 "TAG Round Europe Multihull Race," and Class II of the 1986 "TransAtlantic Race." *Apricot* is capable of 30 knots under full sail. The *Colt Cars GB II*, built by Mitsubishi Marine as an entrant for the 1985-1986 "Whitbread Race," was at the time the world's largest monocoque composite yacht. The *UBS Switzerland* was the first boat to cross the line at the end of the 1985-1986 "Whitbread Race." The 80 foot, 4400 pound hull was constructed with aramid prepreg over aramid honeycomb core and additional aramid fabric resulting in a hull thickness of 0.16 inches.

The Spectrum 42 cruising catamaran incorporates the same structural techniques and materials as the racing catamarans. The laminate is varied throughout the boat to achieve optimal strength and fiber orientation. Unidirectional, aramid and E-glass tri-axial fibers are used. Carbon fibers are used in the crossbeam and in areas where extra reinforcement is needed. The boat's initial production weight was estimated to be 30% lighter than any production multihull of equivalent size. [1-5]

Several classes of boats were pioneers for various construction and production techniques and are presented here as illustrations of the industry's evolutionary process.

Sunfish

The perennial sunfish has served as the introduction to the sport for many sailors. The simplicity of the lanteen rig and the board-like hull make the craft ideal for beaching and cartopping. Alcort has produced over 250,000 of them since their inception in 1952. The basically two-piece construction incorporates a hard chine hull to provide inherent structural stiffening.

Boston Whaler

Boston Whaler has manufactured a line of outboard runabouts since the early 1960's. The 13 foot tri-hull has been in production since 1960 with over 70,000 built. The greatest selling feature of all their boats is the unsinkable hull construction resulting from a thick foam sandwich construction. Hull and deck sections are sprayed-up with ortho-polyester resin to a 33% glass content in massive steel molds before injected with an expanding urethane foam. The 1¾ to 2½ inch core provides significant strength to the hull, enabling the skins to be fairly thin and light. Another interesting component on the Whalers is the seat reinforcement, which is made of fiberglass reinforced Zytel, a thermoplastic resin.

Block Island 40

The Block Island 40 is a 40 foot yawl that was designed by William Tripp and built by the American Boat Building Co. in the late 1950's and early 1960's. At the time of construction, the boat was the largest offshore sailboat built of fiberglass. Intended for transatlantic crossings, a very conservative approach was taken to scantling determination. To determine the damage tolerance of a hull test section, a curved panel was repeatedly run over with the designer's car. The mat/woven roving lay-up proved adequate for this trial as well as many years of in-service performance. At least one of these craft is currently enjoying a second racing career thanks to some keel and rig modifications.

Laser International

Doyle and Hadley-Coates applied a mathematical model to the case of a Laser 14 foot racing dinghy. The model successfully analyzed the causes of structural failure from launching and beaching such boats in Saudi Arabia. [1-6]

Laser International invested $1.5 million in the development and tooling of a new, bigger boat, the 28 foot Farr Design Group Laser 28. The Laser 28 has a PVC foam core deck with aramid fabric inner and outer skins. A dry sandwich mold is injected with a slow curing liquid resin through multiple entry ports, starting at the bottom of the mold and working upward. [1-7]

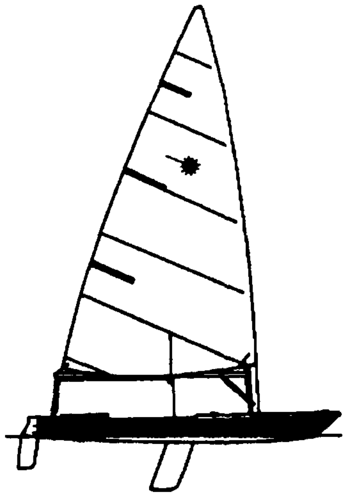


Figure 1-1 14 Foot Laser Sailboat [Laser International]

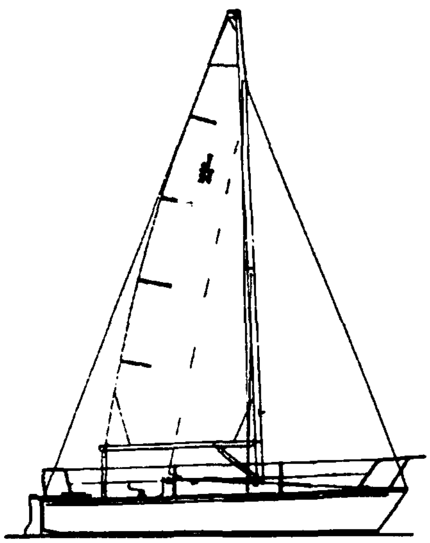


Figure 1-2 International J/24 Sailboat [J /Boats]

J/24

The J/24 fractional rigged sloop has been manufactured since 1977 at the rate of about 500 per year. The vessel has truly become a universally accepted "one-design" class allowing sailors to race on a boat-for-boat basis without regard for handicap allowances. Part of the fleet's success is due to the manufacturer's marketing skills and part is due the boat's all-around good performance. The hull construction is cored with "Contourkore" end-grain balsa. Tillotson-Pearson manufactures J/Boats along with Freedoms, Rampages and Aldens. The company supports extensive R & D and quality control programs.

IMP

IMP is a 40 foot custom ocean racing sloop that represented the U.S. in the Admiral's Cup in 1977 and 1979. She is probably the most successful design of Ron Holland, with much of her performance attributable to sophisticated construction techniques. The hull and deck are of sandwich construction using a balsa core and unidirectional reinforcements in vinyl ester resin. Primary rig and keel loads are anchored to an aluminum box and tube frame system, which in turn is bonded to the hull. In this way, FRP hull scantlings are determined primarily to resist hydrodynamic forces. The resulting hybrid structure is extremely light and stiff. The one-off construction utilized a male mold, which has become the standard technique for custom racing boats.

Bertram

Bertram Yachts has built cruiser and sport fisherman type powerboats since 1962. Their longevity in the business is in part attributable to sound construction and some innovative production techniques. All interior joinery and structural elements are laminated to a steel jig, which positions these elements for precise attachment to the hull. A combination of mat, woven roving, knitted reinforcements and carbon fibers are used during the hand lay-up of Bertram craft.

Westport Shipyard

The Westport Shipyard developed their variable size mold concept when they found that a 70 foot by 20 foot mold was constantly being modified to fabricate vessels of slightly different dimensions. A single bow section is joined to a series of shapable panels that measure up to 10 feet by 48 feet. The panels are used to define the developable sections of the hull. Since 1983, 40 to 50 hulls have been produced using this technique. Expensive individual hull tooling is eliminated thus making custom construction competitive with aluminum. A layer of mat and four woven rovings can be layed-up wet with impregnator machines.

Christensen Motor Yacht

Christensen has been building a line of semi-custom motor yachts over 100 feet long, as illustrated in Figure 1-3. The hulls are foam cored using a vacuum assist process. All yachts are built to ABS✠A1✠AMS classification and inspection.

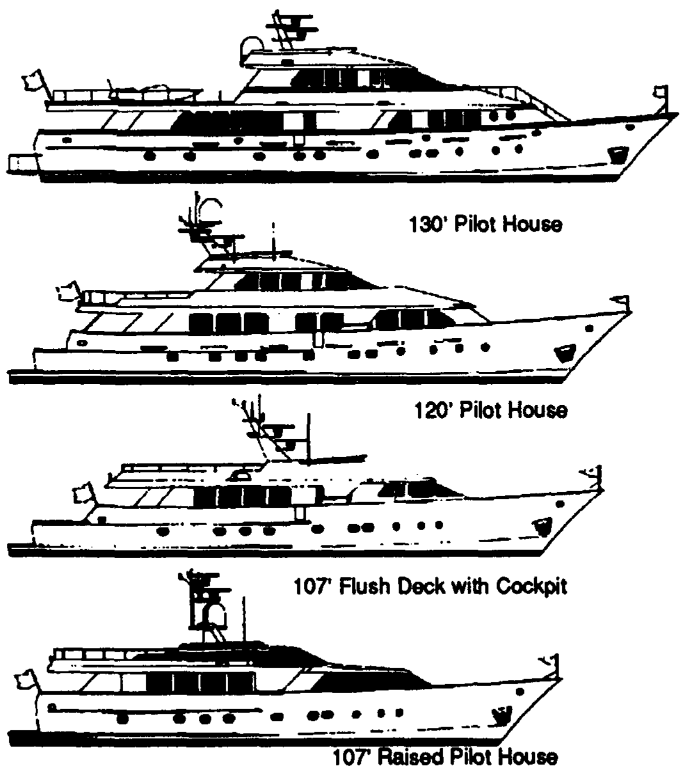


Figure 1-3 Motor Yachts Greater than 100 feet Produced by Christensen Motor Yacht Corporation [Christensen]

Canoes and Kayaks

Competition canoes and kayaks employ advanced composites because of the better performance gained from lighter weight, increased stiffness and superior impact resistance. Aramid fiber reinforced composites have been very successful, and new fiber technologies using polyethylene fiber reinforcement are now being attempted. The boat that won the U.S. National Kayak and Canoe Racing Marathon was constructed with a new high molecular weight polyethylene fiber and was 40% lighter than the identical boat made of aramid fiber. [1-3]

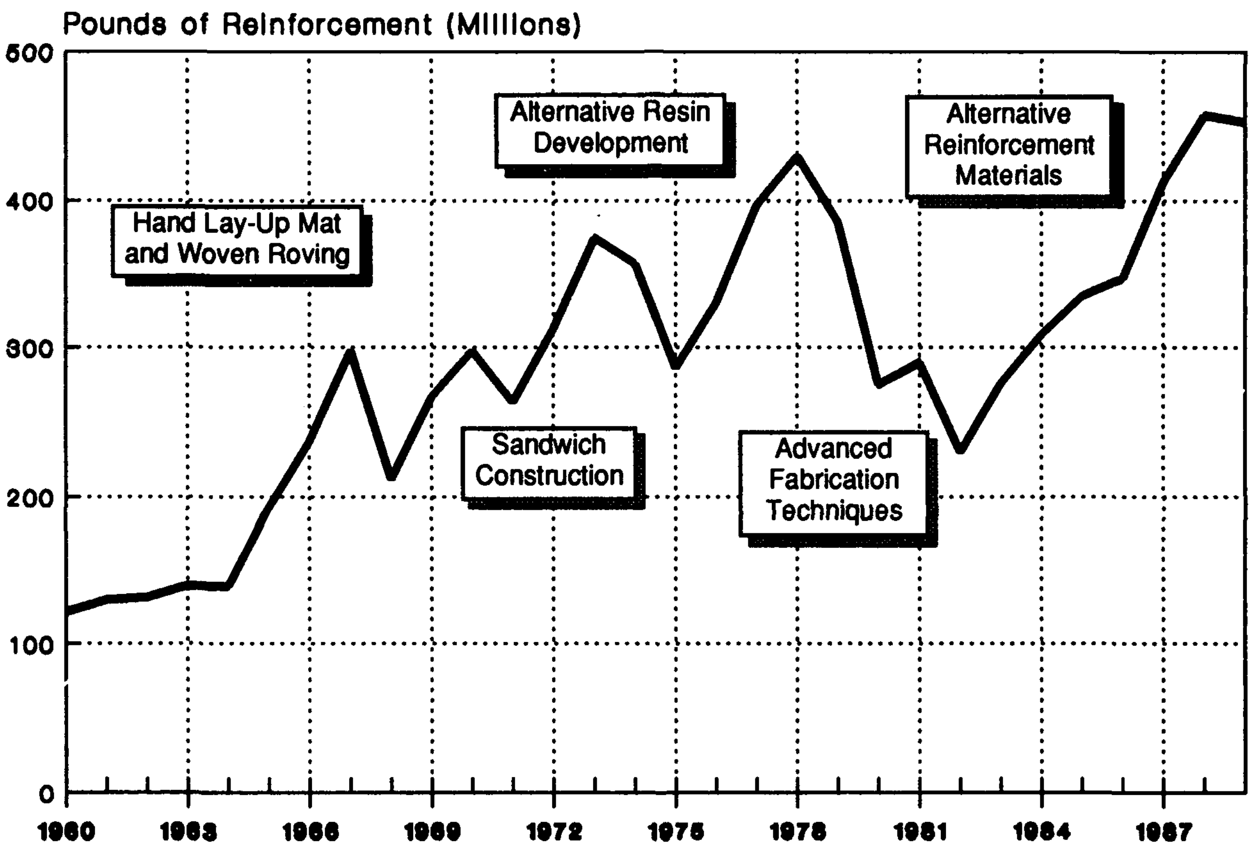


Figure 1-4 Annual Shipment of Reinforced Thermoset and Thermoplastic Resin Composites for the Marine Industry with Associated Construction Developments. [Data Source: SPI Composites Institute (1960-1973 Extrapolated from Overall Data and 1989 is Estimated)]

Evolution of Recreational Boat Construction Techniques

From the 1950's to the 1980's, advances in materials and fabrication techniques used in the pleasure craft industry have helped to reduce production costs and improve product quality. Although every boat builder employs unique production procedures that they feel are proprietary, general industry trends can be traced over time as illustrated in Figure 1-4.

Single-Skin Construction

Early fiberglass boat building produced single-skin structures with stiffeners to maintain reasonable panel sizes. Smaller structures used isotropic chopped strand mat layed-up manually or with a chopper gun. As strength requirements increased, fiberglass cloth and woven roving were integrated into the laminate. An ortho-polyester resin, applied with rollers, was almost universally accepted as the matrix material of choice.

Sandwich Construction

In the early 1970's, designers realized that increasingly stiffer and lighter structures could be realized if a sandwich construction technique was used. By laminating an inner and outer skin about a low density core, reinforcements are located at a greater distance from the panel's neutral axis. These structures perform exceptionally well when subjected to bending loads produced by hydrodynamic forces. PVC foam and end-grain balsa have evolved as the primary core materials.

Resin Development

General purpose ortho-polyester laminating resins still prevail throughout the boating industry due to its low cost and ease of use. However, boat builders of custom and higher-end craft have used a variety of other resins that exhibit better performance characteristics. Epoxy resins have long been known to have better strength properties than polyesters. Their high cost has limited use to only the most specialized of applications. Iso-polyester resin has been shown to resist blistering better than ortho-polyester resin and some manufacturers have switched to this entirely or for use as a barrier coat. Vinyl ester resin has performance properties somewhere between polyester and epoxy, exceeding epoxy in some respects, and has recently been examined for its excellent blister resistance. Cost is greater than polyester but less than epoxy.

Unidirectional and Stitched Fabric Reinforcement

The boating industry was not truly able to take advantage of the directional strength properties associated with fiberglass until unidirectional and stitched fabric reinforcements became available. Woven reinforcements, such as cloth or woven roving, have the disadvantage of "pre-buckling" the fibers, which greatly reduces in-plane strength properties. Unidirectional reinforcements and stitched fabrics that are actually layers of unidirectionals offer superior characteristics in the direction coincident with the fiber axis. Pure unidirectionals are very effective in longitudinal strength members such as stringers or along hull centerlines. The most popular of the knitted fabrics is the 45° by 45° knit which exhibits superior shear strength and is used to strengthen hulls torsionally and to tape-in secondary structure.

Advanced Fabrication Techniques

Spray-up with chopper guns and hand lay-up with rollers are the standard production techniques that have endured for 30 years. In an effort to improve the quality of laminated components, some shops have adapted techniques to minimize voids and increase fiber ratios. One technique involves placing vacuum bags with bleeder holes over the laminate during the curing process. This has the effect of applying uniform pressure to the skin and drawing out any excess resin or entrapped air. Another technique used to achieve consistent laminates involves using a mechanical impregnator which can produce 55% fiber ratios.

Alternate Reinforcement Materials

The field of composites gives the designer the freedom to use various different reinforcement materials to improve structural performance over fiberglass. Carbon and aramid fibers have evolved as two high strength alternatives in the marine industry. Each material has its own advantages and disadvantages, which will be treated in a later chapter. Suffice it to say that both are significantly more expensive than fiberglass but have created another dimension of options with regards to laminate design. Some low-cost reinforcement materials that have emerged lately include polyester and polypropylene. These materials combine moderate strength properties with high strain-to-failure characteristics.

Commercial Marine Industry

The use of fiberglass construction in the commercial marine industry has flourished over time for a number of different reasons. Initially, long-term durability and favorable fabrication economics were the impetus for using FRP. More recently, improved vessel performance through weight reduction has encouraged its use. Since the early 1960's, a key factor that makes FRP construction attractive is the reduction of labor costs when multiple vessels are fabricated from the same mold. Various sectors of the commercial market will be presented via examples of craft and their fabricators. Activity levels have traditionally been driven by the economic factors that influence the vessels' use, rather than the overall success of the vessels themselves.

Fishing Industry

Although the production of commercial vessels has tapered off drastically, there was much interest in FRP trawlers during the early 1970's. These vessels that are still in service provide testimony to the reduced long-term maintenance claims which led to their construction. For example, the 55 foot *POLLY ESTER* has been in service in the North Sea since 1967. Shrimp trawlers were the first FRP fishing vessels built in this country with the *R.C. BRENT*, launched in 1968. Today, commercial fishing fleets are approximately 50% FRP construction. Other aspects of FRP construction that appeal to this industry include increased hull life, reduction in hull weight and cleaner fish holds.

AMT Marine

AMT Marine in Quebec, Canada is probably today's largest producer of FRP commercial fishing vessels in North America. They offer stock pot fishers, autoliners, seiners and stern trawlers from 25 feet to 75 feet. Over 100 craft have been built by the company in the 11 years of their existence, including 80% of all coastal and offshore fishing vessels registered in Quebec in recent years. AMT utilizes a variety of materials and manufacturing processes under the direction of their R & D department to produce rugged utility and fishing craft.

Delta Marine

Delta Marine in Seattle has been designing and building fiberglass fishing, charter and patrol boats for over 20 years. A 70 foot motor yacht has been developed from the highly successful Bearing Sea Crabber. Yachts have been developed with 105 foot and 120 foot molds, which could easily produce fishing boats if there was a demand for such a vessel. The hulls can be fitted with bulbous bows, which are claimed to increase fuel economy and reduce pitching. The bulb section is added to the solid FRP hull after it is pulled from the mold. Delta Marine fabricates sandwich construction decks utilizing balsa core.

Lequerq

Another FRP commercial fishboat builder in Seattle is Lequerq. They specialize in building seiners for Alaskan waters. The average size of the boats they build is 50 feet. At the peak of the industry, the yard was producing 15 boats a year for customers who sought lower maintenance and better cosmetics of their vessels. Some customers stressed the need for fast vessels and as a result, semi-displacement hull types emerged that operated in excess of 20 knots. To achieve this type of performance, Airex® foam cored hulls with directional glass reinforcements were engineered to produce hull laminate weights of approximately three pounds per square foot.

Young Brothers

Young Brothers is typical of a number of FRP boatbuilders in Maine. Their lobster and deck draggers range in size from 30 to 45 feet and follow what would be considered traditional hull lines with generous deadrise and full skegs to protect the props. Solid FRP construction is offered more as a maintenance advantage than for its potential weight savings. Following the path of many commercial builders, this yard offers the same hulls as yachts to offset the decline in the demand for commercial fishing vessels.

Lifeboats

The first FRP lifeboats were built in Holland in 1958 when Airex foam core made its debut in a 24 foot vessel. The service profile of these vessels make them ideally suited for FRP construction in that they are required to be ready for service after years of sitting idle in a marine environment. Additionally, the craft must be able to withstand the impact of being launched and swinging into the host vessel. The ability to economically produce lightweight hull and canopy structures with highly visible gelcoat finishes is also an attribute of FRP construction.

Watercraft America

Watercraft is a 40 year old British company that began operations in the U.S. in 1974. The company manufactures 21, 24, 26 and 28 foot USCG approved, totally enclosed, survival craft suitable for 23, 33, 44 and 58 men, respectively. Design support is provided by Hampton University in England. The vessels are diesel propelled and include compressed air systems and deck washes to dissipate external heat. Figure 1-5 shows the general configuration of these vessels. The plumbing incorporates PVC piping to reduce weight and maintenance. Hull and canopy construction utilizes a spray layup system with MIL-1140 or C19663 gun roving. Resin is MIL-2-21607 or MIL 7575C, Grade 1, Class 1, fire retardant with Polygard iso/mpg gelcoat finish. Each pass of the chopper gun is manually consolidated with a roller and overlaps the previous pass by one third of its width. Quality control methods ensure hardness, thicknesses and weight of the finished laminate.

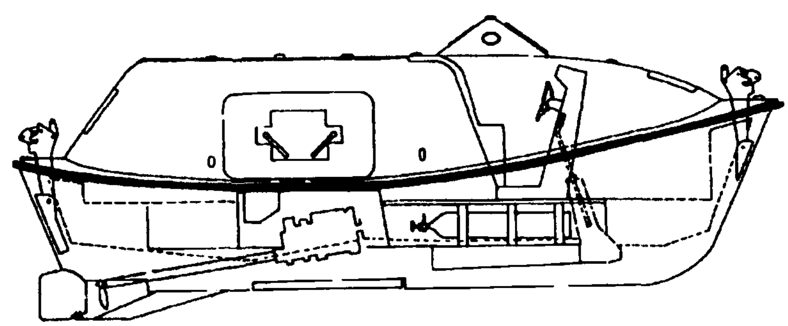


Figure 1-5 Typical Configuration of Watercraft Enclosed Liferaft [Watercraft]

The company has diversified into a line of workboats and Subchapter T passenger vessels to offset the decline in the offshore oil business. Reliance Workboats of England and Watercraft America Inc. have teamed up to build the Workmaster 1100 multipurpose boat. The 36 foot boats can travel in excess of 50 mph and can be custom fitted for groups such as customs and law enforcement agencies, commercial or charter fishing operators, and scuba-diving operators. The boat was introduced in Britain in early 1989 and recently in America. [1-8]

Schat-Marine Safety

A more diversified line of lifeboats meeting CFR 160.035 is offered by the Schat-Marine Safety Corporation. Although they claim that fiberglass construction is the mainstay of the lifeboat industry, steel and aluminum hulls are offered in 27 different sizes ranging from 12 to 37 feet with capacities from 4 to 145 persons. Molds for FRP hulls exist for the more popular sizes. These hulls are made of fiberglass and fire retardant resins which are by far the most maintenance free and feature built-in, foamed in place flotation.

The company also manufacturers FRP rigid hull inflatable rescue boats (RIBs), fairwaters, ventilators, lifefloats and buoyancy apparatus.

Utility Vessels

Boats built for utility service are usually modifications of existing recreational or patrol boat hulls. Laminate schedules may be increased or additional equipment added, depending upon the type of service. Local and national law enforcement agencies including natural resource management organizations compromise the largest sector of utility boat users. Other mission profiles, including pilotage, fire-fighting and launch service, have proven to be suitable applications of FRP construction. To make production of a given hull form economically attractive, manufacturers will typically offer a number of different topside configurations for each hull.

Boston Whaler

Using similar construction methods outlined for their recreational craft, Boston Whaler typically adds some thickness to the skins of their commercial boats. Hulls 17 feet and under are of tri-hull configuration while the boats above 18 feet are a modified deep-'V' with a deadrise angle of 18 degrees. The majority of boats configured for commercial service are for either the Navy, Coast Guard or Army Corps of Engineers. Their durability and proven record make them in demand among local agencies.

LeComte

LeComte Holland BV manufactures versatile FRP landing craft using vacuum-assisted injection molding. S-glass, carbon and aramid fibers are used with polyester resin. The entire hull is molded in one piece using male and female molds via the resin transfer molding (RTM) process.

LeComte introduced a new type of rigid hull, inflatable rescue boat. The deep-'V' hull is made by RTM with hybrid fibers, achieving a 25% weight savings over conventional methods. Boat speeds are in excess of 25 knots. [1-9]

Textron Marine Systems

Textron Marine Systems has long been involved with the development of air cushion and surface effect ships for the government. In 1988, the company implemented an R & D program to design and build a small air cushion vehicle with a minimal payload of 1200 pounds. The result is a line of vessels that range in size from 24 to 52 feet that are fabricated from shaped solid foam block, which is covered with GRP skins. The volume of foam gives the added value of vessel unsinkability. Shell Offshore Inc. has recently taken delivery of a 24 foot version for use near the mouth of the Mississippi River. Figure 1-6 shows a typical cargo configuration of the type of vessel delivered to Shell.

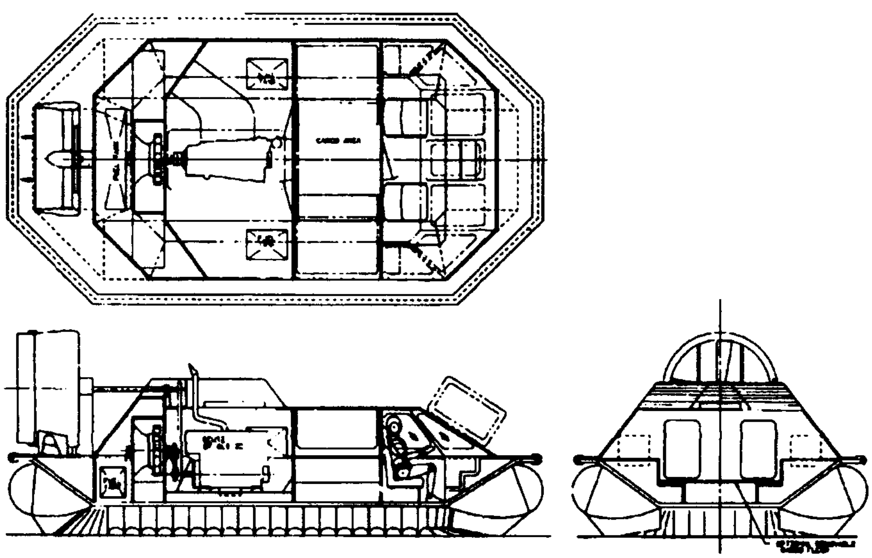


Figure 1-6 Cargo Configuration for Textron Marine's Utility Air Cushion Vehicle - Model 1200 [Textron Marine]

Passenger Ferries

Blount Marine

Blount Marine has developed a proprietary construction process they call Hi-Tech© that involves the application of rigid polyurethane foam over an aluminum stiffening structure. A fleet of these vessels have been constructed for New York City commuter runs.

Karlskronavarvet, AB

Karlskronavarvet, AB in Karlskrona, Sweden, is among several European shipyards that build passenger and automobile ferries. The Surface Effect Ship (SES), *JET RIDER* is a high speed passenger ferry designed and fabricated by Karlskronavarvet in 1986 for service in Norway. The SES *JET RIDER* is an air cushioned vehicle structured entirely of GRP sandwich. The SES configuration resembles a traditional catamaran except that the hulls are much narrower. The bow and stern are fitted with flexible seals that work in conjunction with the hulls to trap the air cushion. Air flow for a surface effect ship is shown in Figure 1-7. The air cushion carries about 85% of the total weight of the ship with the remaining 15% supported by the hulls. The design consists of a low density PVC cellular plastic core material with closed, non-water-absorbing cells, covered with a face material of glass fiber reinforced polyester plastic. The complete hull, superstructure and foundation for the main engines and gears are also built of GRP sandwich. Tanks for fuel and water are made of hull-integrated sandwich panels. The speed under full load is 42 knots (full load includes 244 passengers and payload totaling 27 metric tonnes). [1-10]

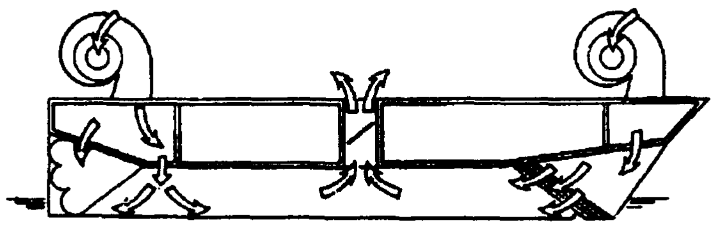


Figure 1-7 Air Flow in a Surface Effect Ship [Hellbratt & Gullberg, *The High Speed Passenger Ferry* SES JET RIDER]

Air Ride Craft

Don Burg has patented a surface effect ship that utilizes a tri-hull configuration and has developed the concept for the passenger ferry market. Although the 109 foot version is constructed of aluminum, the 84 and 87 foot counterparts are constructed from Airex-cored fiberglass to ABS specifications. The FRP vessels are constructed in Hong Kong by Cheoy Lee Shipyards, a pioneer in Far East FRP construction. To their credit is a 130 foot, twin-screw motor yacht that was constructed in 1976.

Italcraft

Italcraft has developed a 70 foot aramid/GRP hull with variable geometry to achieve high speeds. The prototype demonstrated a 50 knot speed potential with 40% fuel savings. The concept is being developed for a high-speed passenger ferry to accommodate 80 passengers and attain a cruising speed of 43 knots. [1-11]

Commercial Ship Construction

In 1971, the Ship Structure Committee published a detailed report entitled "Feasibility Study of Glass Reinforced Plastic Cargo Ship" prepared by Robert Scott and John Sommella of Gibbs & Cox. A 470 foot, dry/bulk cargo vessel was chosen for evaluation whereby engineering and economic factors were considered. It would be instructive to present some of the conclusions of that study at this time.

- The general conclusion was that the design and fabrication of a large GRP cargo ship was shown to be totally within the present state-of-the-art, but the long-term durability of the structure was questionable.
- The most favorable laminate studied was a woven-roving/unidirectional composite, which proved 43% lighter than steel but had 20% of the stiffness.
- GRP structures for large ships currently can't meet present U.S. Coast Guard fire regulations and significant economic incentive would be necessary to pursue variants.

- Cost analyses indicate unfavorable required freight rates for GRP versus steel construction in all but a few of the sensitivity studies.
- Major structural elements such as deckhouses, hatch covers, king posts and bow modules appear to be very well suited for GRP construction.
- Commercial vessels of the 150-250 foot size appear to be more promising than the vessels studied and deserve further investigation.

There are numerous non load-bearing applications of FRP materials in commercial ships where either corrosion resistance, weight or complex geometry justified the departure from conventional materials. As an example, in the early 1980's, Farrell Lines used FRP false stacks in their C10 vessels that weighed over 30 tons. Also, piping for ballast and other applications is commonly made from FRP tubing.

Commercial Deep Sea Submersibles

Foam cored laminates are routinely being used as buoyancy materials in commercial submersibles. The Continental Shelf Institute of Norway has developed an unmanned submersible called the SNURRE, with an operating depth of 1,500 feet, that uses high crush point closed cell PVC foam material for buoyancy. From 1977 to 1984 the SNURRE operated successfully for over 2,000 hours in the North Sea. The French manned submersible, NAUTILE, recently visited the sea floor at the site of the Titanic. The NAUTILE is a manned submersible with operating depths of 20,000 feet and uses high crush point foam for buoyancy and FRP materials for non-pressure skins and fairings. The oil industry is making use of a submersible named DAVID that not only utilizes foam for buoyancy, but uses the foam in a sandwich configuration to act as the pressure vessel. The use of composites in the DAVID's hull allowed the engineers to design specialized geometries that are needed to make effective repairs in the offshore environment. [1-3]

Slingsby Engineering Limited designed and developed a third-generation remotely operated vehicle, called *SOLO*, for a variety of inspection and maintenance functions in the offshore industry. *SOLO* carries a comprehensive array of sophisticated equipment and is designed to operate at a depth of 5,000 feet under a hydrostatic pressure of 2 ksi. The pressure hull, chassis and fairings are constructed of glass fiber woven roving. [1-12]

A prototype civilian submarine has been built in Italy for offshore work. The design consists of an unpressurized, aramid-epoxy outer hull and offers a better combination of low weight with improved stiffness and impact toughness. The operational range at 12 knots has been extended by two hours over the range of a glass hull. [1-13]

Navigational Aids

Steel buoys in the North Sea are being progressively replaced with plastic buoys due to increasing concern of damage to vessels. Balmoral Glassfibre produces a complete line of buoys and a light tower made of GRP that can withstand winds to 125 mph. Anchor mooring buoys supplied to the Egyptian offshore oil industry are believed to be the largest GRP buoys ever produced. These 13 foot diameter, 16.5 ton reserve buoyancy moorings are used to anchor tankers of up to 330,600 ton capacity. [1-14]

Offshore Engineering

Composite materials are already being used in offshore hydrocarbon production because of their lightness, resistance to corrosion and good mechanical properties. One proposed new use for composites is for submarine pipelines, with circumferential carbon fibers providing resistance to external pressure and longitudinal glass fibers providing lengthwise flexibility. [1-9]

Another application for deep sea composites is drilling risers for use at great water depths. Composites would significantly reduce the dynamic stress and increase either the working depth or the safety of deep water drilling. Fifty foot lines made from carbon and glass fibers, with a burst pressure of 25 ksi, have been effectively subjected to three successive drilling sessions to 10 ksi from the North Sea rig *PENTAGONE 84*. [1-9]

Piling Forms and Jackets

Downs Fiberglass, Inc. of Alexandria, VA has developed a line of forms and jackets for use in the building and restoration of bridge columns. The "tidal zone" of maritime structures is known to endure the most severe erosion effects and traditionally is the initial area requiring restoration. Common practice involves the use of a pourable epoxy to encapsulate this portion of decaying piles.

The forms shown in Figure 1-8 are lightweight permanent forms with specially treated inner surfaces to enhance bonding characteristics. The basic jacket material is E-glass mat and woven roving in a polyester resin matrix.

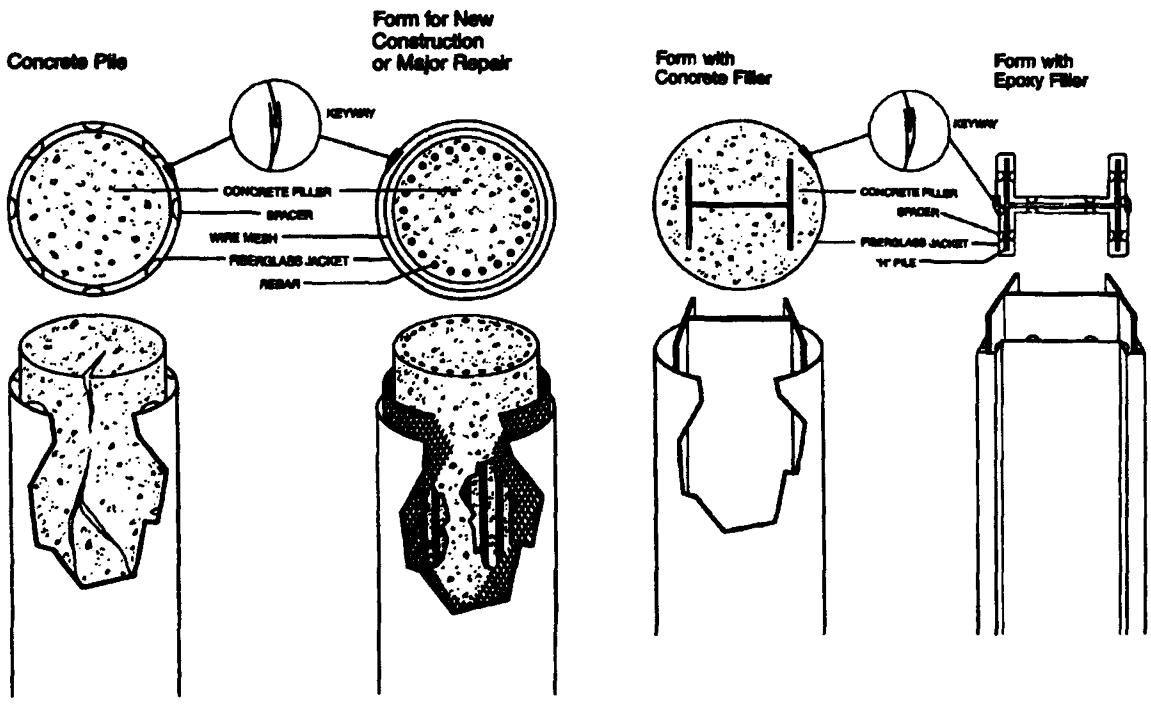


Figure 1-8 Fiberglass Forms and Jackets for Waterline Corrosion Restoration [Downes]

Military Applications of Composites

The Department of Defense has sponsored composites research and development projects to support military applications since World War II. Typically, research has been oriented towards a particular system or platform without regard to integration within or amongst the DoD research entities. Advanced materials investigated by the Air Force and NASA are usually too cost prohibitive for consideration in marine structures. For that reason, this section will deal primarily with the past and current activities of the Navy and the Army.

Navy

According to a study prepared for the U.S. Navy in 1988, the military has been employing composite materials effectively for many years and has an increasing number of projects and investigations underway to further explore the use of composites. [1-3] In 1946, the Navy let two contracts for development of 28 foot personnel boats of laminated plastic. Winner Manufacturing Company used a "bag molding" method while Marco Chemical employed an "injection method." The Navy used the second method for some time with limited success until about 1950 when production contracts using hand layup were awarded. Between 1955 and 1962, 32 Navy craft from 33 to 50 feet in length were manufactured by the "core mold" process, which proved not to be cost effective and was structurally unsatisfactory. [1-15]

During the 1960's, the Navy conducted a series of studies to consider the leasability of using an FRP hull for minesweepers. In 1969, Peterson Builders, Inc. of Sturgeon Bay, WI completed a 34 foot long midship test section. A complete design methodology and process description was developed for this exercise. Although the scale of the effort was formidable, questions regarding economics and materials performance in production units went unanswered. [1-16]

Submarines

One military program which employs composite materials is the *WET SUB*. Its composite components have proven reliable for over 10 years. Both the elevator and the rudders are constructed of a syntactic foam core with fiberglass and polyester skins. The outer skin and hatches, the tail section and the fixed fins on the *WET SUB* are also made of composite materials. [1-3]

The Navy's ROV and mine hunting/neutralization programs have been using composite materials for structural, skin and buoyancy applications. Current ROVs employ composite skins and frames that are constructed from metal molds using the vacuum bagging process. [1-3]

Various submarine structures are made of composite materials, including the periscope fairings on nuclear submarines and the bow dome on combatant submarines. Additionally, the use of filament-wound air flasks for the ballast tanks of the Trident class submarines has been investigated. Unmanned, deep submersibles rely heavily on the use of composites for structural members and for buoyancy. Syntactic foam is used for buoyancy and thick-walled composites are used for pressure housing. One unmanned deep sea submersible, which has a depth rating of 20,000 feet, is constructed with graphite composite by the prepreg fabrication technique. [1-3]

The propellers for the MK 46 torpedo are now being made of composite materials. Molded composite propeller assemblies have replaced the original forged aluminum propellers. The composite propellers are compression molded of glass fiber reinforced polyester resin. Advantages of the new composite propellers include weight savings, chemical inertness and better acoustic properties. Elimination of the metal components markedly reduces detectability. Additionally, studies have projected this replacement to have saved the program about $21 million. [1-3]

A submarine launched missile utilizes a capsule module that is constructed of composite materials. The capsule design consists of a graphite, wet, filament-wound sandwich construction, metal honeycomb core and Kevlar reinforcements. Another torpedo project has investigated using a shell constructed of filament-wound carbon fiber composite in a sandwich configuration. The nose shell of the torpedo was constructed with syntactic foam core and prepreg skins of carbon and epoxy resin. Testing revealed a reduction in noise levels and weight as compared to the conventional aluminum nose shell. [1-3]

Patrol Boats

The Navy has a lot of inshore special warfare craft that are mainly operated by the Naval Reserve Force. More than 500 riverine patrol boats were built between 1965 and 1973. These 32 foot FRP hulls had ceramic armor and waterjet propulsion to allow shallow water operation.

Production of GRP patrol craft for the Navy has not proven to be profitable for several concerns recently. Uniflite built 36 Special Warfare craft, reportedly of GRP/Kevlar® construction, to support SEAL operations in the early 1980's and has since gone out of business. The Sea Viking was conceived as a 35 foot multi-mission patrol boat with provisions for missiles. The project suffered major design and fiscal problems, including an unacceptable weight increase in the lead ship, and eventually its builder, RMI shipyard of San Diego, went out of business.

Mine Counter Measure Vessels

The U.S. Navy in FY 1984 had contracted with Bell Aerospace Textron (now Textron Marine) to design and construct the first of 14 minesweeper hunters (MSH). The hulls were GRP monohulls utilizing surface effect ship technology. Tests showed that the design could not withstand explosive charges and subsequent redesign efforts failed.

In 1986, a contract was issued to Intermarine USA to study possible adaptations of the *LERICI* class craft to carry U.S. systems. The *LERICI* is 167 feet and is made with heavy single skin construction that varies from one to nine inches and uses no frames. Intermarine is currently building the lead ship in Savannah, GA and Avondale Shipyards has been chosen as the Navy's second source for this procurement.

The Swedish and Italian Navies have been building minesweeping operations (MSO) ships with composite technology for many years. The Swedish Navy, in conjunction with the Royal Australian Navy and the U. S. Navy, studied shock loadings during the development of the Swedish composite MSO. Shock loadings (mine explosion simulations) were performed on panels to study candidate FRP materials and configurations such as:

- Shapes of frame terminations
- Frames with different height/width ratio
- Epoxy frames

- Sprayed-up laminates
- Corrugated laminates
- Sandwich with different core densities and thicknesses
- Different types of repairs
- Weight brackets and penetrations on panels
- Adhesion of fire protection coatings in shock
- The effect of double curved surfaces
- Reduced scale panel with bolted and unbolted frames

This extensive testing program demonstrated that a frameless Glass Reinforced Plastic (GRP) sandwich design utilizing a rigid PVC foam core material was superior in shock loading and resulted in better craft and crew survivability. The Swedish shock testing program demonstrates that when properly designed, composite materials can withstand and dampen large shock loads. [1-17] Table 1-1 summarizes the current use of FRP for mine counter measure vessels.

Table 1-1. Current FRP Mine Counter Measure Vessels [ISSC, 1988]

Type of Construction	Class	Country	Builder	Built	Total	Δ (tons)	LOA (m)	Speed (kts)
Stiffened Single Skin	*WILTON*	United Kingdom	Vosper Thornycroft	1		425	46	15
	Hunt	United Kingdom		11	13	725	60	16
	SANDOWN	United Kingdom			9			
	ASTER	Belgium	Beliard	5	10	544	51.5	15
	ERIDAN	France	Lorient Dockyard	6	10	544	49.1	15
	ALKMAAR	Netherlands	Van der Giessen-de Norde	13	15	588	51.5	15
	Modified	Indonesia			2	588	51.5	15
	KIISHI	Finland	Oy Fiskars AB		7	20	15.2	11
	BAMO	France	GESMA MCM		5	900		
Foam Sandwich	*LANDSORT*	Sweden	Karlskronavarvet	4	5	360	47.5	15
	Bay	Australia	Carrington	2	6	170	30.9	10
	Stan Flex 300	Denmark	Danyard Aalborg A/S	7	16	300	54.0	30+
Unstiffened Thick Skin	*LERICI*	Italy	Intermarine, SpA	4	10	520	50	15
	LERICI	Nigeria		2	3	540	51	15.5
	KIMABALU	Malaysia		4	4	540	51	16
	Modified *LERICI*	South Korea	Kang Nam	2	3	540	51	15.5
	OSPREY	United States	Intermarine, USA	0	17	660	57.3	

Components

Composite ship stacks versus conventional steel ship stacks are under investigation for the U.S. surface fleet. Non-structural ship components are being considered as candidates for replacement with composite parts. It is reported that two types of advanced non-structural bulkheads are in service in U.S. Navy ships. One of these consists of aluminum honeycomb with aluminum face sheets, and the other consists of E-glass FRP skins over an aramid core material. [1-3]

The *OSPREY* Class (MHC-51) minehunter incorporates many FRP components including deck gratings, floor plates and support structure. Additional applications for composite materials are being considered for follow-on vessels

The David Taylor Research Center (DTRC) recently contracted for the construction of a shipboard composite foundation. An open design competition attracted proposals featuring hand layup, resin transfer molding, pultrusion and filament winding. A filament wound prototype proposed by Brunswick Defense won out, in part, because the long term production aspects of the manufacturing process seemed favorable. The foundation has successfully passed a shock test.

Development of composite propulsion shafts for naval vessels is being investigated to replace the massive steel shafts that comprise up to 2% of the ship's total weight. Composite shafts of glass and carbon reinforcing fibers in an epoxy matrix are projected to weigh 75% less than the traditional steel shafts and offer the advantages of corrosion resistance, low bearing loads, reduced magnetic signature, higher fatigue resistance, greater flexibility, excellent vibration damping and improved life-cycle cost. [1-3]

Composite pressure vessels are being developed, tested and manufactured for space and military uses. Composite pressure vessels were used in three propulsion systems and the environmental control and life support system for the Space Shuttle *ORBITER*. Johnson Space Center estimated a cost savings of $10 million in fuel over the life-span of the *ORBITER* as compared to all-metal vessels of the Apollo program type. Filament-wound pressure vessels constructed of graphite, fiberglass or Kevlar® with epoxy resins over a titanium liner have been used. Aramid composites are used in the Space Shuttle program to reinforce equipment storage boxes, pressure vessels, purge and vent lines, thus allowing for weight savings and increased stiffness. [1-3]

The U.S. Navy studied the benefits of hydrofoils in 1966. The USN experimental patrol craft hydrofoil (PCH-1) *HIGHPOINT* was evaluated for weight savings. The overall weight savings over HY 80 steel were 44% for glass reinforced plastic, 36% for titanium alloy and 24% for HY 130 steel. In the mid 1970's a hydrofoil control flap (Figure 1-9) and a hydrofoil box beam element applying advanced graphite-epoxy composites were evaluated by the Navy. [1-9]

A recent program evaluated the use of advanced composites instead of steel in the stabilizing flaps of the Italian RHS 160 hydrofoil. Carbon fibers were the primary reinforcement, with glass added for galvanic corrosion resistance. [1-9]

Composite blades of carbon-glass FRP skins over polyurethane foam core have been developed for and used successfully by hovercraft. The FRP blade weighs about 28 pounds, as compared to 40 pounds for its duraluminum counterpart, and tested better in fatigue than the metal blade. [1-9]

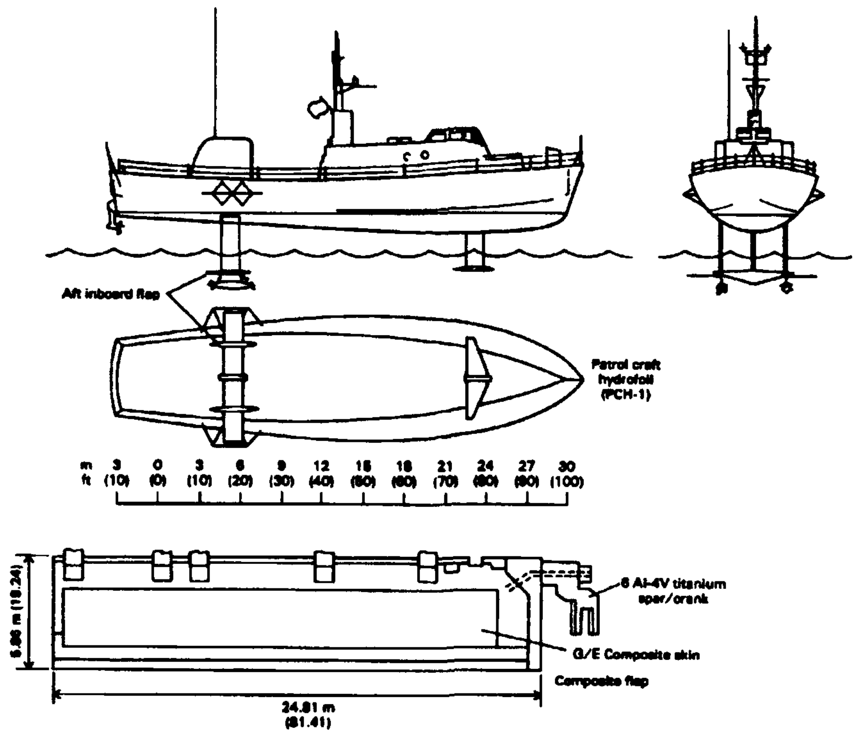


Figure 1-9 U.S. Navy Patrol Craft Hydrofoil (PCH-1) Composite Flap [*ASM Engineer's Guide to Composite Materials*]

The skirts surrounding the air cushion on hovercraft are made with fiber reinforced elastomers. Design and fabrication of three types, bag and finger skirts, loop and segment skirts, and pericell skirts, have been evaluated and are reviewed in the reference. [1-9]

Army

Some pressure vessels constructed of fiberglass and epoxy resin have evidenced burst pressures of 50,000 psi. Kevlar®/epoxy structured pressure vessels had burst pressures of 57,000 psi, and graphite/epoxy structures had burst pressures of 60,000 psi. These lightweight, high pressure composite vessels have the potential for use not only as air supplies in submersibles but also as compressed-air-energy storage systems. [1-3]

Composites are being considered for structural, non-structural and ballistic applications in military combat and logistical support vehicles. In addition to weight reduction, composites will improve maneuvering capability, corrosion resistance, deployability and vehicle survival. Applications already investigated or considered include composite covers for external storage boxes, internal ducts, electrical boxes (non-structural), composite brackets, seat components, and turret basket assembly (structural). Also under development are a composite torsion tube with steel splines to substitute for heavy steel bars, which are used for vehicle suspension. [1-18]

The U.S. Army has investigated the use of composite materials for combat vehicle hull structures, stowage equipment and other mission critical structural components. A feasibility study was performed by FMC Corporation, San Jose, CA under contract to the U.S. Army Tank Automotive Command (TACOM), Warren, MI to determine the technical and economic feasibilities of a composite lower weapon station basket for the M-2 Bradley Fighting Vehicle (BFV). Critical issues were encountered and resolved in regard to design, producibility, material testing and evaluations, crew survivability, and quality assurance and control. FMC Corporation is continuing their development and refinement of composite manufacturing processes to meet the needs of the future. Some projects include composite battery trays, ammunition boxes and other stowage components. The U.S. Army Materials Technology Laboratory is investigating major vehicle component applications such as hulls, turrets and ramp doors. [1-19]

TACOM recognizes the advantages of composite materials for combat and tactical military ground vehicles and is investigating composites for various military vehicle applications. Composite vehicle bodies are being evaluated. One-piece graphite/epoxy driveshafts are being tested on the High Mobility Multipurpose Wheeled Vehicle (HMMWV) to replace the multi-piece metal shaft. TACOM sponsored a contract with General Dynamics that identified components in the Abrams Tank, which are currently fabricated from aluminum or steel but could be made from composites. Non-ballistic components were considered, such as seats, fenders, storage box, air ducts, torsion bar covers and fire extinguisher brackets. Composite road wheels have been designed for the Abrams Tank with equivalent strength as their forged aluminum counterparts but with the potential of reducing vehicle weight by 1,100 pounds; field testing of these is required. Track pins and track shoes for ground vehicles have also been investigated. The M113A3 armored personnel carriers manufactured after June 1987 contain Kevlar spall liners mounted inside the aluminum body to catch spall fragments as a result of projectile impact and prevent further damage to personnel or equipment. [1-20]

Components for the Five Ton Truck were fabricated of composites and road tested. The composite components include the frame (graphite reinforced epoxy), front and rear springs (continuous glass reinforced epoxy), the drive shaft (filament wound graphite reinforced epoxy), wheels (compression molded glass reinforced epoxy), cargo bed (balsa core with fiberglass reinforced polyester and steel plate), seat slats (pultruded glass reinforced polyester), and hood/fender assembly (chopped glass reinforced polyester). The final report on this project is available through DTIC. [1-20]

The U.S. Army is also evaluating two prototype, composite, 7,500 gallon, bulk fuel tankers and comparing them to standard metal tankers. The composite tankers have a composite frame and a flame resistant foam core with glass reinforced resin skins. [1-20]

In addition to the composite material evaluations cited here, composites are currently being used in some military vehicles. The current HMMWV has a glass reinforced, polyester, hood/fender assembly, and some versions have a composite roof. Kevlar® is used in some versions of the HMMWV, such as the ambulance, for the walls and roof. The Commercial Utility Cargo Vehicle has a composite cap. [1-20]

Transportation Industry

The transportation industry represents the best opportunity for growth in structural composites use. As manufacturing technologies mature, the cost and quality advantages of composite construction will introduce more, smaller manufacturers into a marketplace that will be increasingly responsive to change. [1-21] Current FRP technology has long been utilized in the recreational vehicle industry where limited production runs preclude expensive tooling and complex forms are common. Truck hoods and fairing assemblies have been prevalent since the energy crisis in 1974.

Automotive Applications

The automotive industry has been slowly incorporating composite and FRP materials into cars to enhance efficiency, reliability and customer appeal. In 1960, the average car contained approximately 20 pounds of plastic material, while a car built in 1985 has on the average 245 pounds of plastic. Plastic materials are replacing steel in body panels, grills, bumpers and structural members. Besides traditional plastics, newer materials that are gaining acceptance include reinforced urethane, high heat distortion thermoplastics, high glass loaded polyesters, structural foams, super tough nylons, high molecular weight polyethylenes, high impact polypropylenes and polycarbonate blends. New processes are also accelerating the use of plastics in automobiles. These new processing technologies include reaction injection molding of urethane, compression molding, structural foam molding, blow molding, thermoplastic stamping, sheet molding, resin injection molding and resin transfer molding. [1-22]

MOBIK

The MOBIK company in Gerlingen, West Germany, is researching and developing advanced composite engineering concepts in the automotive industry. They believe that tomorrow's car must be economical and functional and more environmentally compatible. Composite Intensive Vehicles (CIVs) will weigh less and thus enable considerable savings in other areas. Lower horsepower engines, less assembly time and cost, longer lifespan and fewer repairs are among the benefits of composite intensive automobiles. In addition, these advanced composites will dampen noise and vibrations, allow for integration of parts, experience less corrosion, need less tooling and equipment transformation, and are recyclable. Obstacles they face include present lack of a high-speed manufacturing technology for advanced composites and new engineering solutions to overcome structural discontinuities. [1-23]

The April 1989 issue of *Plastics Technology* magazine reports that MOBIK has developed a high speed method for making advanced composite preforms for use in structural automotive components. The preforms are made from woven glass fabric and polyetherimide (PEI) thermoplastic. The method enables vacuum forming of 3 by 3 foot preforms in less than 30 seconds at about 20 psi. The method involves high speed fiber placement while the sheet is being thermoformed. MOBIK plans to produce prototype automotive preforms at a pilot plant scheduled to open this fall. Initial applications will also include preforms for aircraft interior cabins.

Ford

Composite driveshafts are being used in the automotive industry. During the 1985 Society of Plastics Industries (SPI) exhibit, Ford Motor Company won the transportation category with a graphite composite driveshaft for the 1985 Econoline van. The driveshaft was constructed of 20% carbon fiber and 40% E-glass fiber in a vinyl ester resin system. The shaft is totally corrosion resistant and weighs 61% less than the steel shaft it replaces. [1-22] Merlin Technologies and Celanese Corporation developed carbon/fiberglass composite driveshafts that, in addition to weight savings, offer reduced complexity, warranty savings, lower maintenance, cost savings, and noise and vibration reduction as compared to their metal counterparts. [1-24]

Another structural composite developmental program, initiated in 1981 by Ford Motor Company, focused on designing a composite rear floor pan for a Ford Escort model. Finite element models predicted that the composite part would not be as stiff but its strength would be double that of the identical steel part. The composite floor pan was made using fiberglass/vinyl ester sheet (SMC) and directionally reinforced sheet (XMC) molding compounds. Stock Escort components were used as fasteners. Ten steel components were consolidated into one composite molding, and a weight savings of 15% was achieved. A variety of static and dynamic material property tests were performed on the prototype, and all the specimens performed as had been predicted by the models. The structural integrity of the part was demonstrated, hence the feasibility of molding a large structural part using selective continuous reinforcements was shown. [1-25]

A sheet molding compound (SMC) material is used to make the tailgate of the Ford Bronco II and is also used in heavy truck cabs. [1-22]

Ford utilizes a blow molded TPE air duct on its Escort automobiles. The front and rear bumper panels of Hyundai's Sonata are made from engineered blow molding (EBM). [1-26]

A study completed by Ford in 1988 confirms the feasibility of extensive plastics use as a means of reducing production costs for low volume automobiles, such as electric powered cars. According to the study, plastics yield a parts reduction ratio of 5:1, tooling costs are 60% lower than for steel stamping dies, adhesive bonding costs are 25-40% lower than welding, and structural composites demonstrate outstanding durability and crashworthiness. Composite front axle crossmember parts have undergone extensive testing in Detroit and await a rationale for production. [1-27]

The Ford Taurus and Mercury Sable cars utilize plastics extensively. Applications include exterior, interior and under the hood components, including grills, instrument panels and outside door handles, to roof trim panels and insulations, load floors, cooling fans and battery trays. The polycarbonate/PBT wraparound front and rear bumpers are injection molded of General Electric's Xenoy® material. [1-28]

Other significant new plastic applications in Ford vehicles include the introduction of the high density polyethylene fuel tank in the 1986 Aerostar van. [1-28]

A prototype graphite reinforced plastic vehicle was built in 1979 by Ford Motor Company. The project's objective was to demonstrate concept feasibility and identify items critical to production. The prototype car weighed 2,504 pounds, which was 1,246 pounds lighter than the same car manufactured of steel. Automotive engineers are beginning to realize the advantages of part integration, simplified production and reduced investment cost, in addition to weight savings and better durability. [1-22]

The Ford Motor Company in Redford, MI established engineering feasibility for the structural application of an HSMC Radiator Support, the primary concern being weight savings. [1-29]

The Ford Motor Company and Dow Chemical Company combined efforts to design, build and test a structural composite crossmember/transverse leaf spring suspension module for a small van. Prototype parts were fabricated and evaluated in vehicle and laboratory tests, and results were encouraging. [1-30]

General Motors

Buick uses Hoechst Celanese's Riteflex® BP 9086 polyester elastomer alloy for the bumper fascia on its 1989 LeSabre for its paintability, performance and processability. [1-26]

The Pontiac Fiero has an all plastic skin mounted on an all steel space frame. The space frame provides all the functional strengthening and stiffening and consists of a five-piece modular design, and the plastic body panels are for cosmetic appearance. The shifter trim plate for the Pontiac Fiero is made of molded styrene maleic anhydride (SMA) and resists warping and scratching, readily accepts paints and exceeds impact targets.

Drive axle seals on the 1985 GM front wheel drive cars and trucks are made of Hytrel polyester elastomer for improved maintenance, performance and life.

Wheel covers for the Pontiac Grand AM are molded of Vydyne mineral reinforced nylon for high temperature and impact resistance. [1-28]

GenCorp Automotive developed a low density sheet molding compound (SMC) that is claimed to be 30% lighter than standard SMC. The material has been introduced on the all-plastic-bodied GM 200 minivan and the 1989 Corvette. [1-26] The automotive exterior panels on the GM 200 APV minivan are plastic. The minivan has polyurea fenders and SMC skin for roofs, hoods and door panels. BMW also uses plastic exterior panels on its Z1 model. [1-31]

Chrysler

In a joint program initiated in 1984 between the Shell Development Company, Houston, TX and the Chrysler Corporation, a composite version of the steel front crossmember for Chrysler's T-115 minivan was designed, fabricated and tested. Chrysler completed in-vehicle proving grounds testing in March 1987. The program increased confidence that composites made from non-exotic commercially available materials and fabrication processes can withstand severe service in structural automotive applications. [1-32]

Chrysler uses nearly 40 pounds of acrylonitrile-butadiene-styrene (ABS) in its single-piece, four-segment molded interior unit for the Dodge Caravan and Plymouth Voyager. [1-28]

Leafsprings

Research and testing has been performed by the University of Michigan on a composite elliptic spring, which was designed to replace steel coil springs used in current automobiles. The composite spring consists of a number of hollow elliptic elements joined together, as shown in Figure 1-10. The elliptic spring elements were manufactured by winding fiber reinforced epoxy tapes to various thicknesses over a collapsible mandrel. The work performed indicates that FRP springs have considerable potential as a substitute for steel coil springs. Among the advantages of the composite design are a weight savings of almost 50%, easier repairability, and the potential elimination of shock absorbers due to the high damping characteristics inherent in fiber reinforced plastics. [1-33]

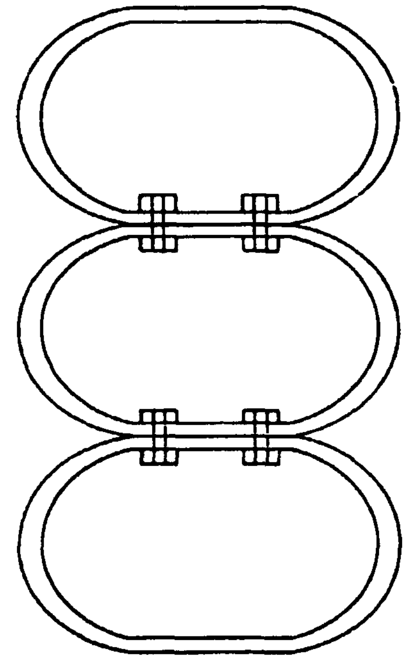


Figure 1-10 Composite Elliptic Spring
[*ASM Engineers' Guide to Composite Materials*]

Composite leaf springs for heavy trucks have been designed, manufactured and tested. In one program, a fiberglass sheet molding compound and epoxy resin were used with a steel main leaf in a compression-molding process. Mechanical testing of the finished parts demonstrated that design requirements for the component can be met using composites while achieving a minimum of 40% weight reduction over steel leaf springs. [1-34]

Frames

Graphite and Kevlar fibers with epoxy resin were used to make a composite heavy truck frame developed by the Convair Division of General Dynamics. The composite frame weighs 62% less than steel and has the same strength and stiffness. The frame was tested for one year (18,640 miles) on a GMC truck without any problems. No structural damage was evident, bolt holes maintained their integrity, and there was no significant creep of the resin matrix. [1-35]

A torsionally stiff, lightweight monocoque chassis was designed and fabricated in 1986 by the Vehicle Research Institute at Western Washington University, Bellingham, WA. Called the Viking VIII, this high performance, low cost sports car utilizes composite materials throughout and weighs only 1,420 pounds. Fiberglass, Kevlar® and carbon fiber were used with vinyl ester resin, epoxy adhesive and aluminum honeycomb core in various sandwich configurations. Final detailed test results were not available in the literature, however, most of the performance goals were met with the model. [1-36]

Safety Devices

Honeycomb structures can absorb a lot of mechanical energy without residual rebound and are particularly effective for cushioning air dropped supplies or instrument packages in missiles, providing earthquake damage restraints for above ground pipelines, or protecting people in rapid transit vehicles. A life-saving cushioning device called the Truck Mounted Crash Cushion (TMCC) has been used by the California Department of Motor Transportation. The TMCC has proven effective in preventing injury to, and saving the lives of, highway workers and motorists. The TMCC is mounted to slow moving or stopped transportation department maintenance and construction vehicles. In case of an accident, after an initial threshold stress (that can be eliminated by prestressing the honeycomb core) at which compressive failure begins, the core carries the crushing load at a controlled, near linear rate until it is completely dissipated without bouncing the impacting car or truck into a work crew or oncoming traffic.

Manufacturing Technologies

Many competitive, stampable reinforced thermoplastic sheet products have been used during the past few years in the auto industry both in the U.S. and abroad. In 1988, Exxon Automotive Industry Sector, Farmington Hills, MI, introduced its Taffen STC (structural thermoplastic composite) stampable and compression-moldable sheet. This long-glass reinforced polypropylene sheet has already been used by European auto makers Peugeot, Audi, Vauxhall (GM) and Renault for instrument panel components, load floors, battery trays and other structural parts. A spokesman for Exxon claims that the material is under evaluation for 40 different programs at Ford, General Motors and Chrysler. [1-26]

A North American automotive engineering company has been designing and testing blow molded fuel tanks for cars. Hedwin Corporation, West Bloomfield, MI recently announced the application of an all-HDPE blow molded fuel tank forward of the drive shaft. The tank was produced for the 1989 Ford Thunderbird and Mercury Cougar, and Hedwin claims it is the fist in a U.S.-built car to be mounted forward of the drive shaft. Because of the tank's location, the design had to allow the shaft to pass through the middle of the tank, making it necessary to go to an exceedingly complex shape. [1-26]

At the Spring 1989 Society of Automotive Engineers International Congress & Exposition, significant developments in quality-enhancing polymer systems and materials technology were demonstrated. General achievements include: [1-26]

- Breakthroughs in high-productivity reaction injection molding (RIM) formulations and the equipment to handle them.
- Success for thermoplastic elastomer (TPE) fascia; with an ultra-soft thermoplastic styrenic-based product soon to emerge.
- Upgraded engineering and sound-damping foams for interior automotive and other specialty applications.
- More high-heat polyethylene terephthalate PET materials.
- A polyphenylene sulfide sulfone grade for underhood use.
- Long-steel-fiber reinforced resins designed for EMI shielding.
- Impact-modified polycarbonates, high-heat ABS grades, glass-reinforced acrylic-styrene-acrylonitrile/polybutylene terephthalate (ASA/PBT) blends, and impact acrylics.

Also at the Spring 1989 Exposition, Mobay Chemical Co. introduced a RIM polyurea formulation that is claimed to offer dramatic productivity gains, excellent thermal stability, a surface finish as smooth as steel, and good abrasion, corrosion and wear resistance. Mobay is building a facility at New Martinsville, WV to produce a patented amine-terminated polyether (ATPE) claimed to improve the quality of auto body panels and other components made with its polyurea systems. Mobay claims that its unreinforced STR-400 structural RIM (SRIM) system, which can be used for automotive applications such as bumper beams, trunk modules, truck boxes, spare-tire covers and roof caps, offers 50% greater notched Izod strength than its earlier grade of SRIM. [1-26]

Dow Chemical announced at the show its completion of the design and engineering of ultra high speed equipment to run the fast new RIM materials. [1-26]

Proof of SRIM's practicality was seen on a bumper beam on the 1989 Corvette on display at the Dow exhibit. It is molded by Ardyne Inc., Grand Haven, MI, using Dow's Spectrim MM 310 system. The SRIM beam combines a directional and random glass preform with a matrix of thermosetting polycarbamate resin and saves 18% in weight and 14% in labor and material costs, according to Chevrolet. [1-26]

Hercules announced two new SRIM systems at the Exposition. One, Grade 5000 is a SRIM system designed for glass reinforcement and intended for such uses as hoods, trunk lids, door panels, side fairings and fenders. The other, Grade 1537, is said to offer a higher heat deflection temperature (185°F) and better impact, stiffness and strength properties and is intended primarily for bumper covers, side fairing extensions, roof panels and sun visors. It is claimed to maintain ductility from -30° to 150°F. [1-26]

Materials

The following is a list of some promising material systems that have been introduced for automotive applications:

- Porsche uses Du Pont's Bexoly V thermoplastic polyester elastomer for the injection molded front and rear fascias on its new Carrera 4 model.
- Shell Chemical is introducing new styrenic-based Kraton elastomers, which are extremely soft with "excellent" compression set and moldability. Its applications in the transportation industry include window seals and weather gasketing, where softness, better than average heat resistance, and low compression set are important.
- A foam that debuted at the Spring 1989 Exposition is a cold curing flexible PUR from Mobay, which is designed to reduce noise levels inside automobiles. BMW now uses the foam system, called Bayfit SA, on all its models.
- General Electric Plastics has designed and developed a one-piece, structural thermoplastic, advanced instrument panel module, called AIM, for automobiles. The one-piece design sharply reduces production time. [1-26]

- Glass reinforced thermoplastic polyesters such as PBT (polybutylene terephthalate) are used extensively in the automotive industry for exterior body parts such as grilles, wheel covers and components for doors, windows and mirrors. PBT is also in demand for underhood applications such as distributor caps, rotors and ignition parts. Other uses include headlamp parts, windshield wiper assemblies, and water pump and brake system components.
- Du Pont's Bexloy K 550 RPET has been accepted by Chrysler for use on fenders on some 1992 models. [1-37]
- The Polimotor/Lola T-616 is the world's first competition race car with a plastic engine. The four cylinder Polimotor engine is ⅔ plastic and contains dynamic parts of injection molded polymer supplied by Amoco Chemicals. The race car weighs 1500 pounds and has a carbon fiber chassis and body.
- Torlon® is a high performance polyamideimide thermoplastic made by Amoco. Torlon® has a very low coefficient of thermal expansion, which nearly matches that of steel and is stronger than many other types of high temperature polymers in its price range. It can be injection molded to precise detail with low unit cost. Torlon® thrust washers were incorporated into Cummins' gear-driven diesel engines starting in 1982. [1-28]

Cargo Handling

Shipping containers are now being constructed of FRP materials to achieve weight savings and to facilitate and simplify transshipment. Santa Fe Railway has developed an FRP container unit that is modular, allowing containers to be easily transferred to/from trucks, trains and ships. The containers are constructed using fiberglass in a polyester matrix with a core of balsa wood. The units are aerodynamically designed to reduce wind drag. The containers can be stacked up to six containers high when placed on a ship for transport. Aside from the substantial weight savings achieved using these containers, the transported goods need not be transferred from one form of container to another. This results in lower handling costs and reduces the risk of cargo damage. [1-38]

Rail and truck tanks made from sandwich FRP utilize more effective volume than their traditional metallic cylindrical counterparts. Projects in Northern Europe are now taking advantage of this technology.

Industrial Use of FRP

Thermoplastic resins were first introduced in 1889 and have since developed in form and application with a variety of industrial uses. Reinforced polyester resins were first utilized in 1944 and shall be the focus of this investigation of industrial thermoplastics. FRP's advantages in this field include: lightweight structural applications, wide useful temperature range, chemical resistance, flexibility, thermal and electrical insulation, and favorable fatigue characteristics.

Piping Systems

The use of FRP for large diameter industrial piping is attractive because handling and corrosion considerations are greatly improved. Filament wound piping can be used at working temperatures up to around 300°F with a projected service life of 100 years. Interior surfaces are much smoother than steel or concrete, which reduces frictional losses. The major difficulty with FRP piping installation is associated with connection arrangements. Construction techniques and engineering considerations are presented below, along with specific application examples.

Pipe Construction

The cylindrical geometry of pipes make them extremely well suited for filament winding construction. In this process, individual lengths of fiberglass are wound on to a mandrel form in an engineered geometry. Resin is either applied at the time of winding or pre-impregnated (prepreg) into the fiberglass in a semi-cured state. High pressure pipes and tanks are fabricated using this technique.

A more economical method of producing pipes is called centrifugal casting. In this process, chopped glass fibers are mixed with resin and applied to the inside of a rotating cylindrical mold. The reinforcement fibers end up in a random arrangement making the structure's strength properties isotropic. This process is used for large diameter pipe in low pressure applications.

Contact molding by hand or with automated spray equipment is also used to produce large diameter pipe. The designer has somewhat more flexibility over directional strength properties with this process. Different applications may be more sensitive to either hoop stresses or longitudinal bending stresses. Figure 1-11 shows the typical construction sequence of a contact-molded pipe.

Piping Materials

Fiberglass is by far the most widely used reinforcement material for reinforced piping components. The strength benefits of higher strength fibers do not justify the added cost for large structures. The type of resin system used does vary greatly, depending upon the given application. Table 1-2 lists various resin characteristics.

Engineering Considerations

The general approach to FRP pipe construction involves a chemically resistant inner layer that is surrounded by a high fiber content structural layer and finally a resin rich coating. Additional reinforcement is provided by ribbed stiffeners, which are either solid or hollow.

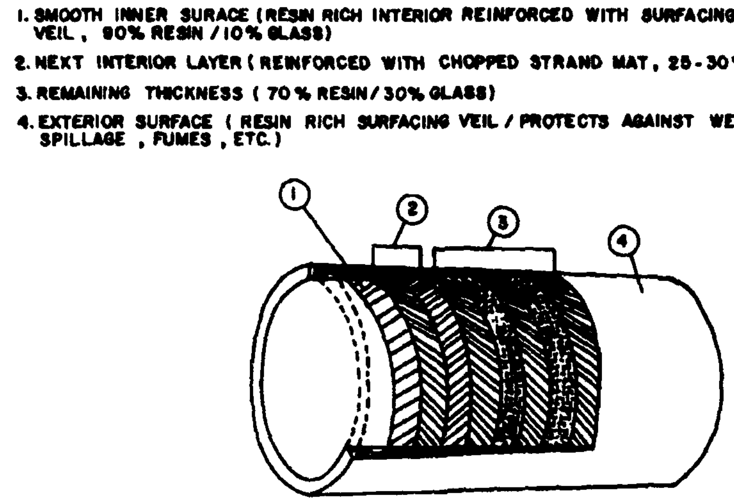


Figure 1-11 Cutaway View of Contact-Molded Pipe [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Table 1-2. FRP Pipe Resin Systems [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Resin	Application
Isophthalic	Mild corrosives at moderate temperatures and general acid wastes
Furmarated bi-sphenol A-type polyester	Mild to severe corrosive fluids including many alkalies and acids
Fire-retardant polyester	Maximum chemical resistance to acids, alkalies and solvents
Various thermoset resins	High degree of chemical resistance to specific chemicals
High-quality epoxy	Extremely high resistance to strong caustic solutions
Vinyl ester and proprietary resin systems	Extremely high resistance to organic acids, oxidizing acids, alkalis and specific solvents operating in excess of 350°F

The joining of FRP pipe to other materials, such as steel, can be accomplished using a simple flange to flange mate; with an encased concrete system that utilizes thrust rings; or with a rubber expansion joint, as shown in Figure 1-12. For straight FRP connections, an 'O' ring seal can be used.

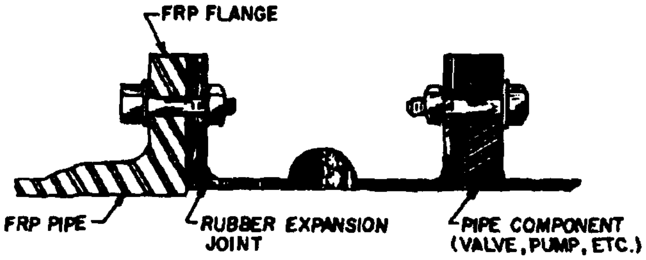


Figure 1-12 Typical Expansion Joint Tie-In [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Practices or codes regarding safe FRP pipe design are established by the following organizations:

- The American Society for Testing and Materials (ASTM)
- The American Society for Mechanical Engineers (ASME)
- The American Petroleum Institute (API)

Table 1-3 presents average properties of FRP pipe manufactured by different methods. Table 1-4 lists some recommended wall thicknesses for filament wound and contact molded pipes at various internal pressures.

FRP Piping Applications

Oil Industry

Approximately 500,000 feet of FRP pipe is installed at a Hodge-Union Texas project near Ringwood, OK and is believed to be the single largest FRP pipe installation. FRP epoxy pipe was selected because of its excellent corrosion resistance and low paraffin buildup. The smoothness of the pipe walls and low thermal conductivity contribute to the inherent resistance to paraffin accumulation. The materials that tend to corrode metallic piping include crudes, natural gases, saltwater and corrosive soils. At an offshore installation in the Arabian Gulf, FRP vinyl ester pipe was selected because of its excellent resistance to saltwater and humidity. At this site, seawater is filtered through a series of 15 foot diameter tanks that are connected by 16 inch diameter piping using a multitude of FRP fittings.

Table 1-3. Average Properties of Various FRP Pipe [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Property	Filament Wound with Epoxy or Polyester Resins	Centrifugally Cast with Epoxy or Polyester Resin	Contact Molded with Polyester Resin
Modulus of Elasticity in Axial Tension @ 77° F, psi	$1.0 - 2.7 \times 10^6$	$1.3 - 1.5 \times 10^6$	$0.8 - 1.8 \times 10^6$
Ultimate Axial Tensile Strength @ 77° F, psi	8,000 - 10,000	25,000	9,000 - 18,000
Ultimate Hoop Tensile Strength @ 77° F, psi	24,000 - 50,000	35,000	9,000 - 10,000
Modulus of Elasticity in Beam Flexure @ 77° F, psi	$1 - 2 \times 10^6$	$1.3 - 1.5 \times 10^6$	$1.0 - 1.2 \times 10^6$
Coefficient of Thermal Expansion, inch/inch/°F	$8.5 - 12.7 \times 10^6$	13×10^6	15×10^6
Heat Deflection Temperature @ 264 psi, °F	200 - 300	200 - 300	200 - 250
Thermal Conductivity, Btu/ft²-hr-°F/inch	1.3 - 2.0	0.9	1.5
Specific Gravity	1.8 - 1.9	1.58	1.3 - 1.7
Corrosive Resistance	E	E	NR
	E = excellent, will resist most corrosive chemicals NR = not recommended for highly alkaline or solvent applications		

Coal Mine

Coal mines have successfully used FRP epoxy resin pipe, according to the Fiber Glass Resources Corporation. The material is capable of handling freshwater, acid mine water and slurries more effectively than mild steel and considerably cheaper than stainless steel. Additionally, FRP is well suited for remote areas, fire protection lines, boreholes and rough terrain installations.

Paper Mill

A paper mill in Wisconsin was experiencing a problem with large concentrations of sodium hydroxide that was a byproduct of the deinking process. Type 316 stainless steel was replaced with a corrosion resistant FRP using bell and spigot-joining methods to further reduce installation costs.

Power Production

Circulating water pipes of 96 inch diameter FRP were specially designed to meet the engineering challenges of the *BIG CAJUN #2* fossil fuel power plant in New Roads, LA. The instability of the soil precluded the use of conventional thrust blocks to absorb axial loads. By custom lay-up of axial fiber, the pipe itself was made to handle these loads. Additionally, custom elbow joints were engineered to improve flow characteristics in tight turns.

Table 1-4. Recommended Pipe Wall Thickness in Inches [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Inside Diam, Inches	Internal Pressure Rating, psi											
	25		50		75		100		125		150	
	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded
2	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.187
4	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.250	0.188	0.250	0.188	0.250
6	0.188	0.187	0.188	0.187	0.188	0.250	0.188	0.250	0.188	0.312	0.188	0.375
8	0.188	0.187	0.188	0.250	0.188	0.250	0.188	0.312	0.188	0.375	0.188	0.437
10	0.188	0.187	0.188	0.250	0.188	0.312	0.188	0.375	0.188	0.437	0.188	0.500
12	0.188	0.187	0.188	0.250	0.188	0.375	0.188	0.437	0.188	0.500	0.214	0.625
18	0.188	0.250	0.188	0.375	0.188	0.500	0.214	0.625	0.268	0.750	0.321	0.937
24	0.188	0.250	0.188	0.437	0.214	0.625	0.286	0.812	0.357	1.000	0.429	1.120
36	0.188	0.375	0.214	0.625	0.321	0.937	0.429	1.250	0.536	1.500	0.643	1.810
48	0.188	0.437	0.286	0.812	0.429	1.250	0.571	1.620	0.714	2.000	0.857	2.440
60	0.188	0.500	0.357	1.000	0.536	1.500	0.714	2.000	0.893	2.500	1.070	3.000
72	0.214	0.625	0.429	1.250	0.643	1.810	0.857	2.440	1.070	3.000	1.290	3.620
96	0.286	0.812	0.571	1.620	0.857	2.440	1.140	3.250	1.430	4.000	1.710	4.810

Tanks

FRP storage tanks are gaining increased attention as of late due to recent revelations that their metallic counterparts are corroding and rupturing in underground installations. The fact that its activity can go unnoticed for some time can lead to severe environmental ramifications.

Construction

A cross-sectional view of a typical FRP tank would closely resemble the pipe described in the previous section with a barrier inner skin followed by the primary reinforcing element. Figure 1-13 shows the typical construction of an FRP tank. A general limit for design strain level is 0.001 inch/inch according to ASTM for filament wound tanks and National Institute of Standards and Technology (NIST) for contact molded tanks. Hoop tensile modulii range from 2.0 x 10^6 to 4.3 x 10^6 for filament winding and 1.0 x 10^6 to 1.2 x 10^6 for contact molding.

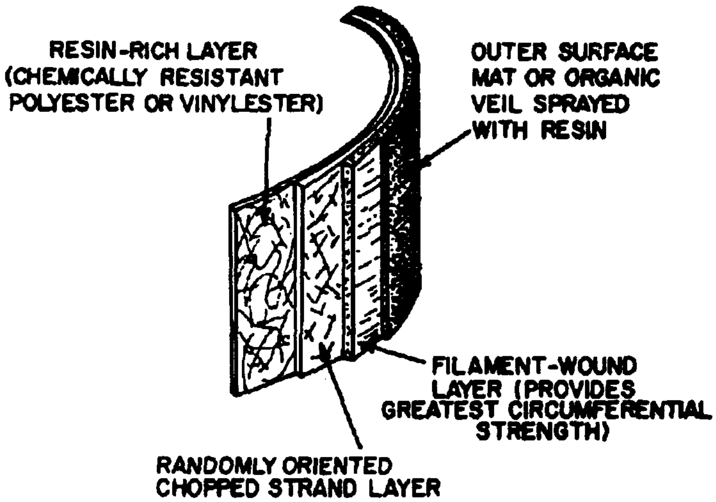


Figure 1-13 Cross-Sectional View of Standard Vertical Tank Wall Laminate [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Application

FRP is used for vertical tanks when the material to be stored creates a corrosion problem for conventional steel tanks. Designs vary primarily in the bottom sections to meet drainage and strength requirements. Horizontal tanks are usually used for underground storage of fuel oils. Owens-Corning has fabricated 48,000 gallon tanks for this purpose that require no heating provision when buried below the frost line.

Air Handling Equipment

FRP blower fans offer protection against corrosive fumes and gases. The ease of moldability associated with FRP fan blades enables the designer to specify an optimum shape. An overall reduction in component weight makes installation easier. In addition to axial fans, various types of centrifugal fans are fabricated of FRP.

Ductwork and stacks are also fabricated of FRP when corrosion resistance and installation ease are of paramount concern. Stacks are generally fabricated using hand lay-up techniques employing some type of fire-retardant resin.

Commercial Ladders

The Fiber Technology Corporation is an example of a company that has adapted an aluminum ladder design for a customer to produce a non-conductive FRP replacement. The intricate angles and flares incorporated into the aluminum design precluded the use of a pultrusion process. Additionally, the design incorporated unique hinges to give the ladder added versatility. All these features were maintained while the objective of producing a lighter, non-conductive alternative was achieved.

Aerial Towers

In 1959, the Plastic Composites Corporation introduced an aerial man-lift device used by electrical and telephone industries. The bucket, upper boom and lower boom insulator are all fabricated of fiberglass. The towers, known today as "cherry pickers," are currently certified to 69 kVA in accordance with ANSI standards and verified for structural integrity using acoustic emission techniques.

Aerospace Composites

The use of composites in the aerospace industry has increased dramatically since the 1970's. Traditional materials for aircraft construction include aluminum, steel and titanium. The primary benefits that composite components can offer are reduced weight and assembly simplification. The performance advantages associated with reducing the weight of aircraft structural elements has been the major impetus for military aviation composites development. Although commercial carriers have increasingly been concerned with fuel economy, the potential for reduced production and maintenance costs has proven to be a major factor in the push towards composites. Composites are also being used increasingly as replacements for metal parts on older planes. Figure 1-14 shows current and projected expenditures for advanced composite materials in the aerospace industry.

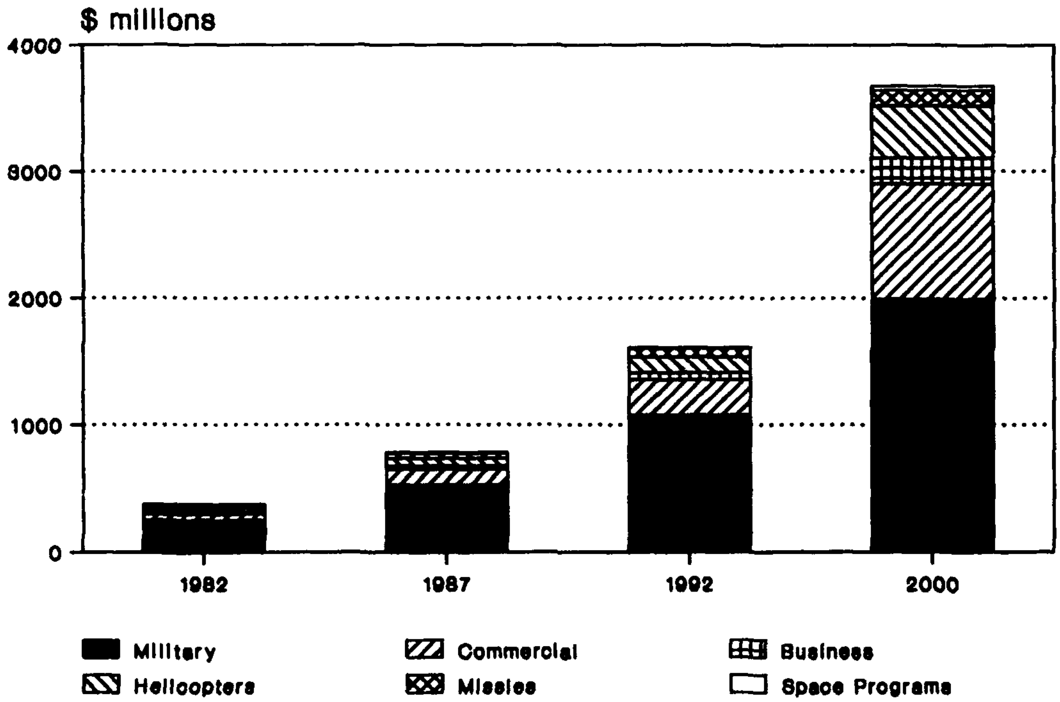


Figure 1-14 Advanced Composite Sales for the Aerospace Industry. [Source: *P-023N Advanced Polymer Matrix Composites,* Business Communication Company, Inc.]

When comparing aerospace composites development to that of the marine industry, it is important to note the differences in economic and engineering philosophies. The research, design and testing resources available to the aerospace designer eclipse what is available to his counterpart in the marine industry by at least an order of magnitude. Aircraft development remains one of the last bastions of U.S. supremacy, which accounts for its broad economic base of support. On the engineering side, performance benefits are much more significant for aircraft than ships. A comparison of overall vehicle weights provides a good illustration of this concept.

Although the two industries are so vastly different, lessons can be learned from aircraft development programs that are applicable to marine structures. Material and process development, design methodologies, qualification programs and long-term performance are some of the fields where the marine designer can adapt the experience that the aerospace industry has developed. New aircraft utilize what would be considered high performance composites in marine terms. These include carbon, boron and aramid fibers combined with epoxy resins. Such materials have replaced fiberglass reinforcements, which are still the backbone of the marine industry. However, structural integrity, producibility and performance at elevated temperatures are some concerns common to both industries. Examples of specific aerospace composites development programs are provided to illustrate the direction of this industry.

Business and Commercial

Lear Fan 2100

As one of the first aircraft conceived and engineered as a "composites" craft, the Lear Fan uses approximately 1880 pounds of carbon, glass and aramid fiber material. In addition to composite elements that are common to other aircraft, such as doors, control surfaces, fairings and wing boxes, the Lear Fan has an all composite body and propeller blades.

Beech Starship

The Starship is the first all-composite airplane to receive FAA certification. Approximately 3000 pounds of composites are used on each aircraft.

Boeing

The Boeing 757 and 767 employ about 3000 pounds each of composites for doors and control surfaces. The 767 rudder at 36 feet is the largest commercial component in service. The 737-300 uses approximately 1500 pounds of composites, which represents about 3% of the overall structural weight. Composites are widely used in aircraft interiors to create luggage compartments, sidewalls, floors, ceilings, galleys, cargo liners and bulkheads. Fiberglass with epoxy or phenolic resin utilizing honeycomb sandwich construction gives the designer freedom to create esthetically pleasing structures while meeting flammability and impact resistance requirements.

Airbus

In 1979, a pilot project was started to manufacture carbon fiber fin box assemblies for the A300/A310 aircraft. A highly mechanized production process was established to determine if high material cost could be offset by increased manufacturing efficiency. Although material costs were 35% greater than a comparable aluminum structure, total manufacturing costs were lowered 65 to 85%. Robotic assemblies were developed to handle and process materials in an optimal and repeatable fashion.

Military

Advanced Tactical Fighter (ATF)

Advanced composites enable the ATF to meet improved performance requirements such as reduced drag, low radar observability and increased resistance to temperatures generated at high speeds. The ATF will be approximately 50% composites by weight using DuPont's Avimid K polyamide for the first prototype. Figure 1-15 depicts a proposed wing composition as developed by McDonnell Aircraft through their Composite Flight Wing Program.

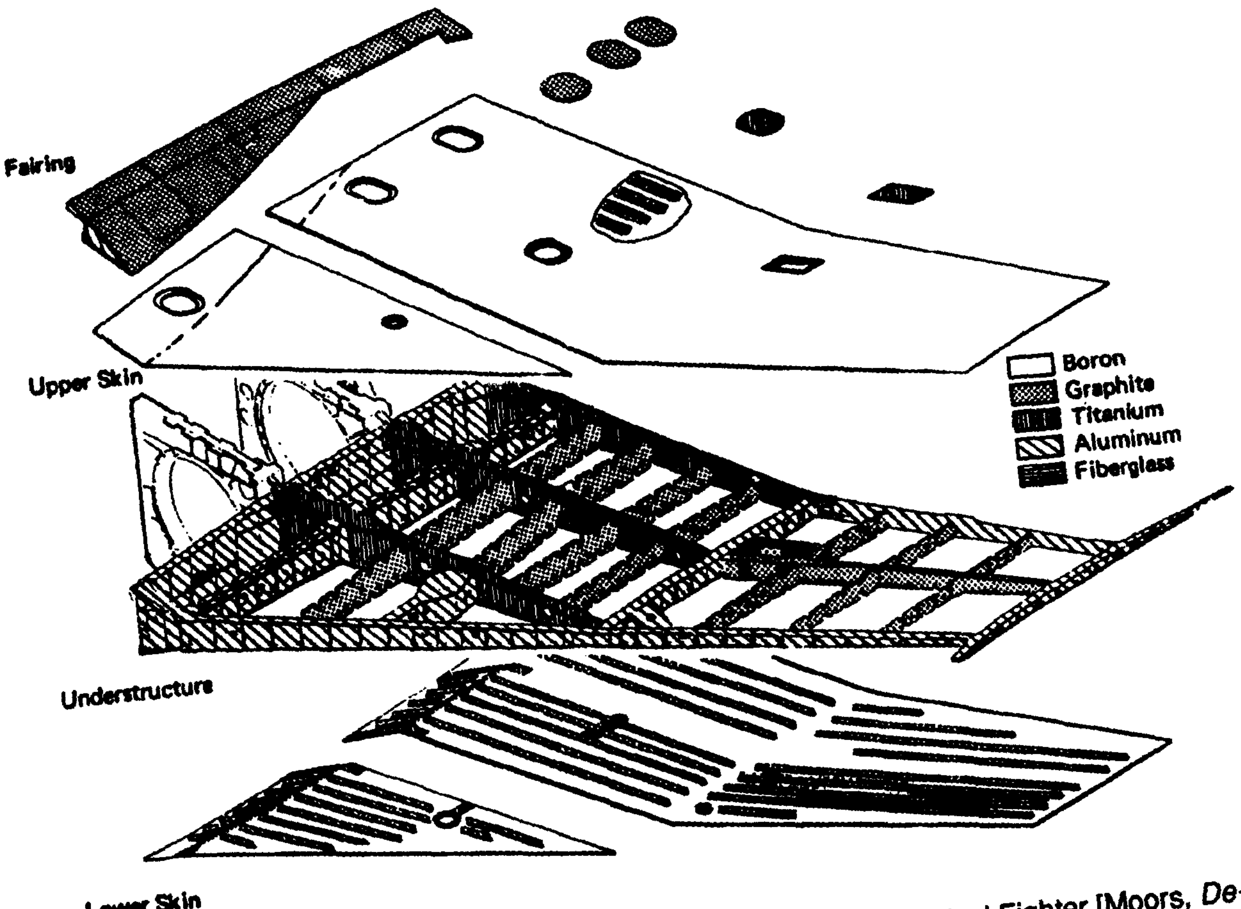


Figure 1-15 Composite Wing Composition for Advanced Tactical Fighter [Moors, *Design Considerations - Composite Flight Wing Program*]

Advanced Technology Bomber (B-2)

The B-2 derives much of its stealth qualities from the material properties of composites and their ability to be molded into complex shapes. Each B-2 contains an estimated 40,000 to 50,000 pounds of advanced composite materials. According to Northrop, nearly 900 new materials and processes were developed for the plane.

Second Generation British Harrier "Jump Jet" (AV-8B)

This vertical take-off and landing (VTOL) aircraft is very sensitive to overall weight. As a result, 26% of the vehicle is fabricated of composite material. Much of the substructure is composite, including the entire wing. Bismaleimides (BMI's) are used on the aircraft's underside and wing trailing edges to withstand the high temperatures generated during take-off and landing.

Navy Fighter Aircraft (F-18A)

The wing skins of the F-18A represented the first widespread use of graphite/epoxy in a production aircraft. The skins vary in thickness up to one inch, serving as primary as well as secondary load carrying members. It is interesting to note that the graphite skins are separated from the aluminum framing with a fiberglass barrier to prevent galvanic corrosion. The carrier based environment that Navy aircraft are subjected to has presented unique problems to the aerospace designer. Corrosion from salt water surroundings is exacerbated by the sulfur emission from the ship's exhaust stacks.

Osprey Tilt-Rotor (V-22)

The tilt-rotor V-22 is also a weight sensitive craft that is currently being developed by Boeing and Bell Helicopter. Up to 40% of the airframe consists of composites, mostly AS-4 and IM-6 graphite fibers in 3501-6 epoxy (both from Hercules). New uses of composites are being exploited on this vehicle, such as shafting and thick, heavily loaded components. Consequently, higher design strain values are being utilized.

Helicopters

Rotors

Composite materials have been used for helicopter rotors for some time now and have gained virtually 100% acceptance as the material of choice. The use of fibrous composites offers improvements in helicopter rotors due to improved aerodynamic geometry, improved aerodynamic tuning, good damage tolerance and potential low cost. Anisotrophic strength properties are very desirable for the long, narrow foils. Additionally, a cored structure has the provision to incorporate the required balance weight at the leading edge. The favorable structural properties of the mostly fiberglass foils allow for increased lift and speed. Fatigue characteristics of the composite blade are considerably better than their aluminum counterparts with the aluminum failing near 40,000 cycles and the composite blade exceeding 500,000 cycles without failure. Vibratory strain in this same testing program was ± 510 $\mu\ inch/inch$ for aluminum and ± 2400 $\mu\ inch/inch$ for the composite.

Sikorsky Aircraft of United Aircraft Corporation has proposed a Cross Beam Rotor (XBR)™, which is a simplified, lightweight system that makes extensive use of composites. The low torsional stiffness of a unidirectional composite spar allows pitch change motion to be accommodated by elastic deformation, whereas sufficient bending stiffness prevents areoelastic instability. Figure 1-16 shows a configuration for a twin beam composite blade used with this system.

Structure and Components

The extreme vibratory environment that helicopters operate in makes composites look attractive for other elements. In an experimental program that Boeing undertook, 11,000 metal parts were replaced by 1,500 composite ones, thus eliminating 90% of the vehicle's fasteners. Producibility and maintenance considerations improved along with overall structural reliability.

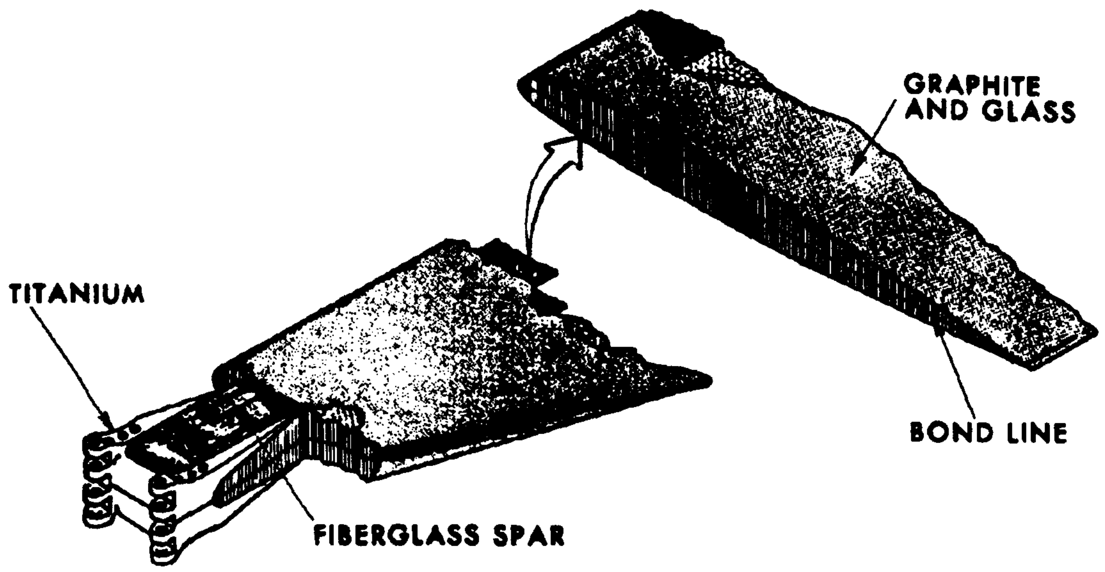


Figure 1-16 Twin Beam Composite Blade for XBR™ Helicopter Rotor System [Salkind, *New Composite Helicopter Rotor Concepts*]

Experimental

Voyager

Nearly 90% of the *VOYAGER* aircraft was made of carbon fiber composites. The strength-to-weight ratio of this material allowed the vehicle to carry sufficient fuel to circle the globe without refueling. The plane's designer and builder, Burt Rutan, is renowned for building innovative aircraft using composites. He has also designed an Advanced Technology Tactical Transport of composites and built the wing sail that was fitted to the 60 foot catamaran used in the last America's Cup defense.

Daedalus

The *GOSSAMER CONDOR* and *GOSSAMER ALBATROSS* caught people's imagination by being the first two human-powered aircraft to capture prize money that was unclaimed for 18 years. These aircraft were constructed of aluminum tubes and mylar wings supported by steel cable. The aerodynamic drag of the cabling proved to be the factor limiting flight endurance. The *DAEDALUS* project's goal was to fly 72 miles from Crete to Santorini. By hand constructing graphite spars over aluminum mandrels, the vehicle's drag was minimized and the overall aircraft structure was reduced to 68 pounds, which made this endurance record possible. Figure 1-17 is a compilation of sketches showing various details of the Daedalus.

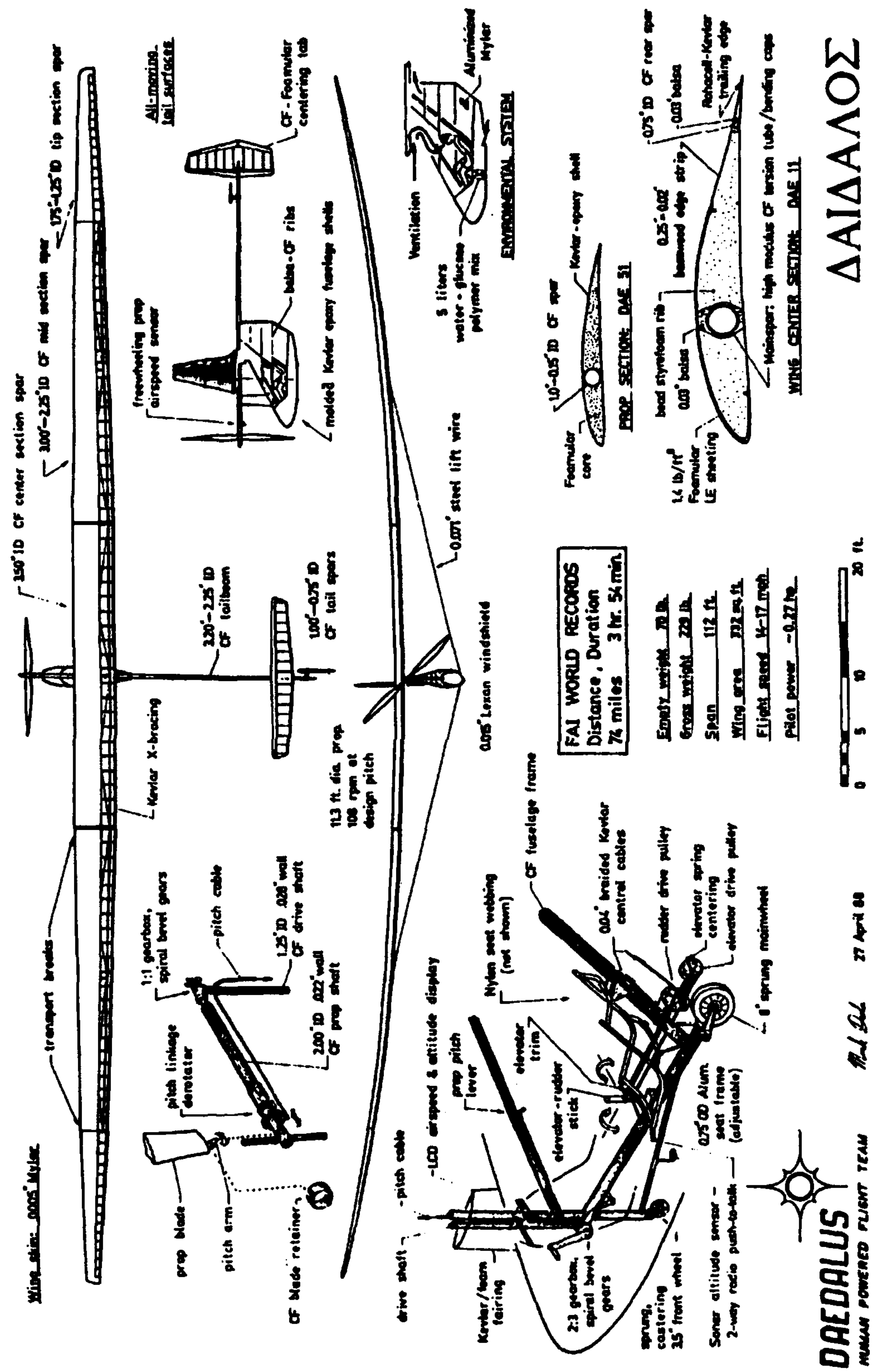


Figure 1-17 Engineer's Representation of the *DAEDALUS* [Drella, *Technology Review*]

This page intentionally left blank

Composite Materials

Reinforcement Materials

Fiberglass

Glass fibers account for over 90% of the fibers used in reinforced plastics because they are inexpensive to produce and have relatively good strength to weight characteristics. Additionally, glass fibers exhibit good chemical resistance and processability. The excellent tensile strength of glass fibers, however, has been shown to deteriorate when loads are applied for long periods of time. [2-1] Continuous glass fibers are formed by extruding molten glass to filament diameters between 5 and 25 micrometers. Table 2-1 depicts the designations of fiber diameters commonly used in the FRP industry.

Individual filaments are coated with a sizing to reduce abrasion and then combined into a strand of either 102 or 204 filaments. The sizing acts as a coupling agent during resin impregnation. Table 2-2 lists some typical glass finishes and their compatible resin systems. E-glass (lime aluminum borosilicate) is the most common reinforcement used in marine laminates because of its good strength properties and resistance to water degradation. S-glass (silicon dioxide, aluminum and magnesium oxides) exhibits about one third better tensile strength, and in general, demonstrates better fatigue resistance. Table 2-3 lists the composition by weight for both E- and S-glass. The cost for this variety of glass fiber is about three to four times that of E-glass. Table 2-4 contains data on raw E-glass and S-glass fibers.

Table 2-1. Glass Fiber Diameter Designations [Shell, *Epon® Resins for Fiberglass Reinforced Plastics*]

Designation	Mils	Micrometers (10^{-6} meters)
C	0.18	4.57
D	0.23	5.84
DE	0.25	6.35
E	0.28	7.11
G	0.38	9.65
H	0.42	10.57
K	0.53	13.46

Polymer Fibers

The most common aramid fiber is Kevlar® developed by DuPont. This is the predominant organic reinforcing fiber whose use dates to the early 1970's as a replacement for steel belting in tires. The outstanding features of aramids are low weight, high tensile strength and modulus, impact and fatigue resistance, and weaveability. Compressive performance of aramids is relatively poor, as they show nonlinear ductile behavior at low strain values. Although the fibers are resistant to strong acids and bases, ultraviolet degradation can cause a problem as can water absorption with Kevlar® 49. Ultra-high modulus Kevlar® 149 absorbs almost two thirds less water at a given relative humidity. Aramids tend to be difficult to cut and wet-out during lamination.

Table 2-2. Typical Glass Finishes [BGF, Shell and SP Systems]

Designation	Type of Finish	Resin System
114	Methacrylato chromic chloride	Epoxy
161	Soft, clear with good wet-out	Polyester
Volan®	Methacrylato chromic chloride	Polyester or Epoxy
504	Volan® finish with .03%-.06% chrome	Polyester or Epoxy
504A	Volan® finish with .06%-.07% chrome	Polyester or Epoxy
A-100	Amino silane	Epoxy
538	A-1100 amino silane plus glycerine	Epoxy
550	Modified Volan®	Polyester
558	Epoxy-functional silane	Epoxy
627	Silane replacement for Volan®	Polyester or Epoxy
SP 550	Proprietary	Polyester or Epoxy
Y-2967	Amino silane	Epoxy
Y-4086/7	Epoxy-modified methoxy silane	Epoxy
Z-6040	Epoxy-modified methoxy silane	Epoxy
Z-6030	Methacrylate Silane	Polyester
Garan	Vinyl silane	Epoxy
NOL-24	Halosilane (in xylene)	Epoxy
S-553	Proprietary	Epoxy
S-920	Proprietary	Epoxy
S-735	Proprietary	Epoxy

Table 2-3. Glass Composition by Weight for E- and S-Glass [BGF]

	E-Glass	S-Glass
Silicone Dioxide	52 - 56%	64 - 66%
Calcium Oxide	16 - 25%	0 - .3%
Aluminum Oxide	12 - 16%	24 - 26%
Boron Oxide	5 - 10%	—
Sodium Oxide & Potassium Oxide	0 - 2%	0 - .3%
Magnesium Oxide	0 - 5%	9 - 11%
Iron Oxide	.05 - .4%	0 - .3%
Titanium Oxide	0 - .8%	—
Fluorides	0 - 1.0%	—

Allied Corporation developed a high strength/modulus extended chain polyethylene fiber called Spectra® that was introduced in 1985. Room temperature specific mechanical properties of Spectra® are slightly better than Kevlar®, although performance at elevated temperatures falls off. Chemical and wear resistance data is superior to the aramids. Data for both Kevlar® and Spectra® fibers is also contained in Table 2-4. The percent of manufacturers using various reinforcement materials is represented in Figure 2-1.

Table 2-4. Mechanical Properties of Reinforcement Fibers

Fiber	Density lb/in³	Tensile Strength psi x 10³	Tensile Modulus psi x 10⁶	Ultimate Elongation	Cost $/lb
E-Glass	.094	500	10.5	4.8%	.80-1.20
S-Glass	.090	665	12.6	5.7%	4
Aramid-Kevlar® 49	.052	525	18	2.9%	16
Spectra® 900	.035	375	17	3.5%	22
Polyester-COMPET®	.049	150	1.4	22.0%	1.75
Carbon-PAN	.062-.065	350-700	33-57	0.38-2.0%	17-450

Polyester and nylon thermoplastic fibers have recently been introduced to the marine industry as primary reinforcements and in a hybrid arrangement with fiberglass. Allied Corporation has developed a fiber called COMPET®, which is the product of applying a finish to PET fibers that enhances matrix adhesion properties. Hoechst-Celanese manufactures a product called Treveria®, which is a heat treated polyester fiber fabric designed as a "bulking" material and as a gel coat barrier to reduce "print-through." Although polyester fibers have fairly high strengths, their stiffness is considerably below that of glass. Other attractive features include low density, reasonable cost, good impact and fatigue resistance, and potential for vibration damping and blister resistance.

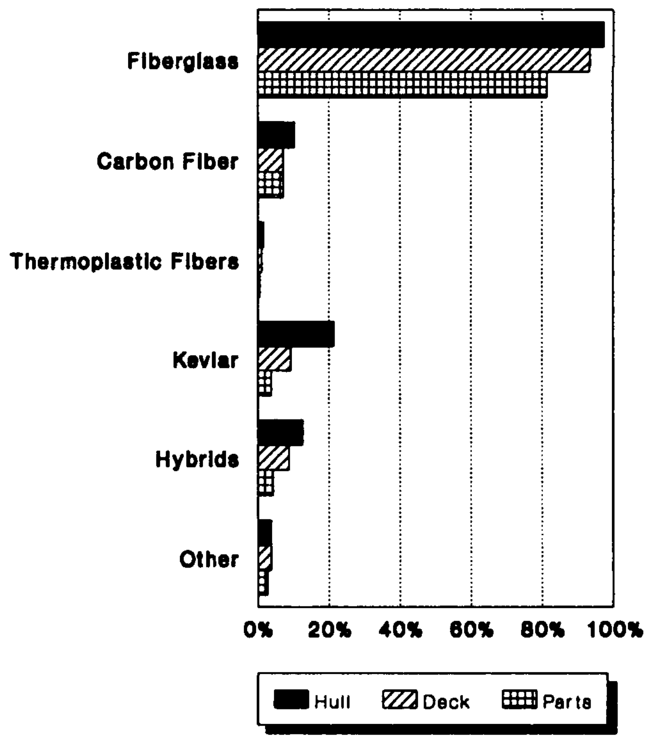


Figure 2-1 Marine Industry Reinforcement Material Use [EGA Survey]

Carbon Fibers

The terms "carbon" and "graphite" fibers are typically used interchangeably, although graphite technically refers to fibers that are greater than 99% carbon composition versus 93 to 95% for PAN-base fibers. All continuous carbon fibers produced to date are made from organic precursors, which in addition to PAN (polyacrylonitrile), include rayon and pitches, with the latter two generally used for low modulus fibers.

Carbon fibers offer the highest strength and stiffness of all the reinforcement fibers. The fibers are not subject to stress rupture or stress corrosion, as with glass and aramids. High temperature performance is particularly outstanding. The major drawback to the PAN-base fibers is their relative cost, which is a function of high precursor costs and an energy intensive manufacturing process. Table 2-5 shows some comparative fiber performance data.

Reinforcement Construction

Reinforcement materials are combined with resin systems in a variety of forms to create structural laminates. The percent of manufacturers using various reinforcement styles is represented in Figure 2-3. Table 2-5 provides definitions for the various forms of reinforcement materials. Some of the lower strength non-continous configurations are limited to fiberglass due to processing and economic considerations.

Table 2-5. Description of Various Forms of Reinforcements [Shell, *Epon® Resins for Fiberglass Reinforced Plastics*]

Form	Description	Principal Processes
Filaments	Fibers as initially drawn	Processed further before use
Continuous Strands	Basic filaments gathered together in continuous bundles	Processed further before use
Yarns	Twisted strands (treated with after-finish)	Processed further before use
Chopped Strands	Strands chopped ¼ to 2 inches	Injection molding; matched die
Rovings	Strands bundled together like rope but not twisted	Filament winding; sheet molding; spray-up; pultrusion
Milled Fibers	Continuous strands hammermilled into short lengths 1/32 to ⅛ inches long	Compounding; casting; reinforced reaction injection molding (RRIM)
Reinforcing Mats	Nonwoven random matting consisting of continuous or chopped strands	Hand lay-up; resin transfer molding (RTM); centrifugal casting
Woven Fabric	Cloth woven from yarns	Hand lay-up; prepreg
Woven Roving	Strands woven like fabric but coarser and heavier	Hand or machine lay-up; resin transfer molding (RTM)
Spun Roving	Continuous single strand looped on itself many times and held with a twist	Processed further before use
Nonwoven Fabrics	Similar to matting but made with unidirectional rovings in sheet form	Hand or machine lay-up; resin transfer molding (RTM)
Surfacing Mats	Random mat of monofilaments	Hand lay-up; die molding; pultrusion

Wovens

Woven composite reinforcements generally fall into the category of cloth or woven roving. The cloths are lighter in weight, typically from 6 to 10 ounces per square yard and require about 40 to 50

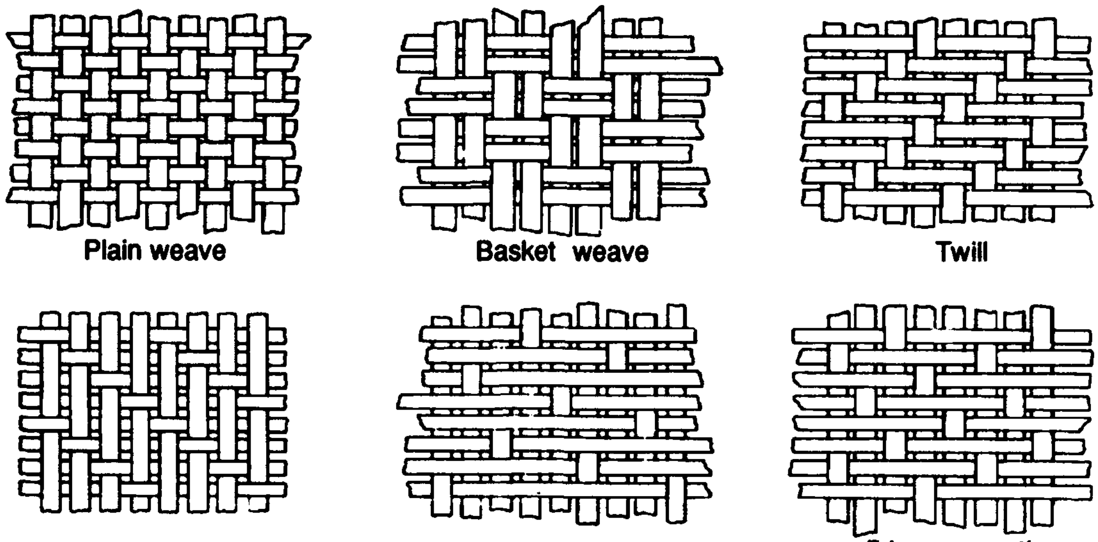


Figure 2-2 Reinforcement Fabric Construction Variations [*ASM Engineered Materials Handbook*]

plies to achieve a one inch thickness. Their use in marine construction is limited to small parts and repairs. Particular weave patterns include plain weave, which is the most highly interlaced; basket weave, which has warp and fill yarns that are paired up; and satin weaves, which exhibit a minimum of interlacing. The satin weaves are produced in standard four-, five- or eight-harness configurations, which exhibit a corresponding increase in resistance to shear distortion (easily draped). Figure 2-2 shows some commercially available weave patterns.

Woven roving reinforcements consist of flattened bundles of continuous strands in a plain weave pattern with slightly more material in the warp direction. This is the most common type of reinforcement used for large marine structures because it is available in fairly heavy weights (24 ounces per square yard is the most common), which enables a rapid build up of thickness. Also, directional strength characteristics are possible with a material that is still fairly drapable. Impact resistance is enhanced because the fibers are continuously woven.

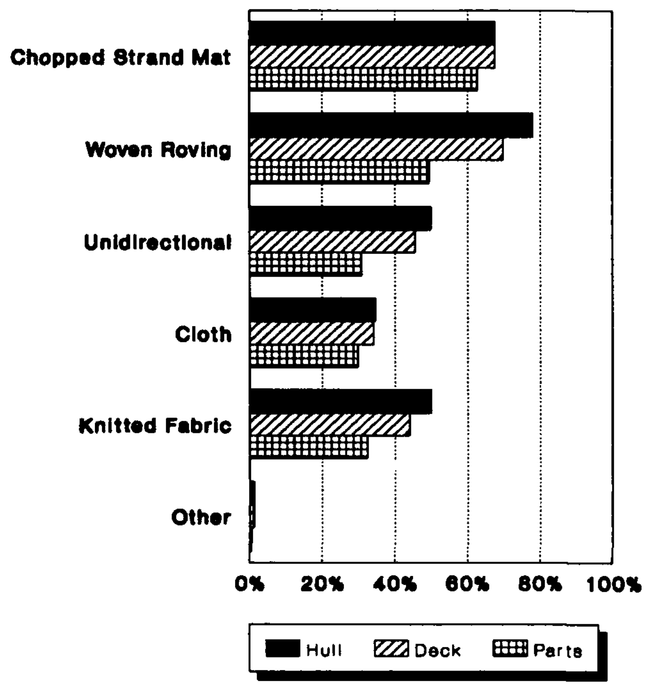


Figure 2-3 Marine Industry Reinforcement Style Use [EGA Survey]

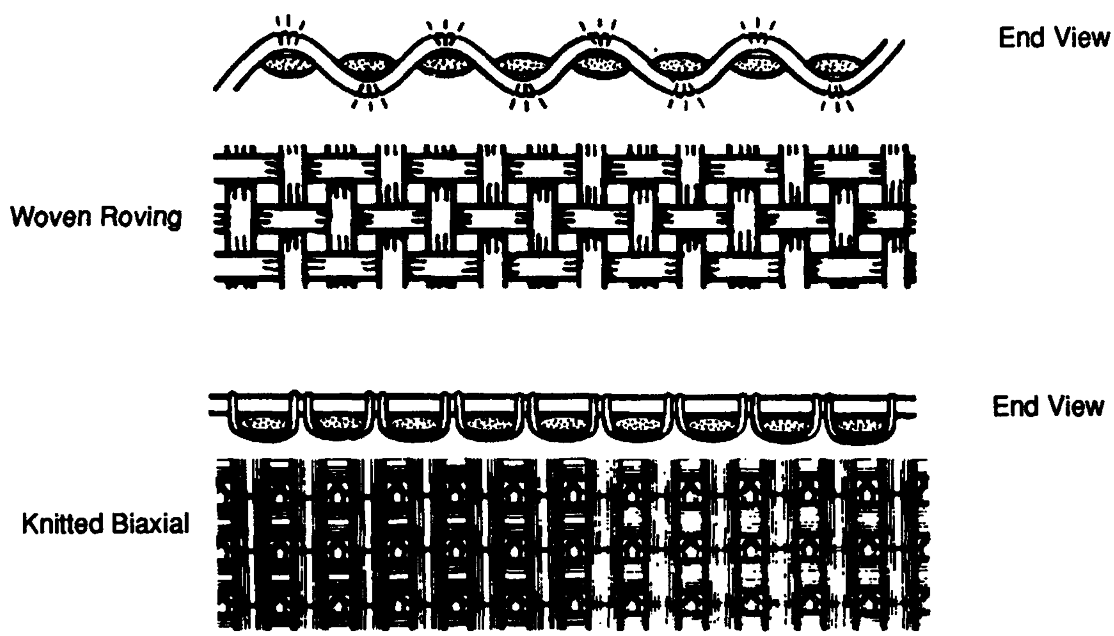


Figure 2-4 Comparison of Conventional Woven Roving and a Knitted Biaxial Fabric Showing Theoretical Kink Stress in Woven Roving [Composites Reinforcements, Inc.]

Knits

Knitted reinforcement fabrics were first introduced by Knytex® in 1975 to provide greater strength and stiffness per unit thickness as compared to woven rovings. A knitted reinforcement is constructed using a combination of unidirectional reinforcements that are stitched together with a non-structural synthetic such as polyester. A layer of mat may also be incorporated into the construction. The process provides the advantage of having the reinforcing fiber lying flat versus the crimped orientation of woven roving fiber. Additionally, reinforcements can be oriented along any combination of axes. Superior glass to resin ratios are also achieved, which makes overall laminate costs competitive with traditional materials. Figure 2-4 shows a comparison of woven roving and knitted construction.

Omnidirectional

Omnidirectional reinforcements can be applied during hand lay-up as prefabricated mat or via the spray-up process as chopped strand mat. Chopped strand mat consists of randomly oriented glass fiber strands that are held together with a soluble resinous binder. Continuous strand mat is similar to chopped strand mat, except that the fiber is continuous and layed down in a swirl pattern. Both hand lay-up and spray-up produce plies with equal properties along the x and y axes and good interlaminar shear strength. This is a very economical way to build up thickness, especially with complex molds. The ultimate mechanical properties are, of course, not on par with the continuous strand reinforcements.

Unidirectional

Pure unidirectional construction implies no structural reinforcement in the fill direction. Ultra high strength/modulus material, such as carbon fiber, is sometimes used in this form due to its high cost and specificity of application. Material widths are generally limited due to the difficulty of handling and wet-out. Anchor Reinforcements has recently introduced a line of unidirectionals that are held together with a thermoplastic web binder that is compatible with thermoset resin systems. The company claims that the material is easier to handle and cut than traditional pure unidirectional material. Typical applications for unidirectionals include stem and centerline stiffening as well as the tops of stiffeners. Entire hulls are fabricated from unidirectional reinforcements when an ultra high performance laminate is desired.

Resins

Polyester

The percent of manufacturers using various resin systems is represented in Figure 2-5. Polyester resins are the simplest, most economical resin systems that are easiest to use and show good chemical resistance. Almost one half million tons of this material is used annually in the United States. Unsaturated polyesters consist of unsaturated material, such as maleic anhydride or fumaric acid, that is dissolved in a reactive monomer, such as styrene. Polyester resins have long been considered the least toxic thermoset to personnel, although recent scrutiny of styrene emissions in the workplacc has led to the development of alternate formulations (see Chapter Five). Most polyesters are air inhibited and will not cure when exposed to air. Typically, paraffin is added to the resin formulation, which has the effect of sealing the surface during the cure process. However, the wax film on the surface presents a problem for secondary bonding or finishing and must be physically removed. Non-air inhibited resins do not present this problem and are, therefore, more widely accepted in the marine industry.

The two basic polyester resins used in the marine industry are orthophthalic and isophthalic. The ortho resins were the original group of polyesters developed and are still in widespread use. They have somewhat limited thermal stability, chemical resistance, and processability characteristics. The iso resins generally have better mechanical properties and show better chemical resistance. Their increased resistance to water permeation has prompted many builders to use this resin as a gel coat or barrier coat in marine laminates.

The rigidity of polyester resins can be lessened by increasing the ratio of saturated to unsaturated acids. Flexible

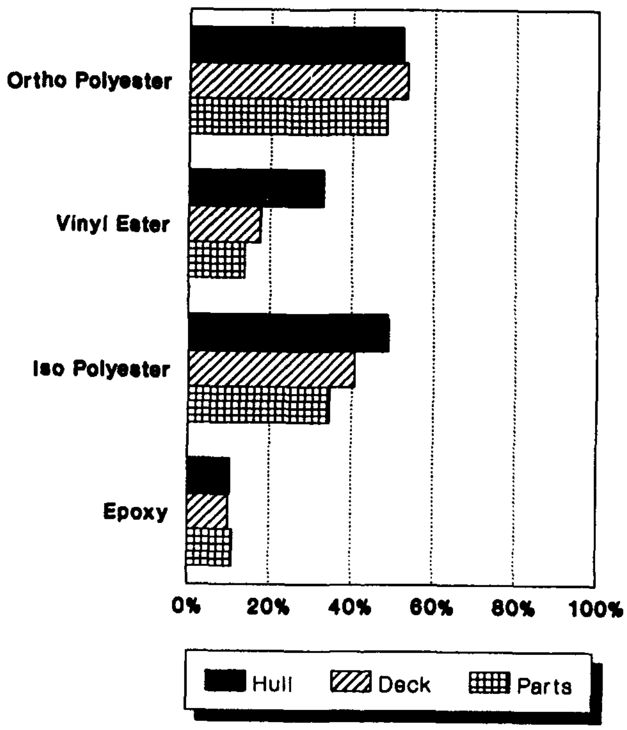


Figure 2-5 Marine Industry Resin System Use [EGA Survey]

resins may be advantageous for increased impact resistance, however, this comes at the expense of overall hull girder stiffness. Non-structural laminate plies, such as gel coats and barrier veils, are sometimes formulated with more flexible resins to resist local cracking. On the other end of the spectrum are the low-profile resins that are designed to minimize reinforcement print-through. Typically, ultimate elongation values are reduced for these types of resins, which are represented by DCPD in Table 2-7.

Curing of polyester without the addition of heat is accomplished by adding accelerator along with the catalyst. Gel times can be carefully controlled by modifying formulations to match ambient temperature conditions and laminate thickness. The following combinations of curing additives are most common for use with polyesters:

Table 2-6. Polyester Resin Catalyst and Accelerator Combinations [Scott, *Fiberglass Boat Construction*]

Catalyst	Accelerator
Methyl Ethyl Keytone Peroxide (MEKP)	Cobalt Napthanate
Cuemene Hydroperoxide	Manganese Napthanate

Other resin additives can modify the viscosity of the resin if vertical or overhead surfaces are being laminated. This effect is achieved through the addition of silicon dioxide, in which case the resin is called thixotropic. Various other fillers are used to reduce resin shrinkage upon cure, a useful feature for gel coats.

Vinyl Ester

Vinyl ester resins are unsaturated resins prepared by the reaction of a monofunctional unsaturated acid, such as methacrylic or acrylic, with a bisphenol diepoxide. The resulting polymer is mixed with an unsaturated monomer, such as styrene. The handling and performance characteristics of vinyl esters are similar to polyesters. Some advantages of the vinyl esters, which may justify their higher cost, include superior corrosion resistance, hydrolytic stability, and excellent physical properties such as impact and fatigue resistance. It has been shown that a 20 to 60 mil inter-layer with a vinyl ester resin matrix can provide an excellent permeation barrier to resist blistering in marine laminates.

Epoxy

Epoxy resins are a broad family of materials that contain a reactive functional group in their molecular structure. Epoxy resins show the best performance characteristics of all the resins used in the marine industry. Additionally, they exhibit the least shrinkage upon cure of all the thermosets. Aerospace applications use epoxy almost exclusively, except when high temperature performance is critical. The high cost of epoxies and handling difficulties have limited their use for large marine structures. Table 2-7 shows some comparative data for various thermoset resin systems.

Thermoplastics

Thermoplastics have one- or two-dimensional molecular structures, as opposed to three-dimensional structures for thermosets. The thermoplastics generally come in the form of molding compounds that soften at high temperatures. Polyethylene, polystyrene, polypropylene, polyamides and nylon are examples of thermoplastics. Their use in the marine industry has generally been limited to small boats and recreational items. Reinforced thermoplastic materials have recently been investigated for the large scale production of structural components. Some attractive features include no exotherm upon cure, which has plagued filament winding of extremely thick sections with thermosets, and enhanced damage tolerance. Processability and strengths compatible with reinforcement material are key areas currently under development.

Table 2-7. Comparative Data for Some Thermoset Resin Systems (castings)

Resin	Barcol Hardness	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^5	Ultimate Elongation	Cost $/lb
Orthophthalic Atlas P 2020	42	7.0	5.9	.91%	.66
Dicyclopentadiene (DCPD) Atlas 80-6044	54	11.2	9.1	.86%	.67
Isophthalic CoRezyn 9595	46	10.3	5.65	2.0%	.85
Vinyl Ester Derakane 411-45	35	11-12	4.9	5-6%	1.44
Epoxy Gouegon GLR 125	84D*	7	4.2	4.0%	2.69

*Hardness values for epoxies are traditionally given on the "Shore D" scale

Core Materials

Balsa

The percent of manufacturers using various core materials is represented in Figure 2-6. End grain balsa's closed-cell structure consists of elongated, prismatic cells with a length (grain direction) that is approximately sixteen times the diameter (see Figure 2-7). In densities between 6 and 9 pounds ft^3, the material exhibits excellent stiffness and bond strength. Balsa will typically absorb more resin than closed cell foam during lamination and is also subject to water migration, although this has been shown to be limited to action parallel to the grain. Although the static strength of balsa panels will generally be higher than the PVC foams, impact energy absorption is lower. End-grain balsa is available in sheet form for flat panel construction or in a scrim-backed block arrangement that conforms to complex curves. Chapter Five goes into further detail regarding the core selection process.

Thermoset Foams

Foamed plastics such as cellular cellulose acetate (CCA), polystyrene, and polyurethane are very light (about 2 lbs/ft^3) and resist water, fungi and decay. These materials have very low mechanical properties and polystyrene will be attacked by polyester resin. These foams will not conform to complex curves. Use is generally limited to buoyancy rather than structural applications. Polyurethane is often foamed in-place when used as a buoyancy material.

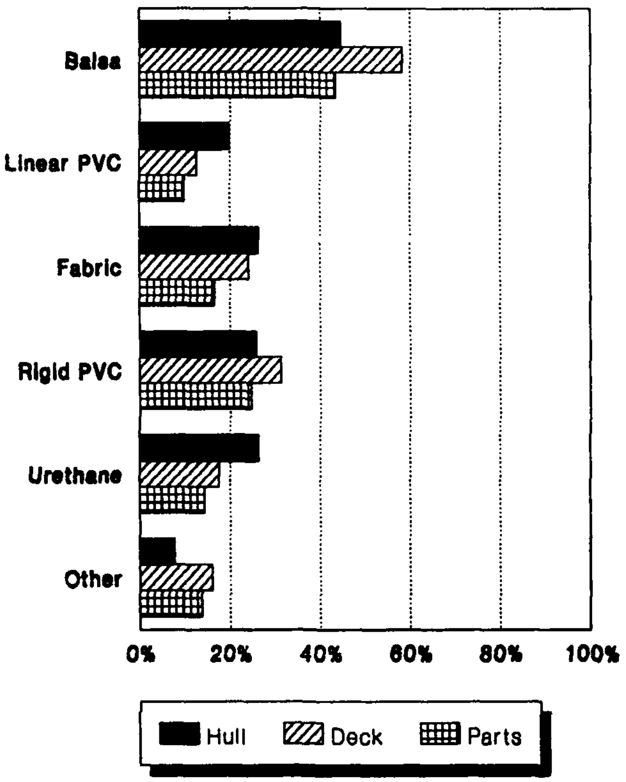


Figure 2-6 Marine Industry Core Material Use [EGA Survey]

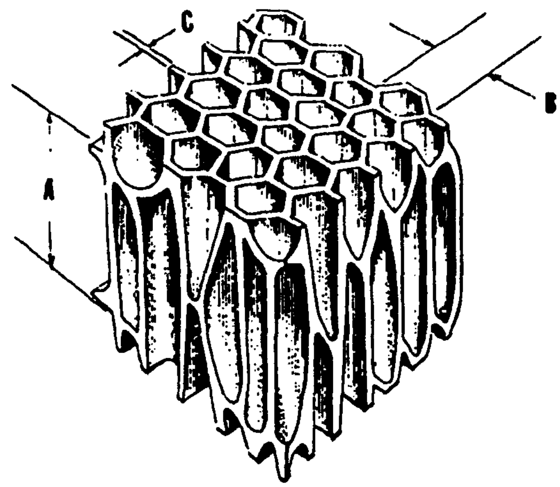


Figure 2-7 Balsa Cell Geometry with **A** = Average Cell Length = .025"; **B** = Average Cell Diameter = .00126"; **C** = Average Cell Wall Thickness = .00006" [Baltek Corporation]

Syntactic Foams

Syntactic foams are made by mixing hollow microspheres of glass, epoxy and phenolic into fluid resin with additives and curing agents to form a moldable, curable, lightweight fluid mass. Omega Chemical has introduced a sprayable syntactic core material called SprayCore™. The company claims that thicknesses of ⅜" can be achieved at densities between 30 and 43 lbs/ft^3. The system is being marketed as a replacement for core fabrics with superior physical properties. Material cost for a square foot of ⅜" material is approximately $2.20.

Cross Linked PVC Foams

Polyvinyl foam cores are manufactured by combining a polyvinyl copolymer with stabilizers, plasticizers, cross-linking compounds and blowing agents. The mixture is heated under pressure to initiate the cross-linking reaction and then submerged in hot water tanks to expand to the desired density. Cell diameters range from .0100 to .100 inches (as compared to .0013 inches for balsa). [2-2] The resulting material is thermoplastic, enabling the material to conform to compound curves of a hull. PVC foams have almost exclusively replaced urethane foams as a structural core material, except in configurations where the foam is "blown" in place. A number of manufacturers market cross-linked PVC products to the marine industry in sheet form with densities ranging from 2 to 12 pounds per ft^3. As with the balsa products, solid sheets or scrim backed block construction configurations are available.

Linear PVC Foam

Airex® is currently the only linear PVC foam core produced for the marine industry. Its unique mechanical properties are a result of a non-connected molecular structure, which allows significant displacements before failure. In comparison to the cross linked (non-linear) PVCs, Airex® will exhibit less favorable static properties and better impact absorption capability. Individual cell diameters range from .020 to .080 inches. [2-3] A detailed comparison of core material performance will be presented in the Section on Mechanical Testing of Composite Materials. Table 2-8 shows some of the physical properties of the core materials presented here.

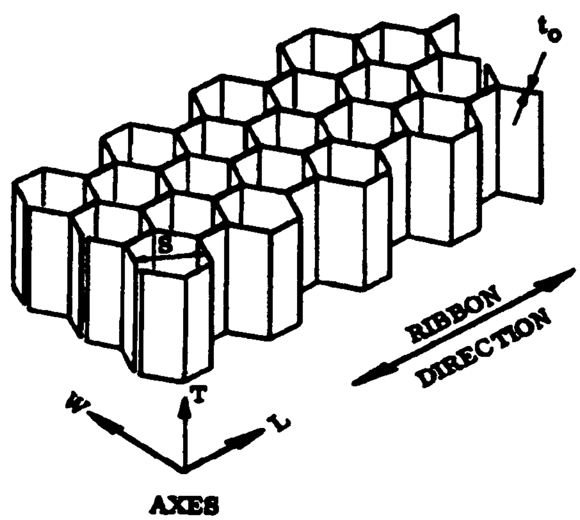


Figure 2-8 Hexagonal Honeycomb Geometry [MIL-STD-401B]

Honeycomb

Various types of manufactured honeycomb cores are used extensively in the aerospace industry. Constituent materials include aluminum, phenolic resin impregnated fiberglass, polypropylene and aramid fiber phenolic treated paper. Densities range from 1 to 6 lbs/ft^3 and cell sizes vary from ⅛ to ⅜ inches. [2-4] Physical properties vary in a near linear fashion with density, as illustrated in Figure 2-9. Although the fabrication of extremely lightweight panels is possible with honeycomb cores, applications in a marine environment are limited due to the difficulty of bonding to complex face geometries and the potential for significant water absorption. The Navy has had some corrosion problems when an aluminum honeycomb core was used for ASROC housings. Data on a Nomex® honeycomb product is presented in Table 2-8.

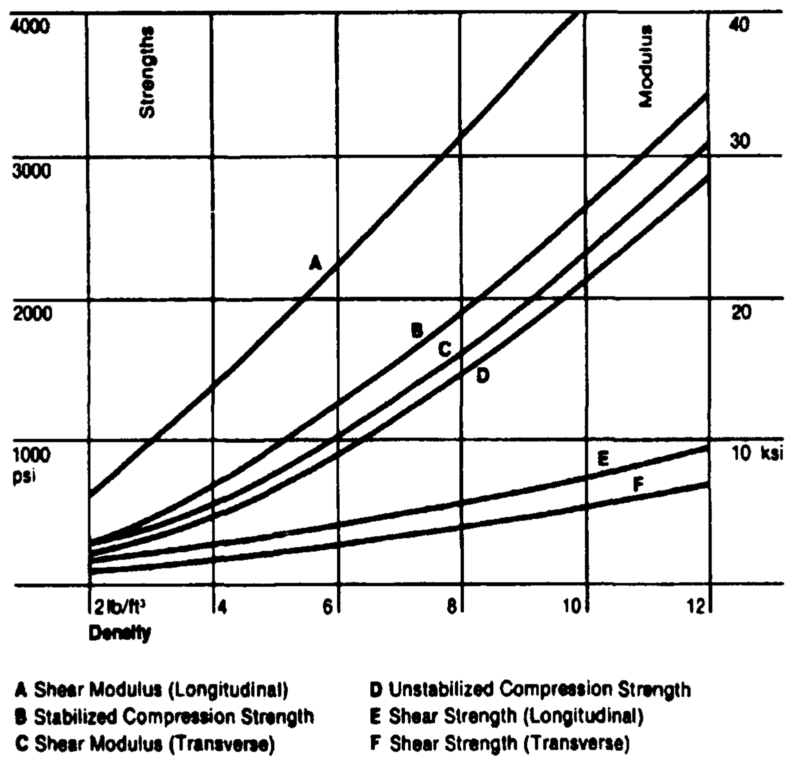


Figure 2-9 Core Strengths and Moduli for Various Core Densities of Aramid Honeycomb [Ciba-Geigy]

PMI Foam

Rohm Tech, Inc. markets a polymrthacrylimide (PMI) foam for composite construction called Rohacell®. The material requires minimum laminating pressures to develop good peel strength. The most attractive feature of this material is its ability to withstand curing temperatures in excess of 350°F. Table 2-8 summarizes the physical properties of a common grade of Rohacell®.

FRP Planking

Seemann Fiberglass, Inc. developed a product called C-Flex® in 1973 to help the amateurs build a cost effective one-off hull. The planking consists of rigid fiberglass rods held together with unsaturated strands of continuous fiberglass rovings and a light fiberglass cloth. The self-supporting material will conform to compound curves. Typical application involves a set of male frames as a form. The planking has more rigidity than PVC foam sheets, which eliminates the need for extensive longitudinal stringers on the male mold. A ⅛ inch variety of C-Flex® weighs about ½ pound dry and costs about $2.00 per square foot.

Table 2-8. Comparative Data for Some Sandwich Core Materials

Material	Density lbs/ft³	Tensile Strength psi	Compressive Strength psi	Shear Strength psi	Modulus of Elasticity psi x 10³	Shear Modulus psi x 10³	Cost $/ft² @ 1"
Balsa CK	7	1320	1187	315	370.0	17.4	2.35
Airex® R62.80	5-6	200	125	170	9.2	2.9	5.37
Divinycell® H 100	6	450	290	217	17.4	6.5	6.10
Klegecell II R 100	6.23	479	319	233	11.5	7.0	5.83
Core-Cell™ C70.75	5	210	184	130	9.6	3.7	3.47
Rohacell® 71IG	4.7	398	213	185	13.1	4.3	7.54
Nomex®HRH-78	6	N/A	1125	200	60.0	6.0	13.53
Nidaplast H8PP	4.8	N/A	218	160	—	—	2.35

Core Fabrics

Various natural and synthetic materials are used to manufacture products called core fabrics that are designed to build up laminate thickness economically. One such product that is popular in the marine industry is Firet Coremat, a spun-bound polyester produced by Lantor. Hoechst Celanese has recently introduced a product called Trevira®, which is a continuous filament polyester. The continuous fibers seem to produce a fabric with superior mechanical properties. Ozite produces a core fabric called Compozitex™ from inorganic vitreous fibers. The manufacturer claims that a unique manufacturing process creates a mechanical fiber lock within the fabric. Although many manufacturers have had much success with such materials in the center of the laminate, the use of a non-structural thick ply near the laminate surface to eliminate print-through is a dangerous practice. The high modulus, low strength ply can produce premature failures. Other manufacturers have started to produce "bulking" products that are primarily used to build up laminate thickness. Some physical properties of core fabric materials are presented in Table 2-9.

Table 2-9. Comparative Data for Some "Bulking" Materials (Impregnated with polyester resin to manufacturers' recommendation)

Material	Type	Dry Thickness inches	Cured Density lb/ft²	Tensile Strength psi	Compressive Strength psi	Shear Strength psi	Flexural Modulus psi x 10³	Cost $/ft²
Coremat®	4mm	.157	37-41	551	3191	580	130	.44
Trevira®	Core 100	.100	75	2700	17700	1800	443	.28
Baltek®Mat	T-2000	.098	40-50	1364	—	1364	—	.31
Tigercore	TY-3	.142	35	710	3000	1200	110	.44
Compozitex™	3mm	.118	—	—	—	—	—	.35

Plywood

Plywood should also be mentioned as a structural core material, although fiberglass is generally viewed as merely a sheathing when used in conjunction with plywood. Exceptions to this characterization include local reinforcements in way of hardware installations, where plywood replaces a lighter density core to improve compression properties of the laminate. Plywood is also sometimes used as a form for longitudinals, especially in way of engine mounts. Recent concern over the continued propensity for wood to absorb moisture in a maritime environment, which can cause swelling and subsequent delamination, has precipitated a decline in the use of wood in conjunction with FRP. The uneven surface of plywood makes it a poor bonding surface. Also, the low strength and low strain characteristics of plywood can lead to premature failures.

The technique of laminating numerous thin plies of wood developed by the Gougeon Brothers and known as wood epoxy saturation technique (WEST® System) eliminates many of the shortcomings involved with using wood in composite structures.

Cost Considerations

The owners and designers of composite marine structures have a broad range of materials that they can choose from. The vast majority of construction to date has been with fiberglass reinforcement and ortho-polyester resin because of the relative ease of use and low cost. When weight, strength, stiffness or durability requirements are at a premium, the use of higher performance materials can be rationalized.

Product Description and Test Data Tables are included at the end of this section to assist in the evaluation of economic differences between commercially available reinforcements based on various strength criteria developed in the 1978 ABS Rules for Reinforced Plastic Vessels [2-5] and the 1986 Guide for Offshore Racing Yachts [2-6] and supplier price quotes from Fall, 1989. Cost data is presented to compare various products from a particular vendor. Manufacturers should consult local suppliers to get current regional pricing information.

Laminate Property Assumptions

Each Data Table includes a set of variables that remain constant for the range of reinforcements in the table. The key variable is the selection of a resin system. All entries within a given table should have a common resin system used for test data derivation. A resin system is usually determined before reinforcement selection based on cost, builder's capabilities, barrier performance, toughness and shear strength. Resin cost is entered into the Data Table on a per pound basis to compare laminates that require different amounts of resin.

Laminate schedules in the marine industry are necessarily specified by thickness to conform with established shipbuilding practices. Dry reinforcement material undergoes some degree of compaction during the laminating process. This value is dependent upon the specific manufacturing process utilized and is input in the form of a percentage. Resin also changes density from the published "neat" value when cured. This phenomena, known as shrinkage, is also represented as a percentage.

Labor variables include the hourly wage rate and the rate at which material can be assembled. The latter is expressed in terms of hours to laminate one square foot of one ply. A value of .05 hours per square foot equates to about 12 pounds per hour of the Base Laminate. This is the value that Scott gives for single skin military boats (see Table 2-10). A difficulty factor is assigned for materials other than standard fiberglass products. This factor takes into account handling and wet-out procedures.

Table 2-10. Hand Layup Production Rates for 10 or More Identical Hulls [Scott, *Fiberglass Boat Construction*]

Type of Construction	Type of Boat	Lbs/Hour*	Ft^2/Hour†	Hours/Ft^2‡
Single Skin with Frames	Recreational	20	33	.03
	Military	12	20	.05
Sandwich Construction	Recreational	10	17	.06
	Military	6	10	.10

* Based on mat/woven roving laminate
† Single ply of mat/woven roving laminate
‡ Time to laminate one ply of mat/woven roving

Since all calculated data is thickness and density dependent, an estimate for void volume is included. This value is used to modify the total estimated laminate weight, but is not included in any derived strength calculations.

Reinforcement Description

The manufacturer's designation is used here to identify the commercial product represented. Refer to pages 60-67 for composition and construction information about these products. The base laminate consists of one layer of woven roving and one mat to form what is considered a single ply.

Test Angle

Since the majority of materials listed are anisotropic, information on the orientation of test specimens is included. Much care should be taken in interpreting the comparative data, especially with unidirectional reinforcements. Most material testing is done along axes of primary reinforcement.

Fiber Weight Percentage

The percentage of reinforcement fiber in a given laminate is determined by burnout tests and reported as a weight percentage. Mechanical properties will vary widely with varying fiber ratios. Strength data is often given as a function of fiber ratio, which is why this descriptor must be included in the Data Table entry.

Fiber Volume Percentage

The percentage of fiber by volume is given by the following relationship presented by Chamis: [2-7]

$$k_f = \frac{(1 - k_v)}{\left[1 + \left(\rho_f/\rho_m\right)\left(1/\lambda_f - 1\right)\right]}$$

where:

k_v = void volume
ρ_f = fiber density
ρ_m = resin density
λ_f = percentage of fiber by weight

Dry Fiber and Uncured Resin Density

Densities are presented in pounds per square foot for one inch thickness. This base unit is better for visualization purposes than cubic feet or cubic inches. Data is derived from virgin material properties.

Cured Laminate Density

The cured laminate density is derived as follows:

$$\rho_l = k_v \times \rho_f \times (1 + \Delta\rho_f) + k_m \times \rho_m \times (1 + \Delta\rho_m)$$

where:

$\Delta\rho_f$ = fiber compaction expressed as a percentage
$\Delta\rho_m$ = resin shrinkage expressed as a percentage
k_m = resin volume

Dry Fiber Thickness

This value, given in mils, is representative of the reinforcement material alone without resin and before any mechanical compaction such as vacuum bagging, rollering, squeegeeing or other processing.

Fiber Weight
This value is merely the product of fiber volume and fiber density.

Resin Weight
To calculate resin weight, a value for resin volume must be derived. This is simply: $(1 - k_f - k_v)$. This value is multiplied by the resin density to get the resin weight.

Laminate Weight
The laminate weight is the sum of the fiber weight and the resin weight.

Reinforcement Cost Data
Current pricing is entered either on a per pound basis or per linear yard, based on a 50" wide roll. Cost data for reinforcing material is based on 1000 square yard quantities as of November, 1989.

Total Material Cost
The material cost per square foot is calculated on a weight basis for reinforcement and resin. The sum is presented as ply cost per square foot.

Labor Cost
The input labor rate is multiplied by the productivity value (ft^2/hr) and the assigned material labor factor.

Total and Relative Ply Cost
The total cost per ply is the sum of material and labor costs. This data is also represented as a percentage relative to the base laminate in the form of cost required to achieve an equal thickness.

Strength Data
Derived strength and stiffness properties are from tests performed according to ASTM standards (see Chapter Six). Single skin laminates of at least ⅛ inch should be tested with sufficient numbers of specimens to produce statistical agreement. Hand laid up test samples fabricated under the guidelines recommended by the resin manufacturer are to be used.

Single Skin Strength Criteria Thickness Comparison
The required thickness for the candidate material is expressed in terms of percentage of the base laminate. The relationship used is:

$$\sqrt{\frac{\sigma_{f_{Base}}}{\sigma_f}}$$

where:

$\sigma_{f_{Base}}$ = flexural strength of the base laminate
σ_f = flexural strength of the subject laminate

Single Skin Stiffness Criteria Thickness Comparison

When the design of a structure is limited by deflection criteria, thicknesses should be compared according to the cube root of the material flexural modulus. Hence, the expression:

$$t_l = \sqrt[3]{\frac{E_{f_{Base}}}{E_f}}$$

where:

$E_{f_{Base}}$ = flexural modulus of the base laminate
E_f = flexural modulus of the subject laminate

Sandwich Construction Tension Criteria Thickness Comparison

The thickness relationship to the base laminate is derived from the required section modulus for the outer skin of a sandwich laminate given by section 7.3.2 of ABS Guide [2-6]. The equivalent single skin thickness and new material flexural and tensile strengths are substituted into the section modulus formula and compared linearly to the section modulus derived for a one inch by one inch skin of base material. If the core thickness is held constant for section modulus comparison, the linear relationship of skin thicknesses is valid. Thus, for a given core thickness, the required thickness of alternate material outer skins is represented as a percentage of base skin thickness by the following equation:

$$t_l = \frac{\dfrac{(t_{equiv}^2 \times \sigma_f)}{6 \times \sigma_t}}{SM_{Outer_{Base}}}$$

where:

t_{equiv} = equivalent required single skin thickness expressed as a percentage of base laminate thickness
σ_t = tensile strength of subject laminate
$SM_{Outer_{Base}}$ = outer skin section modulus required for 1" wide sandwich panel to match *SM* of 1" thick single skin base laminate

the above expression is based on the following relationship:

$$SM_{Outer} = \frac{(t^2 \times \sigma_f)}{6 \times \sigma_t}$$

where:

t = single skin thickness

Sandwich Construction Compression Criteria Thickness Comparison

The compression criteria is based on the ABS inner skin section modulus formula in a similar fashion to that detailed above. The relationship reduces to:

$$t_l = \frac{\dfrac{(t^2_{equiv} \times \sigma_f)}{6 \times \sigma_c}}{SM_{Inner_{Base}}}$$

where:

σ_c = compressive strength of subject laminate

$SM_{Inner_{Base}}$ = inner skin section modulus required for 1" wide sandwich panel to match *SM* of 1" thick single skin base laminate

the above expression is based on the following relationship:

$$SM_{Inner} = \frac{(t^2 \times \sigma_f)}{6 \times \sigma_c}$$

Sandwich Construction Stiffness Criteria Thickness Comparison

To achieve a sandwich structure from alternate material with stiffness equal to a panel with base material skins, the relationship presented in Section 7.3.2.c of the ABS Guide [2-6] is used. As with the section modulus comparison developed above, equivalent moments of inertia are compared linearly to represent alternate material skin thickness for a given core dimension. The mathematical relationship used is:

$$t_l = \frac{\dfrac{(t^3_{equiv} \times E_f)}{12 \times ½ \times (E_t + E_c)}}{I_{Base}}$$

where:

E_t = tensile modulus of subject laminate

E_c = compressive modulus of subject laminate

I_{Base} = required moment of inertia of base laminate for 1" wide strip to match *I* of 1" thick single skin laminate

the above expression is based on the following relationship:

$$I_{Sandwich} = \frac{(t^3 \times E_f)}{12 \times ½ \times (E_t + E_c)}$$

Cost Comparisons

All of the above five thickness comparison criteria are further reduced to cost equivalents by multiplying the thickness relationship to the base material by the relative equivalent thickness cost relationship data.

These relationships are developed for the purpose of material comparison at the preliminary design stage. The strength data is derived from test specimens which may have properties significantly different from an as-built laminate. Samples should always be tested to verify the physical properties of a laminate produced by the builder under conditions similar to that of the final product. Additionally, the comparisons developed for sandwich panels were independent of core thickness and properties. Response prediction procedures for cored panels are presented in Chapter Three. This type of analysis is essential for predicting sandwich panel response. It will be shown that different core materials and dimensions are required to achieve true compatibility with the variety of reinforcement materials presented in the Data Tables. However, the analysis presented does give a good relative indication of skin contribution to panel response.

Additional equations relating to sandwich properties are given in the Sandwich Construction Section of Chapter Three. Readers may also refer to specific requirements of governing regulatory bodies or national standards outlined in Chapter Seven.

Costing information is provided for engineering purposes only. Data is current as of August, 1990. Quotations were based on 1000 pound purchases of material. The cost per lineal yard is based on 50 inch wide reinforcement material. Builders should of course consult their local suppliers for current regional pricing, as market fluctuations are common.

Product Descriptions for Various Reinforcement Materials Used in Marine Construction

Trade Name	Product Description	Code	Weight oz/yd²	Weight g/m²	Thick mils	Material	Weave	Cost $/yd	Cost $/lb
Owens/Corning Fiberglas									
Fiberglas W/R	Woven Roving	OC18-54P-107B-T	18.0	610		E-Glass	Plain	$2.13	$1.36
Fiberglas W/R	Woven Roving	OC18-75P-107B-T	18.0	610		E-Glass	Plain	2.16	1.38
Fiberglas W/R	Woven Roving	OC24-54P-107B-T	24.0	814		E-Glass	Plain	2.73	1.31
Fiberglas M-723	Chopped Strand Reinforcing Mat	3/4 oz	6.8	229		E-Glass	Random	0.90	1.54
Fiberglas M-723	Chopped Strand Reinforcing Mat	1 oz	9.0	305		E-Glass	Random	1.17	1.50
Fiberglas M-723	Chopped Strand Reinforcing Mat	1 1/2 oz	13.5	458		E-Glass	Random	1.57	1.34
Fiberglas M-723	Chopped Strand Reinforcing Mat	2 oz	18.0	610		E-Glass	Random	2.09	1.34
Fiberglas M-723	Chopped Strand Reinforcing Mat	3 oz	27.0	915		E-Glass	Random	3.14	1.34
Fiberglas Bi-Ply	Woven Roving w/ Mat	2415	37.5	1271		E-Glass	Plain/Random	5.24	1.61
King Fiber Glass Corporation									
MultiKnit	Woven Roving	1854	18.2	617	30	E-Glass	Plain	1.71	1.08
MultiKnit	Woven Roving (0-90)	2454	23.8	806	34	E-Glass	Plain	2.15	1.04
MultiKnit	Woven Warp Unidirectional (0)	714.5	18.3	620		E-Glass	Plain	2.27	1.43
PPG Industries									
ABM HTX	Chopped Strand Reinforcing Mat	3/4 oz	6.8	229		E-Glass	Random	0.87	1.49
ABM HTX	Chopped Strand Reinforcing Mat	1 oz	9.0	305		E-Glass	Random	1.14	1.47
ABM HTX	Chopped Strand Reinforcing Mat	1 1/2 oz	13.5	458		E-Glass	Random	1.57	1.34
ABM HTX	Chopped Strand Reinforcing Mat	2 oz	18.0	610		E-Glass	Random	2.09	1.34
ABM HTX	Chopped Strand Reinforcing Mat	3 oz	27.0	915		E-Glass	Random	3.14	1.34
HWR HTX	Hybon Woven Roving	HWR-180	18.0	610	30	E-Glass	Plain	1.97	1.26
HWR HTX	Hybon Woven Roving	HWR-240	24.0	814	41	E-Glass	Plain	2.54	1.22
COMBOMAT HTX	Woven Roving w/ Mat	2415	37.8	1282	30	E-Glass	Plain/Random	5.41	1.65
CertainTeed Corporation									
CertainTeed	Chopped Strand Mat 3/4 oz	M113	7.6	256		E-Glass	Random	0.95	1.45
CertainTeed	Chopped Strand Mat 1 1/2 oz	M127	13.5	458		E-Glass	Random	1.51	1.29
CertainTeed	Woven Roving	318	17.6	597		E-Glass	Plain	2.00	1.31
CertainTeed	Woven Roving	322	22.0	746		E-Glass	Plain	2.35	1.23
CertainTeed	Woven Roving	324	24.0	814		E-Glass	Plain	2.56	1.23
CertainTeed Stitchmat	Flat Weave/Mat	518-10	26.9	912		E-Glass	Plain/Random	3.36	1.44
CertainTeed Stitchmat	Flat Weave/Mat	524-15	38.2	1295	49	E-Glass	Plain/Random	4.71	1.42
Fiber Glass Industries, Inc.									
FABMAT	Woven Roving/Mat	1010	18.9	641	40	E-Glass	Plain/Random	3.54	2.16
FABMAT	Woven Roving/Mat	1810	27.0	915	60	E-Glass	Plain/Random	3.68	1.57
FABMAT	Woven Roving/Mat	1815	31.5	1068	70	E-Glass	Plain/Random	4.07	1.49

Product Descriptions for Various Reinforcement Materials Used in Marine Construction

Trade Name	Product Description	Code	Weight oz/yd²	Weight g/m²	Thick mils	Material	Weave	Cost $/yd	Cost $/lb
FABMAT	Woven Roving/Mat	2410	32.4	1099	65	E-Glass	Plain/Random	4.05	1.44
FABMAT	Woven Roving/Mat	2415	38.3	1297	75	E-Glass	Plain/Random	4.62	1.39
Lightweight FABMAT	Woven Roving/Mat	810	17.0	577	35	E-Glass	Plain/Random	5.15	3.49
Lightweight FABMAT	Woven Roving/Mat	815	21.5	729	45	E-Glass	Plain/Random	5.53	2.96
FORTESIL	Unidirectional	1600	24.0	814	30	E-Glass	Unidirectional	3.75	1.80
FORTESIL	Unidirectional	1300	13.0	441	17	E-Glass	Unidirectional	1.94	1.72
FORTESIL FABMAT	Unidirectional/Mat	13025	15.3	517	25	E-Glass	Uni/Mat	2.71	2.05
FORTESIL FABMAT	Unidirectional/Mat	1305	17.5	593	28	E-Glass	Uni/Mat	3.11	2.05
FORTESIL FABMAT	Unidirectional/Mat	13075	19.8	670	36	E-Glass	Uni/Mat	3.27	1.91
FORTESIL FABMAT	Unidirectional/Mat	1310	22.0	746	45	E-Glass	Uni/Mat	3.59	1.88
ROVCLOTH	Woven Roving	1055	10.0	339	17	E-Glass	Plain	1.53	1.76
ROVCLOTH	Woven Roving	1854	18.0	610	26	E-Glass	Plain	1.98	1.27
ROVCLOTH	Woven Roving	1875	18.0	610	26	E-Glass	Plain	2.08	1.33
ROVCLOTH	Woven Roving	2254	22.0	746	32	E-Glass	Plain	2.31	1.21
ROVCLOTH	Woven Roving	2454	24.0	814	40	E-Glass	Plain	2.52	1.21
Lightwt. ROVCLOTH	Woven Roving	785	9.1	309	15	E-Glass	Plain	2.64	3.33
Composite Reinforcements, Inc.									
COFAB	Biaxial	A1118B	18.0	610	30	E-Glass	Knit Biaxial	2.95	1.89
COFAB	Biaxial	A1112	12.0	407	23	E-Glass	Knit Biaxial	2.19	2.10
COFAB	Biaxial	A1110	10.0	339	21	E-Glass	Knit Biaxial	1.85	2.13
COFAB	Warp Unidirectional	A1010	10.0	339	20	E-Glass	Knit Uni	1.85	2.13
COFAB	Weft Unidirectional	A0108	8.0	271	18	Thread	Knit Uni	1.50	2.16
High Performance	Kevlar biaxial	A2208	8.0	271	30	Kevlar	Knit Biaxial	14.93	21.50
High Performance	Kevlar warp unidirectional	A2005	5.0	170	21	Kevlar	Warp Uni	8.46	19.50
High Performance	Kevlar/glass biaxial hybrid	A2110	10.0	339	26	Kevlar/glass	Knit Biaxial	10.21	11.76
COMAT	12 oz biaxial w/ 1-1/2 oz mat	C1112/15	26.0	880		E-Glass	Knit Biax/Mat	4.67	2.07
COMAT	10 oz biaxial w/ 1 oz mat	C1110/10	20.0	678		E-Glass	Knit Biax/Mat	3.59	2.07
COMAT	10 oz biaxial w/ 3/4 oz mat	C1110/08	18.0	610		E-Glass	Knit Biax/Mat	3.23	2.07
COMAT	18 oz biaxial w/ 1-1/2 oz mat	C1118/15	33.0	1119	55	E-Glass	Knit Biax/Mat	5.67	1.98
COMAT	18 oz biaxial w/ 3/4 oz mat	C1118/08	26.0	882	43	E-Glass	Knit Biax/Mat	4.47	1.98
COMAT	12 oz biaxial w/ 3/4 oz mat	C1112/08	20.0	678	39	E-Glass	Knit Biax/Mat	3.59	2.07
Hexcel									
KNYTEX Unidirectional	Woven warp unidirectional	A130	13.0	441	22	E-Glass	Woven Uni	2.26	2.00
KNYTEX Unidirectional	Woven warp unidirectional	A260	25.6	868	40	E-Glass	Woven Uni	3.91	1.76
KNYTEX Unidirectional	Warp unidirectional w/ mat	CM1701	17.1	580	25	E-Glass	Woven Uni	3.25	2.19

Product Descriptions for Various Reinforcement Materials Used in Marine Construction

Trade Name	Product Description	Code	Weight		Thick	Material	Weave	Cost	
			oz/yd^2	g/m^2	mils			$/yd	$/lb
KNYTEX Unidirectional	Warp unidirectional w/ mat	CM1708	24.0	814	35	E-Glass	Woven Uni	4.40	2.11
KNYTEX Biaxial	18 oz biax (0-90)	CD180	18.2	1051	31	E-Glass	Knit Biaxial	3.46	2.19
KNYTEX Biaxial	18 oz biax (0-90)	CD185	19.1	1051	31	E-Glass	Knit Biaxial	3.65	2.20
KNYTEX Biaxial	23 oz biax (0-90)	CD230	23.1	1255	37	E-Glass	Knit Biaxial	4.21	2.10
KNYTEX Promat	18 oz biax (0-90) w/ .8 oz mat	CDM1808	27.2	922	51	E-Glass	Knit Biax/Mat	5.10	2.16
KNYTEX Promat	18 oz biax (0-90) w/ 1.5 oz mat	CDM1815	32.7	1109	55	E-Glass	Knit Biax/Mat	5.88	2.07
KNYTEX Promat	24 oz biax (0-90) w/ .8 oz mat	CDM2408	33.6	1139	60	E-Glass	Knit Biax/Mat	5.48	1.88
KNYTEX Promat	24 oz biax (0-90) w/ 1.5 oz mat	CDM2415	39.0	1322	61	E-Glass	Knit Biax/Mat	6.16	1.82
KNYTEX Double Bias	9 oz double bias	DB090	9.3	315	16	E-Glass	Knit Double Bias	3.39	4.20
KNYTEX Double Bias	12 oz double bias	DB120	12.0	407	21	E-Glass	Knit Double Bias	4.00	3.84
KNYTEX Double Bias	17 oz double bias	DB170	18.0	610	29	E-Glass	Knit Double Bias	4.44	2.84
KNYTEX Double Bias	24 oz double bias	DB240	25.2	854	32	E-Glass	Knit Double Bias	5.18	2.37
KNYTEX X-mat	12 oz double bias w/ .8 oz mat	DBM1208	19.7	668	30	E-Glass	Knit Dbl Bias/Mat	5.47	3.20
KNYTEX X-mat	17 oz double bias w/ .8 oz mat	DBM1708	25.7	871	41	E-Glass	Knit Dbl Bias/Mat	5.69	2.55
KNYTEX X-mat	17 oz double bias w/ 1.5 oz mat	DBM1715	31.2	1058	58	E-Glass	Knit Dbl Bias/Mat	6.55	2.42
KNYTEX X-mat	24 oz double bias w/ .8 oz mat	DBM2408	32.3	1095	56	E-Glass	Knit Dbl Bias/Mat	6.59	2.35
KNYTEX X-mat	24 oz double bias w/ 1.5 oz mat	DBM2415	33.3	1129	66	E-Glass	Knit Dbl Bias/Mat	6.65	2.30
KNYTEX Triaxial	0, +45, -45	CDB200	22.7	770	35	E-Glass	Triaxial Knit	5.77	2.93
KNYTEX Triaxial	0, +45, -45	CDB340	33.9	1149	50	E-Glass	Triaxial Knit	6.97	2.37
KNYTEX Triaxial	23 oz Triax w/ .8 oz mat	CDBM2008	30.4	1031	47	E-Glass	Triaxial Knit	7.05	2.67
KNYTEX Triaxial	34 oz Triax w/ .8 oz mat	CDBM3408	42.1	1427	73	E-Glass	Triaxial Knit	8.44	2.31
KNYTEX Triaxial	90, +45, -45	DDB222	22.5	763	40	E-Glass	Triaxial Knit	5.63	2.88
KNYTEX Triaxial	90, +45, -45	DDB340	34.7	1177	48	E-Glass	Triaxial Knit	7.14	2.37
KNYTEX Graphite	+45, -45	GDB095	9.5	322	20	3K Carbon	Double Bias Knit	47.93	58.12
KNYTEX Graphite	+45, -45	GDB120	12.2	414	25	6K Carbon	Double Bias Knit	47.66	45.00
KNYTEX Graphite	+45, -45	GDB200	20.4	692	40	12K Carbon	Double Bias Knit	60.36	34.09
KNYTEX Graphite	0, +45, -45	GCDB180	19.8	671	40	6K Carbon	Triaxial Knit	93.75	54.55
KNYTEX Graphite	90, +45, -45	GDDB180	19.6	665	40	6K Carbon	Triaxial Knit	93.75	55.10
TREVARNO	Boat and Tooling Fabric	1522	3.7	127	5.5	E-Glass	Plain	2.39	7.36
TREVARNO	Boat and Tooling Fabric	1800	9.7	328	14	E-Glass	Plain	3.23	3.85
TREVARNO	Boat and Tooling Fabric	2532	7.3	248	11	E-Glass	Plain	2.73	4.30
TREVARNO	Boat and Tooling Fabric	3733	5.9	198	10	E-Glass	Plain	2.73	5.38
TREVARNO	Boat and Tooling Fabric	7500	9.7	328	14	E-Glass	Plain	3.62	4.32
TREVARNO	Boat and Tooling Fabric	7520	8.6	290	12	E-Glass	Plain	3.45	4.65
TREVARNO	Boat and Tooling Fabric	7532	7.3	248	11	E-Glass	Plain	2.82	4.44

Product Descriptions for Various Reinforcement Materials Used in Marine Construction									
Trade Name	Product Description	Code	Weight		Thick	Material	Weave	Cost	
			oz/yd²	g/m²	mils			$/yd	$/lb
TREVARNO	Boat and Tooling Fabric	7533	5.9	198	10	E-Glass	Plain	2.76	5.44
TREVARNO	Boat and Tooling Fabric	7544	19.2	651	22	E-Glass	Plain	6.12	3.67
TREVARNO	Boat and Tooling Fabric	7587	20.7	700	30	E-Glass	Mock Leno	7.16	3.99
TREVARNO	Boat and Tooling Fabric	7597	39.2	1328	45	E-Glass	Satin	13.52	3.98
TREVARNO	Advanced Composite Fabrics	4522	3.7	125	5.5	S-Glass	Plain	5.56	17.31
TREVARNO	Advanced Composite Fabrics	4533	5.8	197	9	S-Glass	Plain	6.83	13.57
TREVARNO	Advanced Composite Fabrics	282	5.7	193	7.2	Carbon	Plain	27.43	55.44
TREVARNO	Advanced Composite Fabrics	584	10.9	370	13.5	Carbon	Satin	52.35	55.33
TREVARNO	Advanced Composite Fabrics	613	11.0	373	13.5	Carbon	5HS	33.10	34.66
TREVARNO	Advanced Composite Fabrics	690	19.0	644	24	Carbon	Plain	34.94	21.18
TREVARNO	Advanced Composite Fabrics	716	4.6	156	6.1	Carbon	Plain	13.99	35.04
TREVARNO	Advanced Composite Fabrics	120	1.8	61	4.5	Kevlar	Plain	20.17	129.09
TREVARNO	Advanced Composite Fabrics	281	5.0	170	10	Kevlar	Plain	23.50	54.14
TREVARNO	Advanced Composite Fabrics	285	5.0	170	10	Kevlar	Crowfoot	17.99	41.45
TREVARNO	Advanced Composite Fabrics	500	5.0	170	10	Kevlar	Plain	14.67	33.80
TREVARNO	Advanced Composite Fabrics	900	9.0	305	13	Kevlar	Satin	19.05	24.38
TREVARNO	Advanced Composite Fabrics	1350	13.5	458	26	Kevlar	Basket	25.52	21.78
HERCULES	Graphite Woven Fabrics	A193-P	5.7	193	10.5	AS4 Carbon	Plain	23.22	47.00
HERCULES	Graphite Woven Fabrics	A280-5H	8.3	280	16	AS4 Carbon	5H Satin	33.69	47.00
HERCULES	Graphite Woven Fabrics	A370-5H	10.9	370	21	AS4 Carbon	5H Satin	36.00	38.00
HERCULES	Graphite Woven Fabrics	A370-8H	10.9	370	21	AS4 Carbon	8H Satin	44.52	47.00
HERCULES	Graphite Woven Fabrics	I360-5H	10.6	360	20.4	IM6 Carbon	5H Satin	50.69	55.00
PRECOM International									
AEROTEX	Vertex R-Glass Unidirectional	VRX 16-300	4.7	160		R-Glass	Unidirectional	7.88	19.21
AEROTEX	Vertex R-Glass Unidirectional	VRX 28-300	8.3	280		R-Glass	Unidirectional	10.88	15.18
AEROTEX	Carbotex Carbon Unidirectional	CX 10-300	3.0	100		Int Mod Carbon	Unidirectional	13.00	50.73
AEROTEX	Carbotex Carbon Unidirectional	CX IM 12-267	3.5	120		HTX Carbon	Unidirectional	25.75	83.74
AEROTEX	Carbotex Carbon Unidirectional	CX 16-300	4.7	160		HTX Carbon	Unidirectional	16.63	40.55
AEROTEX	Carbotex Carbon Unidirectional	CX 22-300	6.5	220		HTX Carbon	Unidirectional	19.25	34.15
AEROTEX	Carbotex Carbon Unidirectional	CX 32-300	9.4	320		HTX Carbon	Unidirectional	23.38	28.55
Anchor Reinforcements, Inc.									
ANCAREF	Unidirectional	G135	4.0	136		E-Glass	Unidirectional	4.62	13.30
ANCAREF	Unidirectional	G300	8.8	298		E-Glass	Unidirectional	5.08	6.65
ANCAREF	Unidirectional	G600	17.7	600		E-Glass	Unidirectional	6.41	4.17
ANCAREF	+45, -45	G600A	17.7	600		E-Glass	Unidirectional	11.11	7.23

Product Descriptions for Various Reinforcement Materials Used in Marine Construction

Trade Name	Product Description	Code	Weight		Thick	Material	Weave	Cost	
			oz/yd²	g/m²	mils			$/yd	$/lb
ANCAREF	0, 90	G600B	17.7	600		E-Glass	Unidirectional	11.11	7.23
ANCAREF	Unidirectional	S150	4.4	149		S-2 Glass	Unidirectional	7.88	19.31
ANCAREF	Unidirectional	S300	8.9	302		S-2 Glass	Unidirectional	11.05	15.71
ANCAREF	+45, -45	S300A	8.9	302		S-2 Glass	Unidirectional	18.23	23.60
ANCAREF	0, 90	S300B	8.9	302		S-2 Glass	Unidirectional	18.23	23.60
ANCAREF	Unidirectional	C125	3.7	125		Carbon	Unidirectional	14.92	46.44
ANCAREF	Unidirectional	C250	7.4	251		Carbon	Unidirectional	19.19	29.88
ANCAREF	+45, -45	C250A	7.4	251		Carbon	Unidirectional	33.15	51.60
ANCAREF	0, 90	C250B	7.4	251		Carbon	Unidirectional	33.15	51.60
ANCAREF	Unidirectional	C320	9.4	319		Carbon	Unidirectional	23.42	28.70
ANCAREF	Unidirectional	K150	4.4	149		Kevlar	Unidirectional	16.61	43.50
Allied-Signal, Inc.									
COMPET P	PET Polyester Fabric	1W71-Lo	5.6	190	11	PET Polyester	Plain	2.55	5.25
COMPET P	PET Polyester Fabric	1W71-Lo	10.5	356	29	PET Polyester	Basket	4.45	4.88
COMPET P	PET Polyester Fabric	1W71-Lo	6.0	203	13	PET Polyester	Satin	2.85	5.47
COMPET P	PET Polyester/Glass Hybrid	1W71-Lo/Glass	8.2	278	12	PET/Glass	Plain	3.75	5.27
Clark-Schwebel Fiber Glass Corporation									
SPECTRA	SPECTRA 900 Fabric	901	3.0	102	12	SPECTRA 900	Plain	11.55	44.35
SPECTRA	SPECTRA 900 Fabric	902	5.5	186	18	SPECTRA 900	Plain	17.35	36.34
SPECTRA	SPECTRA 900 Fabric	903	7.0	237	20	SPECTRA 900	Plain	21.05	34.64
SPECTRA	SPECTRA 900 Fabric	912	11.3	383	28	SPECTRA 900	Basket 4 x 4	29.75	30.33
SPECTRA	SPECTRA 900 Fabric	913	15.5	526	38	SPECTRA 900	Basket 8 x 8	42.95	31.92
SPECTRA	SPECTRA 900 Fabric	921	6.2	210	19	SPECTRA 900	4H Satin	18.15	33.72
SPECTRA	SPECTRA 900 Fabric	922	7.3	248	18	SPECTRA 900	8H Satin	22.25	35.11
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	328	6.4	217	12	KEVLAR-49	Plain	15.85	28.53
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	343	5.5	186	11	KEVLAR-49	Crowfoot	30.00	62.84
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	345	1.7	58	3	KEVLAR-49	Crowfoot	16.85	114.18
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	348	4.9	166	8	KEVLAR-49	8H Satin	28.85	67.83
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	350	1.7	58	3.7	KEVLAR-49	Plain	16.05	108.76
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	351	2.2	75	4.6	KEVLAR-49	Plain	14.05	73.57
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	352	5.2	176	10	KEVLAR-49	Plain	13.95	30.90
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	353	5.2	175	9	KEVLAR-49	Crowfoot	13.95	31.20
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	354	4.8	163	10	KEVLAR-49	Plain	12.40	29.76
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	357	5.2	176	10	KEVLAR-49	Plain	13.49	29.89
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	358	6.6	224	11	KEVLAR-49	Crowfoot	20.35	35.52

Product Descriptions for Various Reinforcement Materials Used in Marine Construction

Trade Name	Product Description	Code	Weight oz/yd^2	Weight g/m^2	Thick mils	Material	Weave	Cost $/yd	Cost $/lb
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	383	8.9	302	14	KEVLAR-49	5H Satin	18.85	24.40
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	386	13.6	461	25	KEVLAR-49	Basket 4 x 4	27.50	23.29
C-S KEVLAR-49	CS-800 Scoured Finish Kevlar-49	388	15.0	509	26	KEVLAR-49	Basket 2 x 8	34.87	26.78
Advanced Textiles, Inc.									
ATI	Knit E-Glass (0, 90)	NEWF 120	12.2	412	21	E-Glass	Knit	3.50	3.32
ATI	Knit E-Glass (0, 90)	NEWF 160	15.5	526	24	E-Glass	Knit	3.83	2.85
ATI	Knit E-Glass (0, 90)	NEWF 180	17.7	600	26	E-Glass	Knit	3.58	2.33
ATI	Knit E-Glass (0, 90)	NEWF 230	23.2	787	34	E-Glass	Knit	4.29	2.13
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 1208	18.9	641	35	E-Glass	Knit	4.69	2.86
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 1215	25.6	868	42	E-Glass	Knit	6.29	2.83
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 1608	22.5	763	43	E-Glass	Knit	4.82	2.47
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 1615	29.0	983	49	E-Glass	Knit	6.17	2.45
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 1808	24.4	827	46	E-Glass	Knit	4.11	1.94
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 1815	31.2	1058	56	E-Glass	Knit	5.17	1.91
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 2308	29.0	983	52	E-Glass	Knit	4.91	1.95
ATI	Knit E-Glass (0, 90) w/ mat	NEWFC 2315	36.7	1244	62	E-Glass	Knit	6.12	1.92
ATI	Double Bias (+-45)	NEMP 090	9.5	322	20	E-Glass	Knit	3.30	4.00
ATI	Double Bias (+-45)	NEMP 120	12.4	420	22	E-Glass	Knit	3.93	3.65
ATI	Double Bias (+-45)	NEMP 170	17.6	597	26	E-Glass	Knit	4.17	2.73
ATI	Double Bias (+-45)	NEMP 240	24.2	821	32	E-Glass	Knit	4.83	2.30
ATI	Double Bias w/ mat	NEMPC 1208	19.2	651	34	E-Glass	Knit	5.12	3.07
ATI	Double Bias w/ mat	NEMPC 1215	26.0	882	41	E-Glass	Knit	6.84	3.03
ATI	Double Bias w/ mat	NEMPC 1708	24.4	827	43	E-Glass	Knit	4.96	2.34
ATI	Double Bias w/ mat	NEMPC 1715	31.1	1054	47	E-Glass	Knit	6.16	2.28
ATI	Double Bias w/ mat	NEMPC 2408	31.0	1051	48	E-Glass	Knit	5.95	2.21
ATI	Double Bias w/ mat	NEMPC 2415	37.8	1282	57	E-Glass	Knit	7.19	2.19
ATI	Knit Warp Triaxial	NEWMP 200	20.2	685	32	E-Glass	Knit	4.98	2.84
ATI	Knit Warp Triaxial	NEWMP 230	22.8	773	41	E-Glass	Knit	5.62	2.84
ATI	Knit Warp Triaxial	NEWMP 340	33.1	1122	46	E-Glass	Knit	6.58	2.29
ATI	Knit Fill Triaxial	NEFMP 230	22.8	773	38	E-Glass	Knit	5.62	2.84
ATI	Knit Fill Triaxial	NEFMP 340	33.1	1122	48	E-Glass	Knit	6.58	2.29
ATI	Warp Triaxial w/ mat	NEWMPC 2008	27.1	919	48	E-Glass	Knit	6.05	2.57
ATI	Warp Triaxial w/ mat	NEWMPC 2308	29.5	1000	49	E-Glass	Knit	7.22	2.82
ATI	Fill Triaxial w/ mat	NEFMPC 2308	29.5	1000	50	E-Glass	Knit	7.22	2.82
ATI	Warp Triaxial w/ mat	NEWMPC 3408	40.2	1362	58	E-Glass	Knit	7.99	2.29

Product Descriptions for Various Reinforcement Materials Used in Marine Construction

Trade Name	Product Description	Code	Weight oz/yd^2	Weight g/m^2	Thick mils	Material	Weave	Cost $/yd	Cost $/lb
ATI	Fill Triaxial w/ mat	NEFMPC 3408	40.2	1362	60	E-Glass	Knit	7.78	2.23
ATI	Warp Triaxial w/ mat	NEWMPC 3415	46.8	1587	68	E-Glass	Knit	8.94	2.20
ATI	Warp Unidirectional	VFW 130	13.1	444	23	E-Glass	Woven	2.10	1.85
ATI	Warp Unidirectional	VFW 170	17.3	587	29	E-Glass	Woven	2.70	1.80
ATI	Warp Unidirectional	VFW 260	25.9	878	35	E-Glass	Woven	3.84	1.71
ATI	Fill Unidirectional	NEF 069	6.9	234	14	E-Glass	Knit	1.25	2.08
ATI	Fill Unidirectional	NEF 072	7.3	248	15	E-Glass	Knit	1.30	2.05
ATI	Fill Unidirectional	NEF 090	9.1	309	17	E-Glass	Knit	1.65	2.09
ATI	Fill Unidirectional	NEF 160	15.4	522	23	E-Glass	Knit	2.65	1.98
ATI	Fill Unidirectional	NEF 240	24.1	817	26	E-Glass	Knit	4.04	1.93
Brunswick Technologies, Inc.									
BTI	Knit E-Glass (0, 90)	C-1800	18.0	610		E-Glass	Knit	2.50	1.60
BTI	Knit E-Glass (0, 90) w/ mat	CM-1808	24.8	839		E-Glass	Knit	3.29	1.53
BTI	Knit E-Glass (0, 90) w/ mat	CM-1810	27.0	915		E-Glass	Knit	3.59	1.53
BTI	Knit E-Glass (0, 90) w/ mat	CM-1815	31.5	1068		E-Glass	Knit	4.18	1.53
BTI	Knit E-Glass (0, 90)	C-2400	24.0	814		E-Glass	Knit	3.33	1.60
BTI	Knit E-Glass (0, 90) w/ mat	CM-2408	30.8	1043		E-Glass	Knit	4.08	1.53
BTI	Knit E-Glass (0, 90) w/ mat	CM-2410	33.0	1119		E-Glass	Knit	4.38	1.53
BTI	Knit E-Glass (0, 90) w/ mat	CM-2415	37.5	1271		E-Glass	Knit	4.98	1.53
BTI	Double Bias	X-1800	18.0	610		E-Glass	Knit	3.20	2.05
BTI	Double Bias w/ mat	XM-1808	24.8	839		E-Glass	Knit	4.04	1.88
BTI	Double Bias w/ mat	XM-1815	31.5	1068		E-Glass	Knit	5.14	1.88
BTI	Double Bias	X-2400	24.0	814		E-Glass	Knit	4.27	2.05
BTI	Double Bias w/ mat	XM-2408	30.8	1043		E-Glass	Knit	5.02	1.88
BTI	Double Bias w/ mat	XM-2415	37.5	1271		E-Glass	Knit	6.12	1.88
BTI	Triaxial	TV-3400	34.0	1153		E-Glass	Knit	5.55	1.88
BTI	Triaxial w/ mat	TVM 3408	40.8	1382		E-Glass	Knit	6.65	1.88
Bean Fiber Glass, Inc.									
VECTORPLY	Knit E-Glass (0, 90)	V24	24.0	814	40	E-Glass	Stitch-bonded	3.56	1.71
VECTORPLY	Knit E-Glass (0, 90)	V18	18.0	610	30	E-Glass	Stitch-bonded	2.80	1.79
VECTORPLY	Fill Unidirectional	VF18	18.0	610	30	E-Glass	Stitch-bonded	2.80	1.79
VECTORPLY	Double Bias	VX24	24.0	814	40	E-Glass	Stitch-bonded	4.46	2.14
VECTORPLY	Double Bias	VX18	18.0	610	30	E-Glass	Stitch-bonded	4.31	2.76
VECTORPLY	Knit E-Glass (0, 90) w/ mat	V2410	33.0	1119	57	E-Glass	Stitch-bonded	4.58	1.60
VECTORPLY	Warp Unidirectional w/ mat	VW0910	18.0	610	30	E-Glass	Stitch-bonded	3.08	1.97

Product Descriptions for Various Reinforcement Materials Used In Marine Construction

Trade Name	Product Description	Code	Weight		Thick	Material	Weave	Cost	
			oz/yd²	g/m²	mils			$/yd	$/lb
VECTORPLY	Double Bias w/ mat	VX1808	24.0	814	43	E-Glass	Stitch-bonded	4.63	2.22
VECTORPLY	Knit Warp Triaxial	TW36	36.0	1221	62	E-Glass	Stitch-bonded	6.72	2.15
VECTORPLY	Knit Warp Triaxial	TW24	24.0	814	40	E-Glass	Stitch-bonded	5.71	2.74
VECTORPLY	Knit Fill Triaxial	TF36	36.0	1221	62	E-Glass	Stitch-bonded	6.72	2.15
VECTORPLY	Knit E-glass (0, 90) w/ mat	V1808	24.0	814	43	E-Glass	Stitch-bonded	3.54	1.70
VECTORPLY	Knit E-glass (0, 90) w/ mat	V1810	27.0	915	48	E-Glass	Stitch-bonded	3.94	1.68
Low profile	24 oz. Woven Roving	3	24.0	814	40	E-Glass	Woven Roving	2.08	1.00
Low profile	18 oz. Woven Roving	11	18.0	610	30	E-Glass	Woven Roving	1.63	1.04
Low profile	Fine weave Roving Roving	1109	10.0	339	17	E-Glass	Woven Roving	1.87	2.15
THREE PLY	Mat/18 oz. Knit (0, 90)/Mat	V1808-08	31.0	1051	80	E-Glass	Stitch-bonded	5.09	1.89
WOVMAT	Woven Roving/chopped fibers	1010	20.0	678	32	E-Glass	WR/chopped fbrs	2.95	1.70
WOVMAT	Woven Roving/chopped fibers	1524	38.0	1288	66	E-Glass	WR/chopped fbrs	3.99	1.21
		BGF Industries, Inc.							
Reinforced Plastics	Woven Cloth	1522	11.9	402	5.6	E-Glass	Plain	3.00	2.92
Reinforced Plastics	Woven Cloth	2532	7.3	246	10	E-Glass	Plain	3.36	5.34
Reinforced Plastics	Woven Cloth	3733	5.8	197	8	E-Glass	Plain	2.97	5.90
Reinforced Plastics	Woven Cloth	7500	9.6	325	12	E-Glass	Plain	4.49	5.39
		North American Textiles							
NORTEX	Woven Fabric	N120	2.0	68	5	Kevlar	Plain	15.10	86.98
NORTEX	Woven Fabric	N281	5.0	170	11	Kevlar	Plain	13.00	29.95
NORTEX	Woven Fabric	N285	5.0	170	9	Kevlar	Crowfoot	13.00	29.95
NORTEX	Woven Fabric	N1118	3.0	102	6	Carbon	Plain	48.33	185.59
NORTEX	Woven Fabric	N1122	3.5	119	7	Carbon	Plain	59.06	194.39
NORTEX	Woven Fabric	N3113	6.0	203	11	Carbon	Plain	25.00	48.00
NORTEX	Woven Fabric	N3118	8.5	288	11	Carbon	4 x 4 Twill	35.87	48.61
NORTEX	Woven Fabric	N3125	12.0	407	16	Carbon	8 HS	49.83	47.84
NORTEX	Woven Fabric	N6111	10.5	356	14	Carbon	Plain	25.78	28.28
NORTEX	Woven Fabric	N2577	20.0	678	30	Carbon	Plain	34.17	19.68
NORTEX	Woven Fabric	N3376	3.5	119	8	Carbon/E-Glass	Plain	27.28	89.79
NORTEX	Woven Fabric	N3375	4.5	153	8	Carbon/E-Glass	Plain	18.58	47.56
NORTEX	Woven Fabric	N4476	7.5	254	12	Carbon/E-Glass	Plain	14.95	22.96
NORTEX	Woven Fabric	N1222	3.0	102	6	Carbon/Kevlar	Plain	19.25	73.92
NORTEX	Woven Fabric	N2312	6.0	203	11	Carbon/Kevlar	Plain	14.26	27.38
NORTEX	Woven Fabric	N4375	5.0	170	8	Kevlar/E-Glass	Plain	8.13	18.73
NORTEX	Woven Fabric	N4475	12.5	424	12	Kevlar/E-Glass	Plain	7.01	6.46

Advanced Textiles Reinforcements Tested at FIT Structural Composites Lab with FRP A 100 Polyester Resin

Description	Test Angle	% Fiber by Weight	% Fiber by Volume	Dry Fiber Density	Uncured Resin Density	Cured Laminate Density	Dry Fiber Thickness	Fiber Weight	Resin Weight	Total Laminate Weight	Fiber Cost by Weight	Areal Fiber Cost (50" width rolls)	Ply Material Cost	Ply Labor Cost	Total Ply Cost	Cost Relative to Base Laminate per Thickness
				lbs/in x ft²			mils	lbs/ft²/ply			$/lb	$/ln yd	$/ft²			
Base (WR/ mat)	0	35%	20%	12.96	6.34	8.22	87	0.226	0.419	0.644	$1.35	$4.30	$1.04	$0.25	$1.29	100%
NEWF 120	0	42%	25%	12.96	6.34	8.62	21	0.068	0.094	0.162	3.32	3.50	0.44	0.25	0.69	221%
NEWF 120	90	42%	25%	12.96	6.34	8.62	21	0.068	0.094	0.162	3.32	3.50	0.44	0.25	0.69	221%
NEWF 160	0	58%	39%	12.96	6.34	9.70	24	0.120	0.087	0.208	2.85	3.83	0.45	0.25	0.70	197%
NEWF 160	90	58%	39%	12.96	6.34	9.70	24	0.120	0.087	0.208	2.85	3.83	0.45	0.25	0.70	197%
NEWF 180	0	51%	33%	12.96	6.34	9.21	26	0.110	0.105	0.214	2.33	3.58	0.46	0.25	0.71	184%
NEWF 180	90	51%	33%	12.96	6.34	9.21	26	0.110	0.105	0.214	2.33	3.58	0.46	0.25	0.71	184%
NEWF 230	0	55%	35%	12.96	6.34	9.44	34	0.156	0.130	0.287	2.13	4.29	0.56	0.25	0.81	161%
NEWF 230	90	55%	35%	12.96	6.34	9.44	34	0.156	0.130	0.287	2.13	4.29	0.56	0.25	0.81	161%
NEWFC 1208	0	47%	29%	12.96	6.34	8.96	35	0.133	0.148	0.281	2.86	4.69	0.62	0.25	0.87	168%
NEWFC 1208	90	47%	29%	12.96	6.34	8.96	35	0.133	0.148	0.281	2.86	4.69	0.62	0.25	0.87	168%
NEWFC 1215	0	35%	20%	12.96	6.34	8.21	42	0.108	0.203	0.311	2.83	6.29	0.84	0.25	1.09	175%
NEWFC 1215	90	35%	20%	12.96	6.34	8.21	42	0.108	0.203	0.311	2.83	6.29	0.84	0.25	1.09	175%
NEWFC 1608	0	45%	28%	12.96	6.34	8.82	43	0.154	0.186	0.340	2.47	4.82	0.70	0.25	0.95	148%
NEWFC 1608	90	45%	28%	12.96	6.34	8.82	43	0.154	0.186	0.340	2.47	4.82	0.70	0.25	0.95	148%
NEWFC 1615	0	44%	27%	12.96	6.34	8.76	49	0.170	0.215	0.385	2.45	6.17	0.85	0.25	1.10	151%
NEWFC 1615	90	44%	27%	12.96	6.34	8.76	49	0.170	0.215	0.385	2.45	6.17	0.85	0.25	1.10	151%
NEWFC 1808	0	47%	29%	12.96	6.34	8.93	46	0.173	0.195	0.368	1.94	4.11	0.65	0.25	0.90	132%
NEWFC 1808	90	47%	29%	12.96	6.34	8.93	46	0.173	0.195	0.368	1.94	4.11	0.65	0.25	0.90	132%
NEWFC 1815	0	48%	30%	12.96	6.34	9.03	56	0.219	0.233	0.453	1.91	5.17	0.80	0.25	1.05	127%
NEWFC 1815	90	48%	30%	12.96	6.34	9.03	56	0.219	0.233	0.453	1.91	5.17	0.80	0.25	1.05	127%
NEWFC 2308	0	49%	31%	12.96	6.34	9.05	52	0.206	0.216	0.421	1.95	4.91	0.75	0.25	1.00	130%
NEWFC 2308	90	49%	31%	12.96	6.34	9.05	52	0.206	0.216	0.421	1.95	4.91	0.75	0.25	1.00	130%
NEWFC 2315	0	48%	30%	12.96	6.34	9.03	62	0.243	0.258	0.501	1.92	6.12	0.92	0.25	1.17	127%
NEWFC 2315	90	48%	30%	12.96	6.34	9.03	62	0.243	0.258	0.501	1.92	6.12	0.92	0.25	1.17	127%
NEMPC 1708	0	48%	30%	12.96	6.34	8.98	43	0.165	0.181	0.346	2.34	4.96	0.70	0.25	0.95	149%
NEMPC 1708	45	48%	30%	12.96	6.34	8.98	43	0.165	0.181	0.346	2.34	4.96	0.70	0.25	0.95	149%
NEWMPC 3408	0	54%	35%	12.96	6.34	9.41	58	0.264	0.224	0.488	2.23	7.99	1.01	0.45	1.46	170%
NEWMPC 3408	45	54%	35%	12.96	6.34	9.41	58	0.264	0.224	0.488	2.23	7.99	1.01	0.45	1.46	170%

Advanced Textiles Reinforcements Tested at FIT Structural Composites Lab with FRP A 100 Polyester Resin

Flexural Strength	Flexural Modulus	Tensile Strength	Tensile Modulus	Compressive Strength	Compressive Modulus	Single Skin Strength Criteria	Single Skin Stiffness Criteria	Sandwich Tensile Strength Criteria	Sandwich Compressive Strength Criteria	Sandwich Stiffness Criteria	Single Skin Strength Criteria	Single Skin Stiffness Criteria	Sandwich Tensile Strength Criteria	Sandwich Compressive Strength Criteria	Sandwich Stiffness Criteria	Description
psi x 10^3						Skin Thickness Relative to Base					Ply Cost Relative to Base					
25	1100	18	1000	17	1000	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	Base (WR/ mat)
60	1982	31	2050	15	2252	65%	82%	59%	113%	46%	143%	181%	130%	250%	102%	NEWF 120
37	712	22	1430	14	1272	82%	116%	83%	121%	74%	181%	255%	184%	268%	163%	NEWF 120
48	1393	41	2654	15	2512	72%	92%	44%	113%	39%	142%	182%	87%	223%	76%	NEWF 160
48	1427	41	2193	21	2161	72%	92%	44%	81%	46%	142%	181%	87%	160%	90%	NEWF 160
65	2071	43	2898	15	2007	62%	81%	42%	113%	41%	114%	149%	77%	209%	75%	NEWF 180
31	1001	21	1654	19	1840	90%	103%	86%	90%	57%	165%	190%	158%	165%	105%	NEWF 180
57	2177	33	2652	23	2293	66%	80%	55%	74%	40%	106%	128%	88%	119%	65%	NEWF 230
39	1462	32	2553	26	2098	80%	91%	56%	65%	43%	129%	146%	91%	105%	69%	NEWF 230
66	2296	37	2165	20	2382	62%	78%	49%	85%	44%	103%	131%	82%	143%	74%	NEWFC 1208
35	1257	21	1655	15	1653	85%	96%	86%	113%	60%	142%	161%	144%	190%	101%	NEWFC 1208
43	1562	23	1859	18	1891	76%	89%	78%	94%	53%	133%	156%	137%	165%	93%	NEWFC 1215
29	1139	17	1329	16	1603	93%	99%	106%	106%	68%	163%	173%	186%	186%	119%	NEWFC 1215
57	1783	25	2132	30	1920	66%	85%	72%	57%	49%	98%	126%	107%	84%	73%	NEWFC 1608
42	1387	28	2068	24	1898	77%	93%	64%	71%	50%	114%	137%	96%	105%	75%	NEWFC 1608
51	1880	22	1768	22	2052	70%	84%	82%	77%	52%	106%	127%	124%	117%	79%	NEWFC 1615
48	1667	24	1870	25	1872	72%	87%	75%	68%	53%	109%	132%	114%	103%	81%	NEWFC 1615
64	2074	35	2587	29	2062	63%	81%	52%	59%	43%	83%	107%	68%	78%	57%	NEWFC 1808
34	1120	21	1743	21	1676	86%	99%	86%	81%	58%	114%	132%	114%	107%	77%	NEWFC 1808
58	2383	28	2200	28	1916	66%	77%	64%	61%	48%	83%	98%	82%	77%	61%	NEWFC 1815
39	1605	21	1823	19	1550	80%	88%	86%	90%	59%	101%	112%	109%	113%	75%	NEWFC 1815
56	1898	30	2373	19	2245	67%	83%	60%	90%	43%	87%	108%	78%	116%	56%	NEWFC 2308
51	1421	32	2277	19	2206	70%	92%	56%	90%	44%	91%	119%	73%	116%	58%	NEWFC 2308
51	2029	26	1853	19	2361	70%	82%	69%	90%	47%	89%	104%	88%	114%	60%	NEWFC 2315
46	1686	26	1794	15	1813	74%	87%	69%	113%	55%	94%	110%	88%	144%	70%	NEWFC 2315
30	1004	14	1498	20	1224	91%	103%	129%	85%	73%	136%	153%	192%	126%	109%	NEMPC 1708
52	1745	28	2018	28	2102	69%	86%	64%	61%	48%	103%	127%	96%	90%	72%	NEMPC 1708
65	2591	34	2199	24	2455	62%	75%	53%	71%	43%	105%	128%	90%	120%	73%	NEWMPC 3408
45	1726	25	1815	24	2503	75%	86%	72%	71%	46%	127%	146%	123%	120%	78%	NEWMPC 3408

Brunswick Technologies Reinforcements Tested at COMTEX Development Corporation with G/P Polyester Resin

Description	Test Angle	% Fiber by Weight	% Fiber by Volume	Dry Fiber Density	Uncured Resin Density	Cured Laminate Density	Dry Fiber Thickness	Fiber Weight	Resin Weight	Total Laminate Weight	Fiber Cost by Weight	Areal Fiber Cost (50" width rolls)	Ply Material Cost	Ply Labor Cost	Total Ply Cost	Cost Relative to Base Laminate per Thickness
				lbs/in x ft²			mils	lbs/ft²/ply			$/lb	$/in yd	$/ft²			
Base (WR/ mat)	0	35%	20%	12.96	6.34	7.91	87	0.226	0.419	0.644	$1.35	$4.30	$1.03	$0.25	$1.28	100%
C-1800	0	45%	27%	12.96	6.34	8.37	33	0.117	0.144	0.260	1.60	2.50	0.44	0.25	0.69	141%
CM-1808	0	43%	26%	12.96	6.34	8.28	48	0.161	0.213	0.374	1.53	3.29	0.61	0.25	0.86	122%
CM-1810	0	42%	25%	12.96	6.34	8.23	52	0.169	0.234	0.403	1.53	3.59	0.67	0.25	0.92	120%
CM-1815	0	44%	27%	12.96	6.34	8.33	55	0.190	0.242	0.432	1.53	4.18	0.73	0.25	0.98	121%
C-2400	0	50%	31%	12.96	6.34	8.62	39	0.158	0.160	0.318	1.60	3.33	0.53	0.25	0.78	136%
CM-2408	0	46%	28%	12.96	6.34	8.43	55	0.201	0.236	0.437	1.53	4.08	0.71	0.25	0.96	119%
CM-2410	0	47%	29%	12.96	6.34	8.48	62	0.233	0.263	0.496	1.53	4.38	0.78	0.25	1.03	113%
CM-2415	0	44%	27%	12.96	6.34	8.35	70	0.244	0.307	0.550	1.53	4.98	0.90	0.25	1.15	112%
XM-1808	0	51%	33%	12.96	6.34	8.72	48	0.204	0.192	0.396	1.88	4.04	0.64	0.25	0.89	126%
XM-1808	45	51%	33%	12.96	6.34	8.72	48	0.204	0.192	0.396	1.88	4.04	0.64	0.25	0.89	126%
XM-2408	0	55%	36%	12.96	6.34	8.92	56	0.261	0.213	0.474	1.88	5.40	0.75	0.25	1.00	121%
XM-2408	45	55%	36%	12.96	6.34	8.92	56	0.261	0.213	0.474	1.88	5.40	0.75	0.25	1.00	121%
XM-2415	0	49%	54%	12.96	6.34	10.03	71	0.492	0.191	0.683	1.88	6.12	0.80	0.25	1.05	100%
XM-2415	45	49%	54%	12.96	6.34	10.03	71	0.492	0.191	0.683	1.88	6.12	0.80	0.25	1.05	100%
TV-3400	0	48%	50%	12.96	6.34	9.81	51	0.330	0.149	0.479	1.88	5.55	0.69	0.25	0.94	124%
TV-3400	45	48%	50%	12.96	6.34	9.81	51	0.330	0.149	0.479	1.88	5.55	0.69	0.25	0.94	124%

Brunswick Technologies Reinforcements Tested at COMTEX Development Corporation with G/P Polyester Resin

Flexural Strength	Flexural Modulus	Tensile Strength	Tensile Modulus	Compressive Strength	Compressive Modulus	Single Skin Strength Criteria	Single Skin Stiffness Criteria	Sandwich Tensile Strength Criteria	Sandwich Compressive Strength Criteria	Sandwich Stiffness Criteria	Single Skin Strength Criteria	Single Skin Stiffness Criteria	Sandwich Tensile Strength Criteria	Sandwich Compressive Strength Criteria	Sandwich Stiffness Criteria	Description
psi x 10^3						Skin Thickness Relative to Base					Ply Cost Relative to Base					
25	1100	18	1000	17	1000	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	Base (WR/ mat)
52	2180	29	1900	43	2600	69%	80%	63%	39%	44%	98%	112%	88%	56%	63%	C-1800
45	1900	29	2000	27	1700	75%	83%	62%	63%	54%	91%	102%	75%	76%	66%	CM-1808
47	1860	29	2000	32	2600	73%	84%	62%	54%	43%	88%	101%	74%	65%	52%	CM-1810
43	1900	27	2000	33	2700	77%	83%	67%	52%	42%	93%	101%	81%	63%	51%	CM-1815
65	2400	35	2200	37	2800	62%	77%	52%	46%	40%	84%	105%	70%	62%	54%	C-2400
52	2000	30	1900	30	1800	70%	82%	60%	56%	54%	83%	98%	71%	67%	64%	CM-2408
50	2000	29	1900	37	2700	71%	82%	62%	46%	43%	80%	93%	70%	52%	49%	CM-2410
46	1960	25	1820	36	2700	74%	83%	74%	47%	44%	82%	92%	82%	52%	49%	CM-2415
28	1500	14	1500	23	2100	94%	90%	133%	73%	55%	118%	113%	167%	91%	70%	XM-1808
54	2250	33	2200	36	3160	68%	79%	54%	47%	37%	85%	99%	68%	59%	47%	XM-1808
32	1500	14	1550	33	2200	88%	90%	127%	51%	53%	107%	109%	154%	62%	65%	XM-2408
58	2400	34	2200	38	3250	66%	77%	53%	45%	37%	80%	94%	64%	54%	44%	XM-2408
29	1500	12	1500	40	3100	93%	90%	157%	43%	43%	93%	90%	157%	43%	43%	XM-2415
52	2300	28	2100	43	3700	69%	78%	65%	40%	34%	69%	78%	65%	40%	34%	XM-2415
65	2400	35	2200	37	2800	62%	77%	52%	46%	40%	77%	96%	64%	57%	50%	TV-3400
54	2250	33	2200	36	2800	68%	79%	54%	47%	40%	85%	98%	68%	59%	50%	TV-3400

Knytex Reinforcements Tested by Hexcel with Ortho Polyester Resin

Description	Test Angle	% Fiber by Weight	% Fiber by Volume	Dry Fiber Density	Uncured Resin Density	Cured Laminate Density	Dry Fiber Thickness	Fiber Weight	Resin Weight	Total Laminate Weight	Fiber Cost by Weight	Areal Fiber Cost (50" width rolls)	Ply Material Cost	Ply Labor Cost	Total Ply Cost	Cost Relative to Base Laminate per Thickness
				lbs/in x ft²			mils	lbs/ft²/ply			$/lb	$/in yd	$/ft²			
Base (WR/ mat)	0	35%	20%	12.96	6.34	8.49	87	0.226	0.419	0.645	$1.35	$4.30	$1.04	$0.25	$1.29	100%
A 260 Uni	0	50%	32%	12.96	6.34	9.30	40	0.163	0.163	0.327	1.76	3.91	0.58	0.25	0.83	141%
CM 1701	0	50%	32%	12.96	6.34	9.30	28	0.114	0.114	0.229	2.19	3.25	0.45	0.25	0.70	169%
CD 185	0	55%	36%	12.96	6.34	9.60	34	0.158	0.130	0.288	2.20	3.65	0.51	0.25	0.76	150%
CD 185	90	55%	36%	12.96	6.34	9.60	34	0.158	0.130	0.288	2.20	3.65	0.51	0.25	0.76	150%
CD 230	0	55%	36%	12.96	6.34	9.60	43	0.200	0.164	0.364	2.10	4.21	0.61	0.25	0.86	135%
CD 230	90	55%	36%	12.96	6.34	9.60	43	0.200	0.164	0.364	2.10	4.21	0.61	0.25	0.86	135%
DB 090	45	50%	32%	12.96	6.34	9.30	18	0.074	0.074	0.147	4.20	3.39	0.39	0.25	0.64	241%
DB 120	45	50%	32%	12.96	6.34	9.30	21	0.086	0.086	0.172	3.84	4.00	0.46	0.25	0.71	229%
DB 170	45	50%	32%	12.96	6.34	9.30	31	0.127	0.127	0.253	2.84	4.44	0.57	0.25	0.82	177%
DB 240	45	50%	32%	12.96	6.34	9.30	43	0.176	0.176	0.351	2.37	5.18	0.71	0.25	0.96	150%
DBM 1208	45	50%	32%	12.96	6.34	9.30	42	0.172	0.172	0.343	3.20	5.47	0.72	0.25	0.97	156%
DBM 1708	45	50%	32%	12.96	6.34	9.30	51	0.208	0.208	0.417	2.55	6.55	0.87	0.25	1.12	148%
CDB 200	0	50%	32%	12.96	6.34	9.30	36	0.147	0.147	0.294	2.93	5.77	0.71	0.25	0.96	179%
CDB 200	45	50%	32%	12.96	6.34	9.30	36	0.147	0.147	0.294	2.93	5.77	0.71	0.25	0.96	179%
CDB 340	0	50%	32%	12.96	6.34	9.30	53	0.217	0.217	0.433	2.37	6.97	0.92	0.25	1.17	149%
CDB 340	45	50%	32%	12.96	6.34	9.30	53	0.217	0.217	0.433	2.37	6.97	0.92	0.25	1.17	149%
CDM 1808	0	50%	32%	12.96	6.34	9.30	57	0.233	0.233	0.466	2.16	5.10	0.79	0.25	1.04	124%
CDM 1808	90	50%	32%	12.96	6.34	9.30	57	0.233	0.233	0.466	2.16	5.10	0.79	0.25	1.04	124%
CDM 1815	0	50%	32%	12.96	6.34	9.30	97	0.396	0.396	0.793	2.07	5.88	1.13	0.25	1.38	96%
CDM 1815	90	50%	32%	12.96	6.34	9.30	97	0.396	0.396	0.793	2.07	5.88	1.13	0.25	1.38	96%
CDM 2408	0	50%	32%	12.96	6.34	9.30	73	0.298	0.298	0.597	1.88	5.48	0.93	0.25	1.18	109%
CDM 2408	90	50%	32%	12.96	6.34	9.30	73	0.298	0.298	0.597	1.88	5.48	0.93	0.25	1.18	109%
CDM 2415	0	50%	32%	12.96	6.34	9.30	93	0.380	0.380	0.760	1.82	6.16	1.12	0.25	1.37	100%
CDM 2415	90	50%	32%	12.96	6.34	9.30	93	0.380	0.380	0.760	1.82	6.16	1.12	0.25	1.37	100%
GDB 095	45	50%	32%	12.96	6.34	9.30	27	0.110	0.110	0.221	58.12	47.93	4.02	0.25	4.27	1066%
GDB 120	45	50%	32%	12.96	6.34	9.30	29	0.119	0.119	0.237	45.00	47.66	4.01	0.25	4.26	991%
GDB 200	45	50%	32%	12.96	6.34	9.30	48	0.196	0.196	0.392	34.09	60.36	5.15	0.45	5.60	788%
KDB 170	45	50%	32%	12.96	6.34	9.30	41	0.168	0.168	0.335	24.50	90.26	7.50	0.45	7.95	1308%

Knytex Reinforcements Tested by Hexcel with Ortho Polyester Resin

Flexural Strength	Flexural Modulus	Tensile Strength	Tensile Modulus	Compressive Strength	Compressive Modulus	Single Skin Strength Criteria	Single Skin Stiffness Criteria	Sandwich Tensile Strength Criteria	Sandwich Compressive Strength Criteria	Sandwich Stiffness Criteria	Single Skin Strength Criteria	Single Skin Stiffness Criteria	Sandwich Tensile Strength Criteria	Sandwich Compressive Strength Criteria	Sandwich Stiffness Criteria	Description
psi x 10^3						Skin Thickness Relative to Base					Ply Cost Relative to Base					
25	1100	18	1000	17	1000	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	Base (WR/ mat)
11	3610	74	3510	44	2800	151%	67%	24%	39%	32%	212%	95%	34%	54%	44%	A 260 Uni
77	2740	66	3270	35	1960	57%	74%	27%	49%	38%	96%	124%	46%	82%	64%	CM 1701
69	1976	39	1987	16	2359	60%	82%	46%	106%	46%	90%	124%	69%	160%	69%	CD 185
49	1663	46	2467	16	2053	71%	87%	39%	106%	44%	107%	131%	59%	160%	66%	CD 185
70	1926	36	2604	33	2223	60%	83%	50%	52%	41%	81%	112%	67%	69%	56%	CD 230
63	1693	42	2545	38	2441	63%	87%	43%	45%	40%	85%	117%	58%	60%	54%	CD 230
72	1831	47	2524	45	2420	59%	84%	38%	38%	40%	142%	203%	93%	91%	97%	DB 090
59	1660	45	1840	36	1970	65%	87%	40%	47%	52%	149%	200%	92%	108%	120%	DB 120
56	1720	40	1710	30	1670	67%	86%	45%	57%	59%	119%	153%	80%	101%	105%	DB 170
73	1573	45	2416	37	2339	59%	89%	40%	46%	42%	88%	133%	60%	69%	63%	DB 240
52	1531	35	2086	27	1826	69%	90%	52%	63%	51%	108%	140%	80%	98%	80%	DBM 1208
50	1700	36	1580	26	1390	71%	87%	50%	65%	67%	105%	128%	74%	97%	99%	DBM 1708
57	1620	41	1710	30	1620	66%	88%	44%	57%	60%	119%	157%	79%	102%	107%	CDB 200
42	1290	24	880	23	1150	77%	95%	75%	74%	98%	138%	170%	135%	132%	176%	CDB 200
54	1620	41	1700	26	1620	68%	88%	44%	65%	60%	101%	131%	65%	97%	89%	CDB 340
38	1190	23	1000	21	1070	81%	97%	78%	81%	96%	120%	145%	117%	120%	143%	CDB 340
61	2200	37	1910	30	1570	64%	79%	49%	57%	57%	79%	98%	60%	70%	71%	CDM 1808
49	1800	28	1670	27	1400	71%	85%	64%	63%	65%	88%	105%	80%	78%	80%	CDM 1808
48	1690	36	1700	28	1540	72%	87%	50%	61%	62%	69%	83%	48%	58%	59%	CDM 1815
54	1060	28	1330	29	1460	68%	101%	64%	59%	71%	65%	97%	62%	56%	68%	CDM 1815
57	1820	41	1940	29	1570	66%	85%	44%	59%	57%	72%	92%	48%	64%	62%	CDM 2408
45	1340	31	1280	26	1290	75%	94%	58%	65%	78%	82%	102%	64%	72%	85%	CDM 2408
61	1930	42	1870	29	1770	64%	83%	43%	59%	55%	64%	83%	43%	58%	55%	CDM 2415
44	1020	26	1270	27	1370	75%	103%	69%	63%	75%	75%	102%	69%	63%	75%	CDM 2415
90	2770	67	4979	52	4545	53%	74%	27%	33%	21%	562%	784%	287%	349%	223%	GDB 095
103	3393	67	6192	28	5838	49%	69%	27%	61%	17%	488%	681%	267%	602%	164%	GDB 120
78	3041	58	6936	18	5565	57%	71%	31%	94%	16%	446%	561%	245%	744%	126%	GDB 200
34	585	51	3234	12	n/a	86%	123%	35%	142%	62%	1121%	1614%	463%	1853%	805%	KDB 170

This page intentionally left blank

Loads for FRP Ship Design

Hull as a Longitudinal Girder

Classical approaches to ship structural design treat the hull structure as a beam for purposes of analytical evaluation. [3-1] Obviously, the validity of this approach is related to the vessel's length to beam and length to depth ratios. Consequently, beam analysis is not the primary analytical approach for small craft. Nevertheless, it is instructive to regard hull structure as a beam when considering forces that act on the vessel's overall length. By determining which elements of the hull are primarily in tension, compression or shear, scantling determination can be approached in a more rational manner. This is particularly important when designing with anisotrophic materials where orientation affects the structure's load carrying capabilities to such a great extent.

A variety of different phenomena contribute to the overall longitudinal bending moments experienced by a ship's hull structure. Analyzing these global loading mechanisms statically is not very realistic with smaller craft. Here, dynamic interaction in a seaway will generally produce loadings in excess of what static theory predicts. However, empirical information has led to the development of accepted safety factors that can be applied to the statically derived stress predictions. Force producers are presented here in an order that corresponds to decreasing vessel size, ie., ship theory first.

Still Water Bending Moment

Before a ship even goes to sea, some stress distribution profile exists within the structure. Figure 3-1 shows how the summation of buoyancy and weight distribution curves leads to the development of load, shear and moment diagrams. Stresses apparent in the still water condition generally become extreme only in cases where concentrated loads are applied to the structure, which can be the case when holds in a commercial vessel are selectively filled. The still water bending moment (SWBM) is an important concept for composites design because fiberglass is particularly susceptible to creep or fracture when subjected to long term loads. Static fatigue of glass fibers can reduce their load carrying capability by as much as 70 to 80% depending on load duration, temperature, moisture conditions and other factors. [3-2]

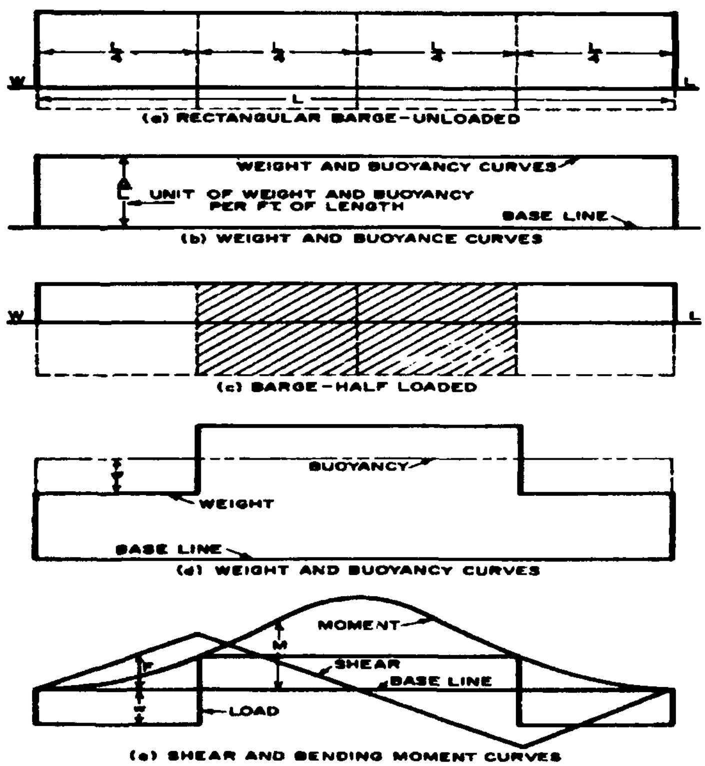


Figure 3-1 Bending Moment Development of Rectangular Barge in Still Water [*Principles of Naval Architecture*]

Wave Bending Moment

A static approach to predicting ship structure stresses in a seaway involves the superposition of a trochoidal wave with a wavelength equal to the vessel's length in a hogging and sagging condition as shown in Figure 3-2. The trochoidal wave form was originally postulated by Froude as a realistic two-dimensional profile, which was easily defined mathematically. The height of the wave is usually taken as $L/20$, $.06L^{.6}$ or $1.1L^{2}$, with the latter most applicable to smaller ships. Approximate calculation methods for maximum bending moments and shearing forces have been developed as preliminary design tools for ships over 300 feet long. [3-3]

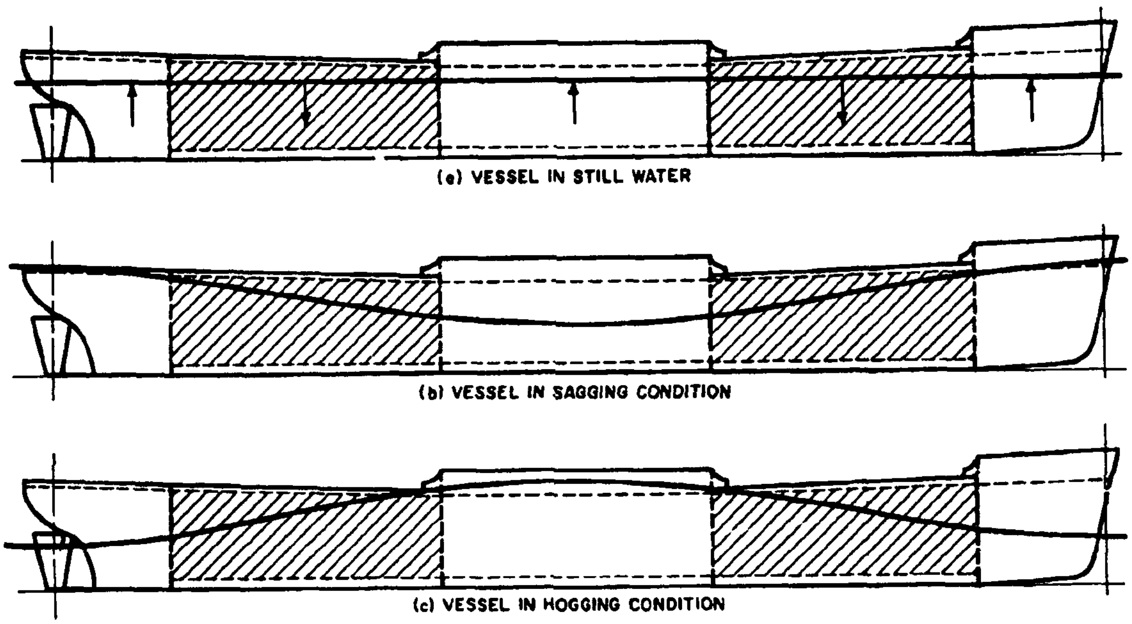


Figure 3-2 Superposition of Static Wave Profile [*Principles of Naval Architecture*]

Ship Oscillation Forces

The dynamic response of a vessel operating in a given sea spectrum is very difficult to predict analytically. Accelerations experienced throughout the vessel vary as a function of vertical, longitudinal and transverse location. These accelerations produce virtual increases of the weight of concentrated masses, hence additional stress. The designer should have a feel for at least the worst locations and dynamic behavior that can combine to produce extreme load scenarios. Figure 3-3 is presented to define the terms commonly used to describe ship motion. It is generally assumed that combined roll and pitch forces near the deck edge forward are indicative of the extreme accelerations throughout the ship.

Dynamic Phenomena

Dynamic loading or vibration can be either steady state, as with propulsion induced phenomena, or transient, such as with slamming through waves. In the former case, load amplitudes are generally within the design limits of hull structural material. However, the fatigue process can lead to premature failures, especially if structural components are in resonance with the forcing frequency. A preliminary vibration analysis of major structural

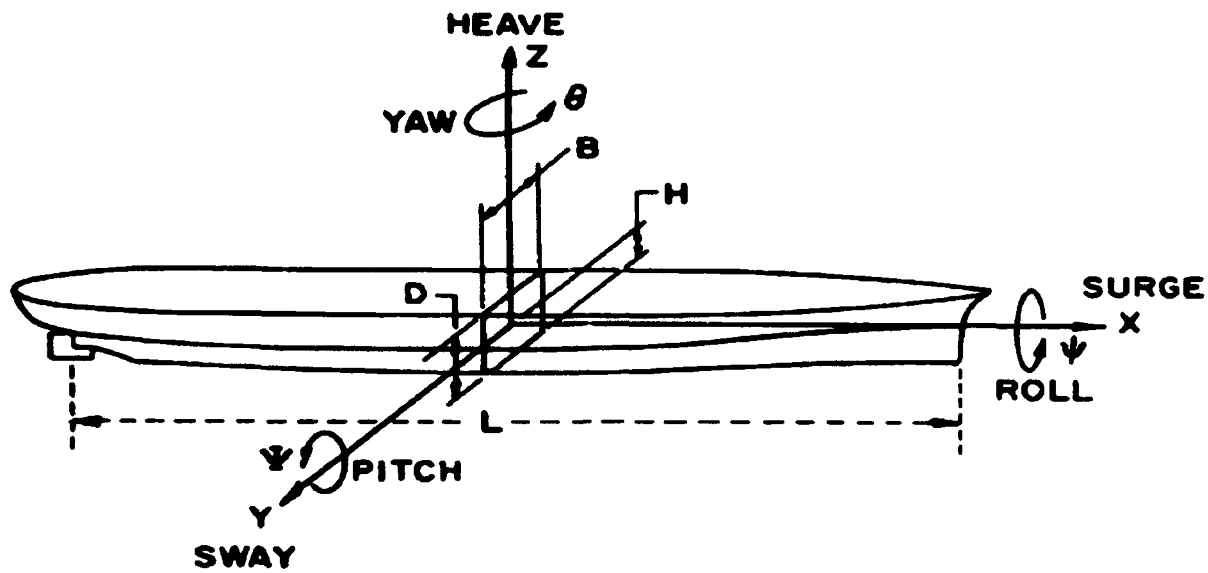


Figure 3-3 Principal Axes and Ship Motion Nomenclature [Evans, *Ship Structural Design Concepts*]

ensure that natural frequencies are not near shaft and blade rate for normal operating speeds. [3-4] The theoretical analysis of vibration characteristics associated with complex composite structures is problematic, at best. Some consolation can be found in the fact that composite structures have superior damping properties when compared to metals. This is especially true for sandwich construction.

The transient dynamic loading referred to generally describes events that occur at much higher load amplitudes. Slamming in waves is of particular interest when considering the design of high-speed craft. This topic will be covered in detail in the following section on panel loading as the intense loading is generally localized. Applying an acceleration factor to the static wave bending analysis outlined above can give some indication of the overall girder stresses produced as a high-speed craft slams into a wave. Other hull girder dynamic phenomena of note include springing and whipping of the hull when wave encounter frequency is coincident with hull natural frequency.

Hauling and Blocking Loads

When a vessel is hauled and blocked for storage, the weight of the vessel is not uniformly supported as in the water. The point loading from slings and cradle fixtures is obviously a problem and will be addressed in the detail design section. The overall hull, however, will be subject to bending stresses when a vessel is lifted with slings at two points. Except in extreme situations, in-service design criteria for small craft up to about 100 feet should be more severe than this case. When undergoing long term storage or over-land transit, consideration must be given to what fixtures will be employed over a given period of time. Large unsupported weights, such as machinery, keels or tanks, can produce unacceptable overall bending moments in addition to the local stress concentrations. During transportation, acceleration forces transmitted through the trailer's support system can be quite high. The onset of fatique damage may be quite precipitous, especially with cored construction.

Sailing Vessel Rigging Loads

The major longitudinal load producing element associated with sailing vessels is the mast operating in conjunction with the headstay and backstay. Upwind sailing performance is often a function of headstay tension, which can be very demanding on a lightweight, racing structure. The mast works in compression under the combined action of the aforementioned longitudinal stays and the more heavily loaded athwartship shroud system (see Shroud Attachment in following section). Hull deflection is in the sagging mode, which can be additive with wave action response. The characteristic design criteria for high performance sailing vessels is usually deflection limitations.

Lateral Loading

Lateral loading on a ship's hull is normally of concern only when the hull form is very long and slender. Global forces are the result of beam seas. In the case of sailing vessels, lateral loads can be significant when the vessel is sailing upwind in a heeled condition. Methods for evaluating wave bending moment should be used with a neutral axis that is parallel to the water.

Lateral loading can also result from docking and tug assisted maneuvers, although the design criteria will usually be dictated by local strength in these instances.

Torsional Loading

Torsional loading of hull structures is often overlooked because there is no convenient analytical approach that has been documented. Quartering seas can produce twisting moments within a hull structure, especially if the hull has considerable beam. In the case of multihulls, this loading phenomena often determines the configuration of cross members. New reinforcement materials are oriented with fibers in the bias direction (± 45°), which makes them extremely well suited for resisting torsional loading.

Loading Normal to Hull and Deck Surfaces

The loads on ship structures are reasonably well established (e.g. PNA, etc), while the loads on small craft structures have received much less attention. There are some generalizations which can be made concerning these loads, however. The dominant loads on ships are global in-plane loads (loads affecting the entire structure), while the dominant loads on small craft are local out of plane loads (loads normal to the hull surface over very small portions of the hull surface). As a result, structural analysis of ships is traditionally approached through approximating the entire ship as a box beam, while the structural analysis of small craft is approached through local panel analysis. The analysis of large boats (or small ships) must include both global and local loads, as either may be the dominant factor. Since out-of-plane loads are dominant for small craft, the discussion of these loads will center on small craft, however, much of the discussion could be applied to ships or other large marine structures. The American Bureau of Shipping provides empirical expressions for the derivation of design heads for sail and power vessels. [3-5, 3-6]

Out-of-plane loads can be divided into two categories: distributed loads (such as hydrostatic and hydrodynamic loads) and point loads (such as keel, rig, and rudder loads on sail boats, or strut, rudder or engine mounts for power boats). The hydrostatic loads on a boat at rest are relatively simple and can be determined from first principles. The hydrodynamic loads are very complex, however, and have not been studied extensively, thus they are usually treated in an extremely simplified manner. The most common approach is to increase the static pressure load by a fixed proportion, called the dynamic load factor. [3-7] The sources of point loads vary widely, but most can be estimated from first principles by making a few basic assumptions.

Hydrodynamic Loads

There are several approaches to estimating the hydrodynamic loads for planing power boats, however most are based on the first comprehensive work in this area, performed by Heller and Jasper. The method is based on relating the strain in a structure from a static load to the strain in a structure from a dynamic load of the same magnitude. The ratio of the dynamic strain to the static strain is called the "response factor," and the maximum response factor is called the "dynamic load factor." This approach is summarized here as an example of this type of calculation. Heller and Jasper instrumented and obtained data on an aluminum hull torpedo boat (YP 110) and then used this data as a basis for the empirical aspects of their load- calculation. An example of the data is presented in Figure 3-4. The dynamic load factor is a function of the impact pressure rise time, t_o, over the natural period of the structure, T, and is presented in Figure 3-5, where C/C_c is the fraction of critical damping. The theoretical

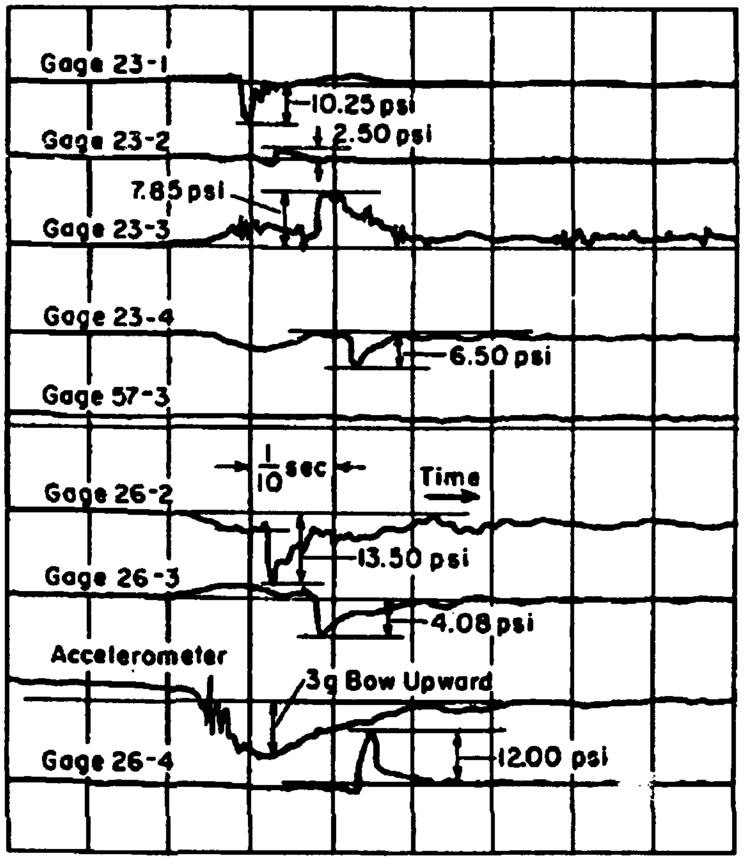


Figure 3-4 Pressures Recorded in Five and Six Foot Waves at a Speed Of 28 Knots [Heller and Jasper, *On the Structural Design of Planing Craft*]

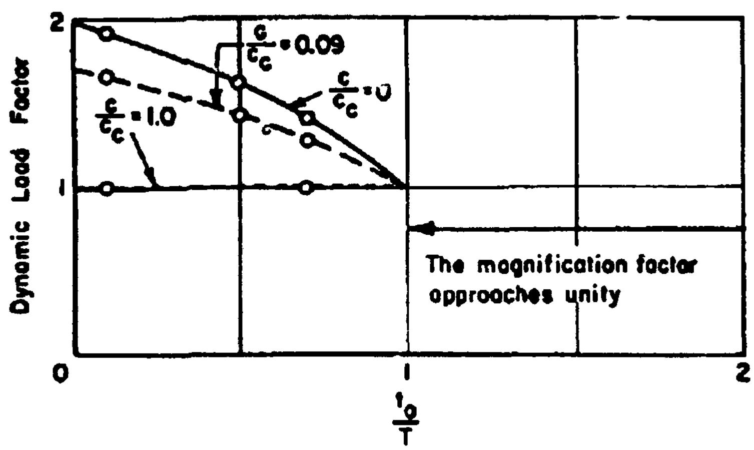


Figure 3-5 Dynamic Load Factors for Typical Time Varying Impact Loads [Heller and Jasper, *On the Structural Design of Planing Craft*]

development of the load prediction leads to the following equations:

Maximum Impact Force Per Unit Length:

$$p_0 = \frac{3W}{2L} \times \left(1 + \frac{y_{CG}}{g}\right)$$

where:

p_0 = maximum impact force per unit length
W = hull beam
L = waterline length
y_{CG} = vertical acceleration of the CG
g = gravitational acceleration

Maximum Effective Pressure at the Keel

$$p_{01} = \frac{3p_0}{G}$$

where:

p_{01} = maximum effective pressure at the keel
G = half girth

Maximum Effective Pressure

$$\bar{P} = p_{01} \times DLF$$

where:

$\bar{P}$ = the maximum effective pressure for design
DLF = the Dynamic Load Factor from Figure 3-5 (based on known or measured critical damping)

An example of the pressure calculation for the YP110 is also presented by Heller and Jasper:

Maximum Force Per Unit Length:

$$p_0 = \frac{3 \times 109{,}000}{2 \times 900}(1 + 4.7) = 1{,}036 \text{ lbs/in}$$

Maximum Effective Pressure at the Keel:

$$p_{01} = \frac{1036 \times 3}{96} = 32.4 \text{ psi}$$

Maximum Effective Pressure:

$$\bar{P} = 32.4 \times 1.1 = 35.64 \text{ psi}$$

This work is the foundation for most prediction methods. Other presentations of load calculation, measurement, or design can be found in the following: Jones (1984), Reichard (1985), Savitsky (1964), Savitsky and Brown (1978), Savitsky (1985), American Bureau of Shipping Guidelines, Lloyd's Register of Shipping Rules, and Det Norske Veritas Rules.

Point Loads

Out-of-plane point loads occur for a variety of reasons. The largest loads on a boat often occur when the boat is in dry storage, transported over land, removed from the water or placed into the water. The weight of a boat is distributed over the hull while the boat is in the water, but is concentrated at support points of relatively small area when the boat is out of the water. As an example, an 80 foot long 18 foot wide power boat weighing 130,000 pounds would probably only experience a hydrostatic pressure of a few psi. If the boat was supported on land by 12 blocks with a surface area of 200 square inches each, the support areas would see an average load of 54 psi. Equipment mounting, such as rudders, struts, engines, mast and rigging, booms, cranes, etc. can also introduce out-of-plane point loads into the structure through mechanical fasteners.

General Response of FRP Marine Structures

Hull Girder Stress Distribution

When the primary load forces act upon the hull structure as a long, slender beam, stress distribution patterns look like Figure 3-6 for the hogging condition with tension and compression interchanged for the sagging case. The magnitude of stress increases with distance from the neutral axis. On the other hand, shear stress becomes maximum at the neutral axis. Figure 3-7 shows the longitudinal distribution of principal stresses for a long, slender ship.

The relationship between bending moment and hull stress can be estimated from simple beam theory for the purposes of preliminary design. The basic relationship is stated as follows:

$$\sigma = \frac{M}{SM} = \frac{Mc}{I}$$

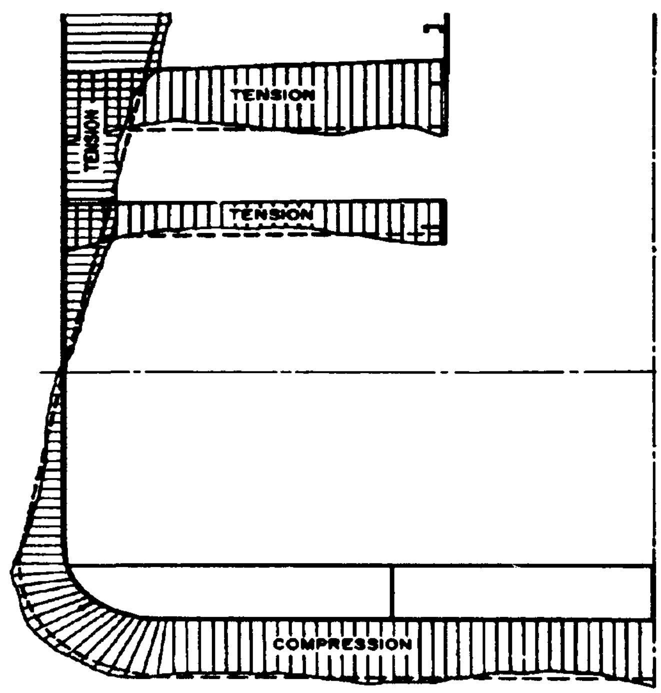


Figure 3-6 Theoretical and Measured Stress Distribution for a Cargo Vessel Midship Section [*Principles of Naval Architecture*]

where:

σ = unit stress

M = bending moment

SM = section modulus

c = distance to neutral axis

I = moment of inertia

The neutral axis is at the centroid of all longitudinal strength members, which for composite construction must take into account specific material properties along the ship's longitudinal axis. The actual neutral axis rarely coincides with the geometric center of the vessel's midship section. Hence, values for σ and c will be different for extreme fibers at the deck and hull bottom.

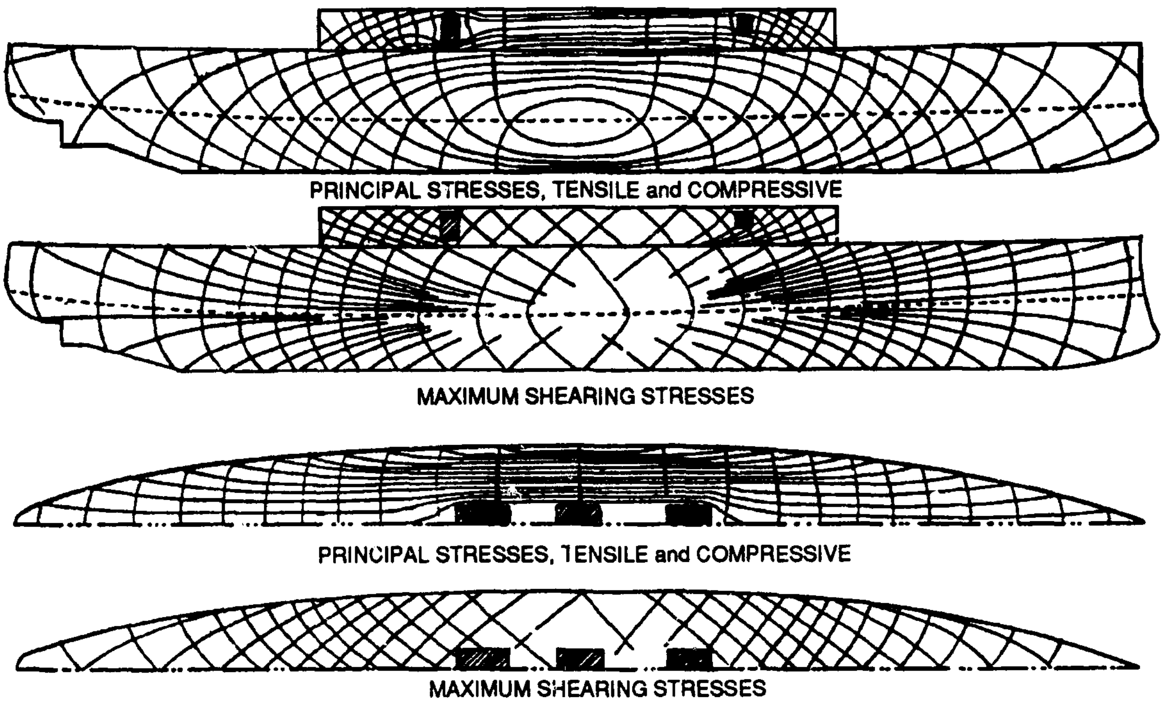


Figure 3-7 Longitudinal Distribution of Stresses in a Combatant [Hovgaard, *Structural Design of Warships*]

Buckling of Hat-Stiffened Panels

FRP laminates generally have ultimate tensile and compressive strengths that are comparable with mild steel but stiffness is usually only 5% to 10%. A dominant design consideration then becomes elastic instability under compressive loading. Analysis of the buckling behavior of FRP grillages common in ship structures is complicated by the anisotrophic nature of the materials and the stiffener configurations typically utilized. Smith [3-8] has developed a series of data curves to make approximate estimates of the destabilizing stress, σ_x, required to produce catastrophic failure in transversely framed structures (see Figure 3-8). Theories for sandwich laminates will be presented in the section covering sandwich construction.

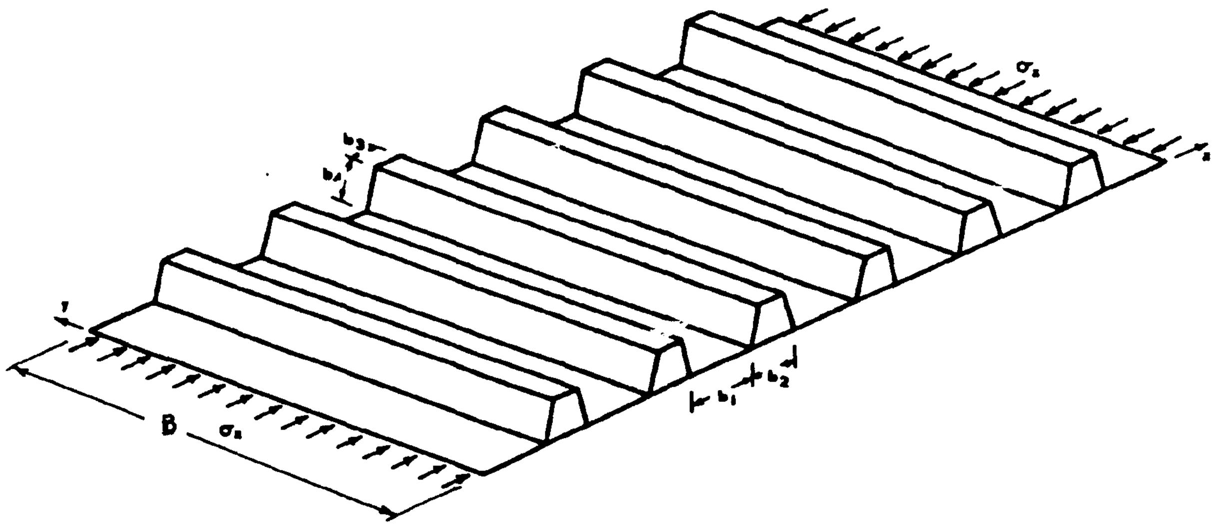


Figure 3-8 Transversely Stiffened Panel [Smith, *Buckling Problems in the Design of Fiberglass-Reinforced Plastic Ships*]

The lowest buckling stresses of a transversely framed structure usually correspond to one of the interframe modes illustrated in Figure 3-9.

The first type of buckling (a) involves maximum flexural rotation of the shell/stiffener interface and minimal displacement of the actual stiffener.

This action is dependent upon the restraining stiffness of the stiffener and is independent of the transverse span.

The buckling phenomena shown in (b) is the result of extreme stiffener rotation, and as such, is a function of transverse span which influences stiffener torsional stiffness.

The third type of interframe buckling depicted (c) is unique to FRP structures but can often proceed the other failure modes. In this scenario, flexural deformation of the stiffeners produces bending of the shell plating at a half-wavelength coincident with the stiffener spacing. Large, hollow top-hat stiffeners can cause this effect. The restraining influence of the stiffener as well as the transverse span length are factors that control the onset of this type of buckling. All buckling modes are additionally influenced by the stiffener spacing and dimensions and the flexural rigidity of the shell.

Buckling of the structure may also occur at half-wavelengths greater than the spacing of the stiffeners. The next mode encountered is depicted in Figure 3-9 with nodes at or between stiffeners. Formulas for simply supported orthotropic plates show good agreement with more rigorous folded-plate analysis in predicting critical loads for this type of failure. [3-8] The approximate formula is:

$$N_{xcr} = \frac{\pi^2 D_y}{B^2}\left[\frac{D_1 B^2}{D_y \lambda^2} + \frac{2D_{xy}}{D_y} + \frac{\lambda^2}{B^2}\right]$$

where:

N_{xcr} = critical load per unit width

D_y = flexural rigidity per unit width

D_1 = flexural rigidity of the shell in the x-direction

D_{xy} = stiffened panel rigidity = ½ ($C_x + C_y$) with C_y = torsional rigidity per unit width and C_x = twisting rigidity of the shell (first term is dominant)

λ = buckling wavelength

Longitudinally framed vessels are also subject to buckling failure, albeit at generally higher critical loads. If the panel in question spans a longitudinal distance L, a suitable formula for estimating critical buckling stress, σ_{ycr}, based on the assumption of simply supported end conditions is:

$$\sigma_{ycr} = \frac{\dfrac{\pi^2 EI}{AL^2}}{1 + \dfrac{\pi^2 EI}{L^2 GA_s}}$$

where:

EI = flexural rigidity of a longitudinal with assumed effective shell width

A = total cross-sectional area of the longitudinal including effective shell

GA_s = shear rigidity with A_s = area of the stiffener webs

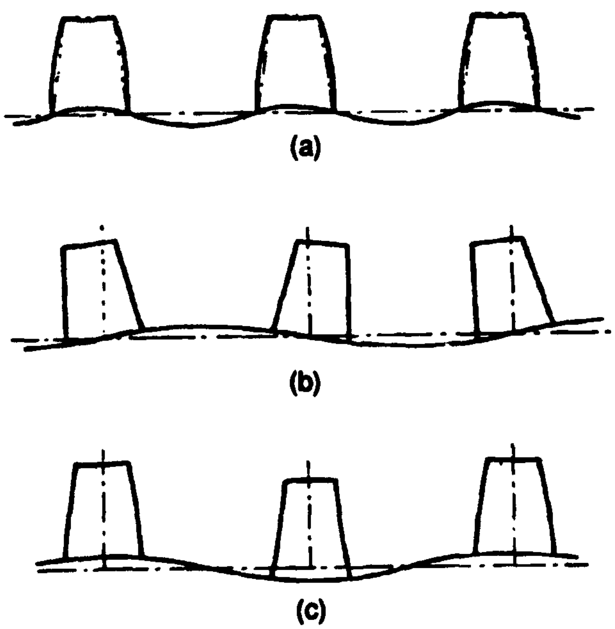


Figure 3-9 Interframe Buckling Modes [Smith, *Buckling Problems in the Design of Fiberglass-Reinforced Plastic Ships*]

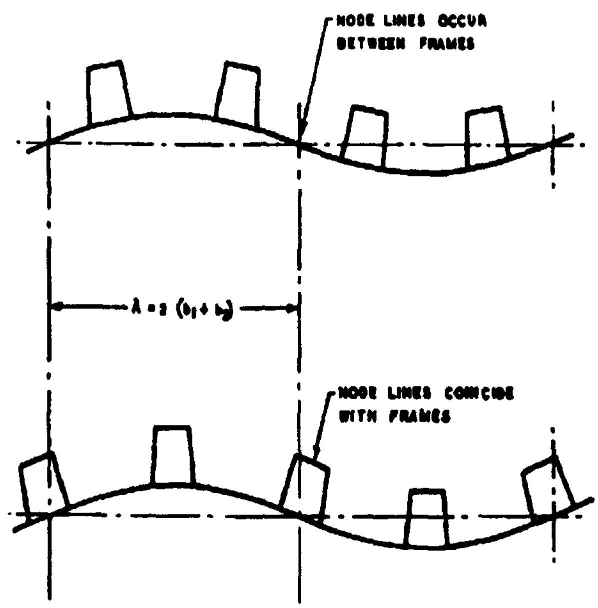


Figure 3-10 Extraframe Buckling Modes [Smith, *Buckling Problems in the Design of Fiberglass-Reinforced Plastic Ships*]

Buckling failure can occur at reduced primary critical stress levels if the structure is subjected to orthogonal compressive stresses or high shear stresses. Areas where biaxial compression may occur include side shell where lateral hydrodynamic load can be significant or in way of frames that can cause secondary transverse stress. Areas of high shear stress include side shell near the neutral axis, bulkheads and the webs of stiffeners.

Large hatch openings are notorious for creating stress concentrations at their corners, where stress levels can be 3-4 times greater than the edge midspan. Large cut-outs reduce the compressive stability of the grillage structure and must therefore be carefully analyzed. Smith [3-8] has proposed a method for analyzing this portion of an FRP vessel whereby a plane-stress analysis is followed by a grillage buckling calculation to determine the distribution of destabilizing forces (see Figure 3-11). Figure 3-12 shows the first two global failure modes and associated average stress at the structure's mid-length.

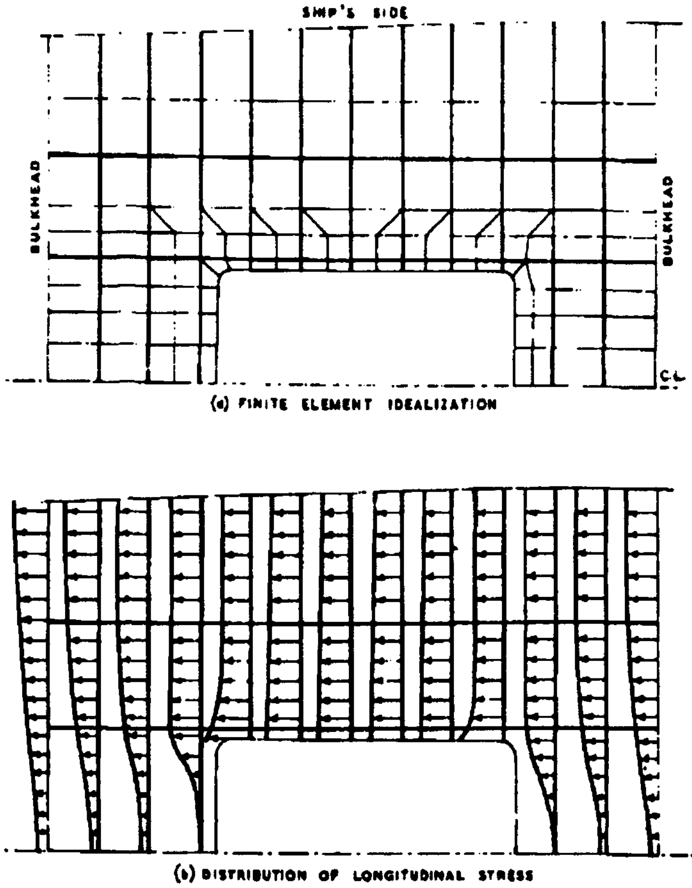


Figure 3-11 Plane Stress Analysis of Hatch Opening [Smith, *Buckling Problems in the Design of Fiberglass-Reinforced Plastic Ships*]

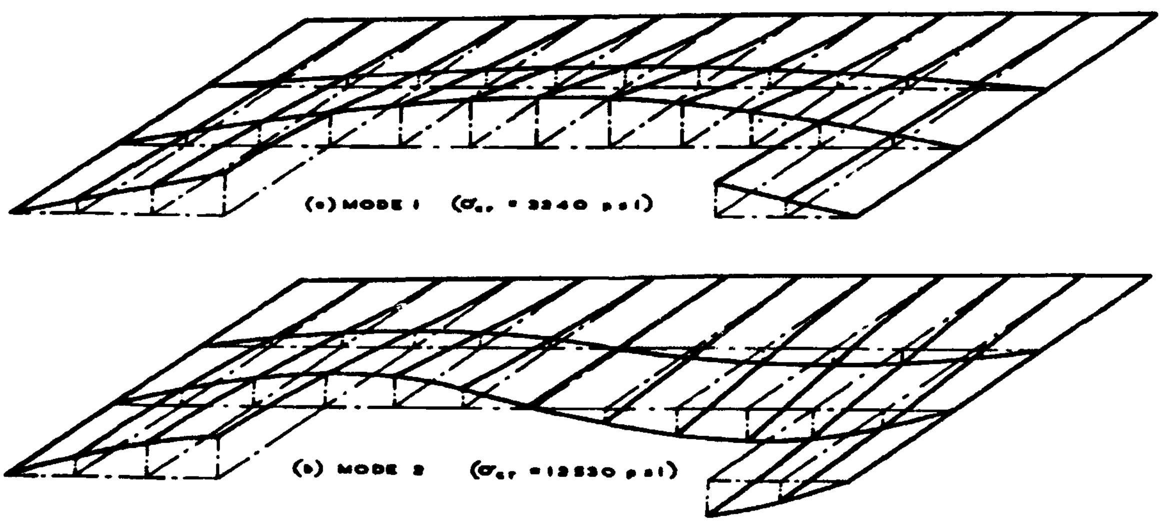


Figure 3-12 Deck Grillage Buckling Modes Near Hatch Opening [Smith, *Buckling Problems in the Design of Fiberglass-Reinforced Plastic Ships*]

Mechanics of Composite Materials

The physical behavior of composite materials is quite different from that of most common engineering materials that are homogeneous and isotropic. Metals will generally have the same composition regardless of where or in what orientation a sample is taken. On the other hand, the makeup and physical properties of composites will vary with location and orientation of principal axes. These materials are termed anisotrophic, which means they exhibit different properties when tested in different directions. Most composite structures are, however, orthotropic having three mutually perpendicular planes of symmetry.

The mechanical behavior of composites is traditionally evaluated on both microscopic and macroscopic scale to take into account inhomogeneity. Micromechanics attempts to quantify the interactions of fiber and matrix (reinforcement and resin) on a microscopic scale on par with the diameter of a single fiber. Macromechanics treats composites as homogeneous materials with mechanical properties representative of the medium as a whole. The latter analytical approach is more realistic for the study of marine laminates that are often thick and laden with through-laminate inconsistencies. However, it is instructive to understand the concepts of micromechanics as the basis for macromechanic properties. The designer is again cautioned to verify all analytical work by testing builder's specimens.

Micromechanic Theory

General Fiber/Matrix Relationship

The theory of micromechanics was developed about 30 years ago to help explain the complex mechanisms of stress and strain transfer between fiber and matrix within a composite. [3-9] Mathematical relationships have been developed whereby knowledge of constituent material properties can lead to behavior predictions. Theoretical predictions of composite stiffness have traditionally been more accurate than predictions of ultimate strength. Table 3-1 describes the input and output variables associated with micromechanics.

Table 3-1. Micromechanics Concepts
[Chamis, *ASM Engineers' Guide to Composite Materials*]

Input	Output
Fiber properties	Uniaxial strengths
Matrix properties	Fracture toughness
Environmental conditions	Impact resistance
Fabrication process variables	Hygrothermal effects
Geometric configuration	

The basic principles of the theory can be illustrated by examining a composite element under a uniaxial force. Figure 3-13 shows the state of stress and transfer mechanisms of fiber and matrix when subjected to pure tension. On a macroscopic scale, the element is in simple tension, while internally a number of stresses can be present. Represented in Figure 3-13 are compressive stresses (vertical arrows pointing inwards) and shear stresses (half arrows along the fiber/matrix interface). This combined stress state will determine the failure point of the material. The bottom illustration in Figure 3-13 is representative of a poor fiber/matrix bond or void within the laminate. The resulting imbalance of stresses between the fiber and matrix can lead to local instability causing the fiber to shift or buckle. A void along 1% of the fiber surface generally reduces interfacial shear strength by 7%. [3-9]

Fiber Orientation

Orientation of reinforcements in a laminate is widely known to dramatically effect the mechanical performance of composites. Figure 3-14 is presented to understand tension failure mechanisms in unidirectional composites on a microscopic scale. Note that at an angle of 0°, the strength of the composite is almost completely dependent on fiber tensile strength. The following equations refer to the three failure mechanisms shown in Figure 3-14:

Fiber tensile failure:

$$\sigma_c = \sigma$$

Matrix or interfacial shear:

$$\tau = \sigma \sin\Phi \cos\Phi$$

Composite tensile failure:

$$\sigma_u = \sigma \sin\Phi$$

where:

σ_c = composite tensile strength

σ = applied stress

Φ = angle between the fibers and tensile axis

τ = shear strength of the matrix or interface

σ_u = tensile strength of the matrix

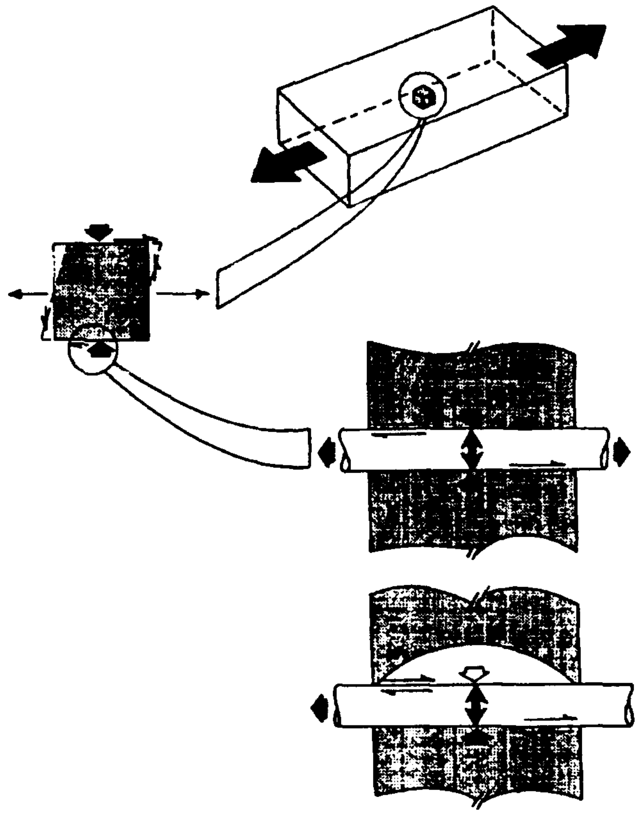


Figure 3-13 State of Stress and Stress Transfer to Reinforcement [*Material Engineering*, May, 1978 p. 29]

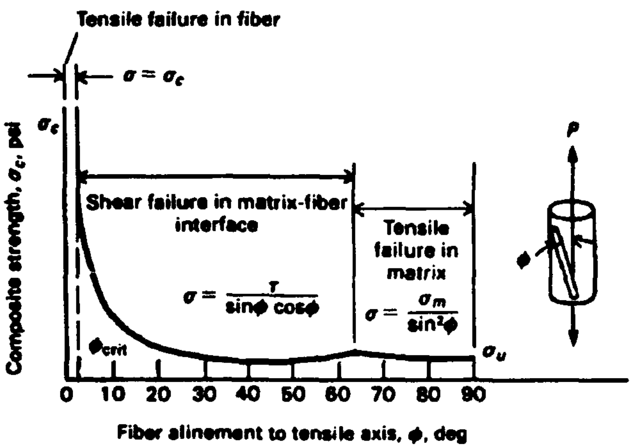


Figure 3-14 Failure Mode as a Function of Fiber Alignment [*ASM Engineers' Guide to Composite Materials*]

Micromechanics Geometry

Figure 3-15 shows the orientation and nomenclature for a typical fiber composite geometry. Properties along the fiber or x direction (1-axis) are called longitudinal; transverse or y (2-axis) are called transverse; and in-plane shear (1-2 plane) is also called intralaminar shear. The through-thickness properties in the z direction (3-axis) are called interlaminar. Ply properties are typically denoted with a letter to describe the property with suitable subscripts to describe the constituent material, plane, direction and sign (with strengths). As an example, S_{m11T} indicates matrix longitudinal tensile strength.

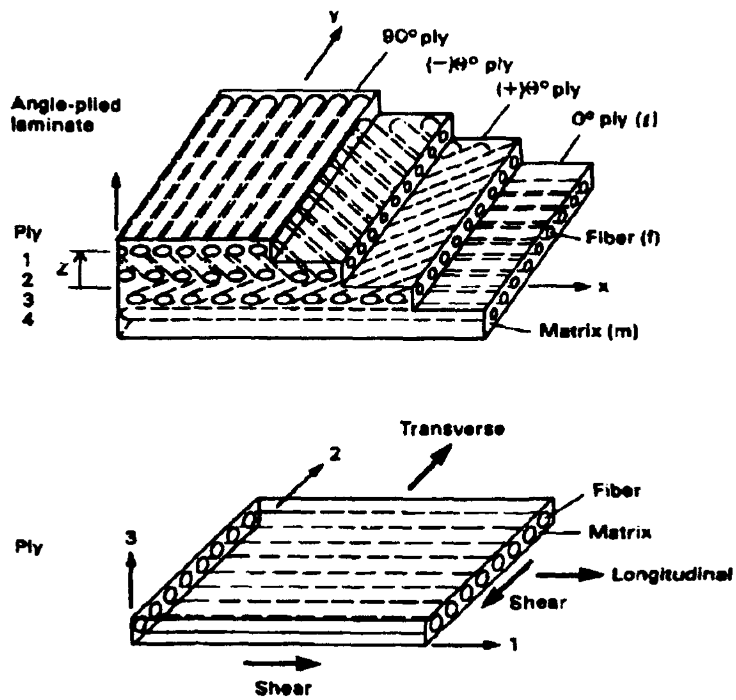


Figure 3-15 Fiber Composite Geometry [Chamis, *ASM Engineers' Guide to Composite Materials*]

The derivation of micromechanics equations is based on the assumption that 1) the ply and its constituents behave linearly elastic until fracture (see Figure 3-16), 2) bonding is complete between fiber and matrix and 3) fracture occurs in one of the following modes: a) longitudinal tension, b) fiber compression, c) delamination, d) fiber microbuckling, e) transverse tension, or f) intralaminar shear. [3-2] The following equations describe the basic geometric relationships of composite micromechanics:

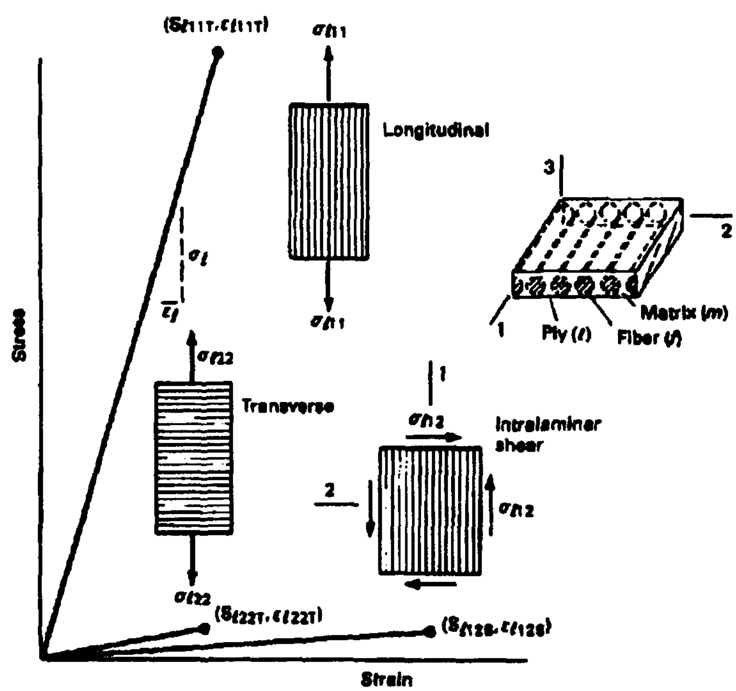


Figure 3-16 Typical Stress-Strain Behavior of Unidirectional Fiber Composites [Chamis, *ASM Engineers' Guide to Composite Materials*]

Partial volumes:

$$k_f + k_m + k_v = 1$$

Ply density:

$$\rho_l = k_f\,\rho_f + k_m\,\rho_m$$

Resin volume ratio:

$$k_m = \frac{(1 - k_v)}{\left[1 + \left(\frac{\rho_m}{\rho_f}\right)\left(\frac{1}{\lambda_m} - 1\right)\right]}$$

Fiber volume ratio:

$$k_f = \frac{(1 - k_v)}{\left[1 + \left(\frac{\rho_f}{\rho_m}\right)\left(\frac{1}{\lambda_f} - 1\right)\right]}$$

Weight ratio:

$$\lambda_f + \lambda_m = 1$$

where:

f = fiber
m = matrix
v = void
l = ply
λ = weight percent

Elastic Constants

The equations for relating elastic moduli and Poisson's ratios are given below. Properties in the 3-axis direction are the same as the 2-axis direction because the ply is assumed transversely isotropic in the 2-3 plane (see bottom illustration of Figure 3-15).

Longitudinal modulus:

$$E_{l11} = k_f E_{f11} + k_m E_m$$

Transverse modulus:

$$E_{l22} = \frac{E_m}{1 - \sqrt{k_f}\left(1 - \frac{E_m}{E_{f22}}\right)} = E_{l33}$$

Shear modulus:

$$G_{l12} = \frac{G_m}{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f12}}\right)} = G_{l13}$$

$$G_{l23} = \frac{G_m}{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f23}}\right)} = G_{l13}$$

Poisson's ratio:

$$\nu_{l12} = k_f\, \nu_{l12} + k_m \nu_m = \nu_{l13}$$

In-Plane Uniaxial Strengths

The equations for approximating composite strength properties are based on the fracture mechanisms outlined above under micromechanics geometry. Three of the fracture modes fall under the heading of longitudinal compression. It should be emphasized that prediction of material strength properties is currently beyond the scope of simplified mathematical theory.

The following approximations are presented to give insight into which physical properties dominate particular failure modes.

Approximate longitudinal tension:

$$S_{l11T} \approx k_f S_{fT}$$

Approximate fiber compression:

$$S_{l11C} \approx k_f S_{fC}$$

Approximate delamination/shear:

$$S_{l11C} \approx 10\, S_{l12S} + 2.5 S_{mT}$$

Approximate microbuckling:

$$S_{l11C} \approx \frac{G_m}{1 - k_f\left(1 - \frac{G_m}{G_{f12}}\right)}$$

Approximate transverse tension:

$$S_{l22T} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f22}}\right)\right] S_{mT}$$

Approximate transverse compression:

$$S_{l22C} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f22}}\right)\right] S_{mC}$$

Approximate intralaminar shear:

$$S_{l12S} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{G_m}{G_{f12}}\right)\right] S_{mS}$$

Approximate void influence on matrix:

$$S_m \approx \left\{1 - \left[\frac{4k_v}{(1 - k_f)\,\pi}\right]^{½}\right\} S_m$$

Through-Thickness Uniaxial Strengths

Estimates for properties in the 3-axis direction are given by the equations below. Note that the interlaminar shear equation is the same as that for in-plane. The short beam shear depends heavily on the resin shear strength and is about 1½ times the interlaminar value. Also, the longitudinal flexural strength is fiber dominated while the transverse flexural strength is more sensitive to matrix strength.

Approximate interlaminar shear:

$$S_{l13S} \approx \left[1 - (\sqrt{k_f} - 1)\left(1 - \frac{G_m}{G_{f12}}\right)\right] S_{mS}$$

$$S_{l23S} \approx \left[\frac{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f23}}\right)}{1 - k_f\left(1 - \frac{G_m}{G_{f23}}\right)}\right] S_{mS}$$

Approximate flexural strength:

$$S_{l11F} \approx \frac{3\,k_f S_{fT}}{1 + \frac{S_{fT}}{S_{fC}}}$$

$$S_{l22F} \approx \frac{3\left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f22}}\right)\right] S_{mT}}{1 + \frac{S_{mT}}{S_{mC}}}$$

Approximate short-beam shear:

$$S_{l13SB} \approx 1.5\, S_{l13S}$$

$$S_{l23SB} \approx 1.5\, S_{l23S}$$

Uniaxial Fracture Toughness

Fracture toughness is an indication of a composite material's ability to resist defects or discontinuities such as holes and notches. The fracture modes of general interest include: opening mode, in-plane shear and out-of-plane shear. The equations to predict longitudinal, transverse and intralaminar shear fracture toughness are beyond the scope of this text and can be found in the cited reference. [3-2]

In-Plane Uniaxial Impact Resistance

The impact resistance of unidirectional composites is defined as the in-plane uniaxial impact energy density. The five densities are: longitudinal tension and compression; transverse tension and compression; and intralaminar shear. The reader is again directed to reference [3-2] for further elaboration.

Through-Thickness Uniaxial Impact Resistance

The through-thickness impact resistance is associated with impacts normal to the surface of the composite, which is generally of particular interest. The energy densities are divided as follows: longitudinal interlaminar shear, transverse interlaminar shear, longitudinal flexure, and transverse flexure. The derivation of equations and relationships for this and the remaining micromechanics phenomena can be found in the reference.

Thermal

The following thermal behavior properties for a composite are derived from constituent material properties: heat capacity, longitudinal conductivity, and longitudinal and transverse thermal coefficients of expansion.

Hygral Properties

The ply hygral properties predicted by micromechanics equation include diffusivity and moisture expansion. Additional equations have been derived to estimate moisture in the resin and composite as a function of the relative humidity ratio. An estimate for moisture expansion coefficient is also postulated.

Hygrothermal Effects

The combined environmental effect of moisture and temperature is usually termed hygrothermal. All of the resin dominated properties are particularly influenced by hygrothermal influences. The degraded properties that are quantified include: glass transition temperature of wet resin, mechanical characteristics, and thermal behavior.

Macromechanic Theory

Laminae or Plies

The most elementary level considered by macromechanic theory is the lamina or ply. This consists of a single layer of reinforcement and associated volume of matrix material. In aerospace applications, all specifications are expressed in terms of ply quantities. Marine applications typically involve thicker laminates and are usually specified according to overall thickness, especially when successive plies are identical.

For most polymer matrix composites, the reinforcement fiber will be the primary load carrying element because it is stronger and stiffer than the matrix. The mechanism for transferring load throughout the reinforcement fiber is the shearing stress developed in the matrix. Thus, care must be exercised that the matrix material does not become a strain limiting factor. As an extreme example, if a polyester reinforcement with an ultimate elongation of about 20% was combined with a polyester resin with 1.5% elongation to failure, cracking of the resin would occur before the fiber was stressed to a level that was 10% of its ultimate strength.

Laminates

A laminate consists of a series of laminae or plies that are bonded together with a material that is usually the same as the matrix of each ply. Indeed, with contact molding, the wet-out and laminating processes are continuous operations. A potential weak area of laminates is the shear strength between layers of a laminate, especially when the entire lamination process is not continuous. This concept is further described in the Design of Details section and Chapter Five.

A major advantage to design and construction with composites is the ability to vary reinforcement material and orientation throughout the plies in a laminate. In this way, the physical properties of each ply can be optimized to resist the loading on the laminate as a whole, as well as the out of plane loads that create unique stress fields in each ply. Figure 3-17 illustrates the concept of stress field discontinuity within a laminate.

Laminate Properties

Predicting the physical properties of laminates based on published data for the longitudinal direction (1-axis) is not very useful as this data was probably derived from samples fabricated in a very controlled environment. Conditions under which marine laminates are fabricated can severely limit the resultant mechanical properties. To date, safety factors have generally been sufficiently high to prevent widespread failure. However, instances of stress concentration, resin-rich areas and voids can negate even large safety factors.

There are essentially three ways in use today to predict the behavior of a laminated structure under a given loading scenario. In all cases, estimates for Elastic properties are more accurate than those for Strength properties. This is in part due to the variety of failure mechanisms involved. The analytical techniques currently in use include:

- Property charts called "Carpet Plots" that provide mechanical performance data based on orientation composition of the laminate;

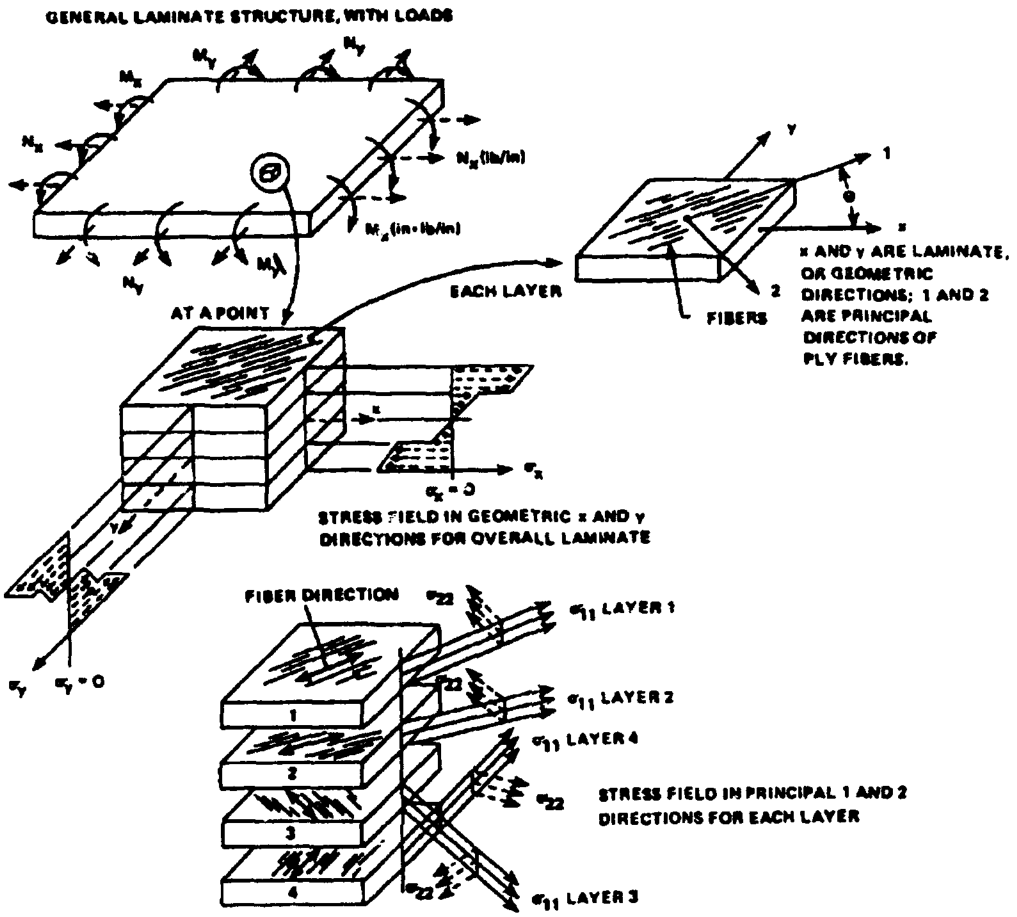


Figure 3-17 Elastic Properties of Plies within a Laminate [Schwartz, *Composite Materials Handbook*]

- Laminate analysis software that allows the user to build a laminate from a materials database and view the stress and strain levels within and between plies in each of the three mutually perpendicular axes;
- Test data based on identical laminates loaded in a similar fashion to the design case.

Carpet Plots

Examples of Carpet Plots based on a Carbon Fiber/Epoxy laminate are shown in Figures 3-18, 3-19 and 3-20 for modulus, strength and Poisson's ratio, respectively. The resultant mechanical properties are based on the assumption of uniaxial loading (hence, values are for longitudinal properties only) and assume a given design temperature and design criterion (such as B-basis where there is 90% confidence that 95% of the failures will exceed the value). [3-2] Stephen Tsai, an acknowledged authority on composites design, has dismissed this technique as a valid design tool in favor of the more rigorous laminated plate theory. [3-10]

Carpet plots have been a common preliminary design tool within the aerospace industry where laminates typically consist of a large number of thin plies. Additionally, out of plane loads are not of primary concern as is the case with marine structures. An aerospace designer essentially views a laminate as a homogeneous engineering material with some degraded mechanical properties derived from carpet plots. Typical marine laminates consist of much fewer plies that are primarily not from unidirectional reinforcements. Significant out of plane loading and high aspect ratio structural panels render the unidirectional data from carpet plots somewhat meaningless for designing FRP marine structures.

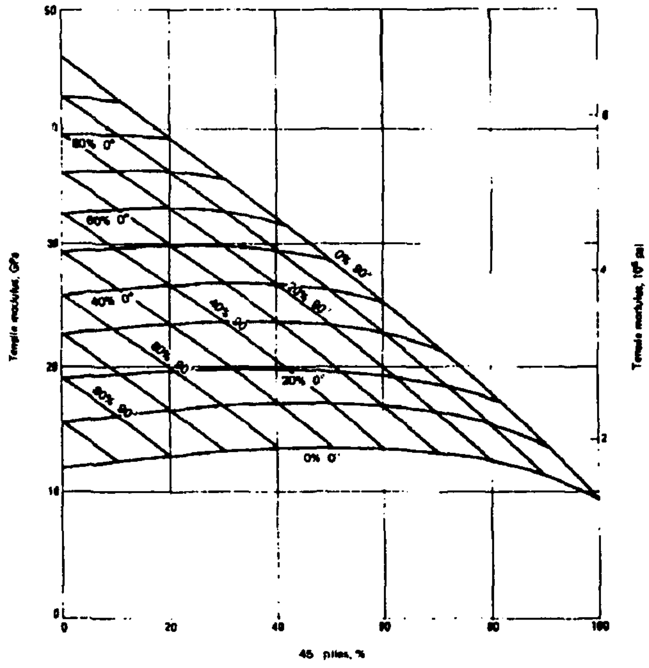


Figure 3-18 Carpet Plot Illustrating Laminate Tensile Modulus [*ASM Engineered Materials Handbook*]

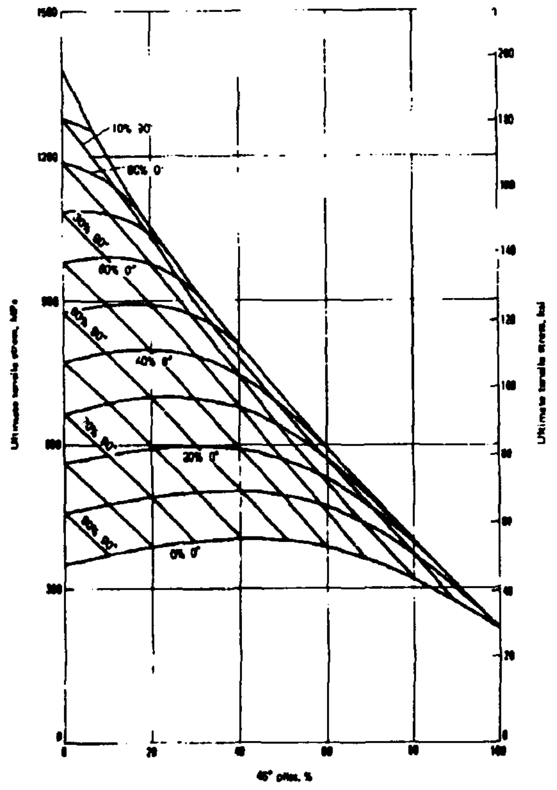


Figure 3-19 Carpet Plot Illustrating Tensile Strength [*ASM Engineered Materials Handbook*]

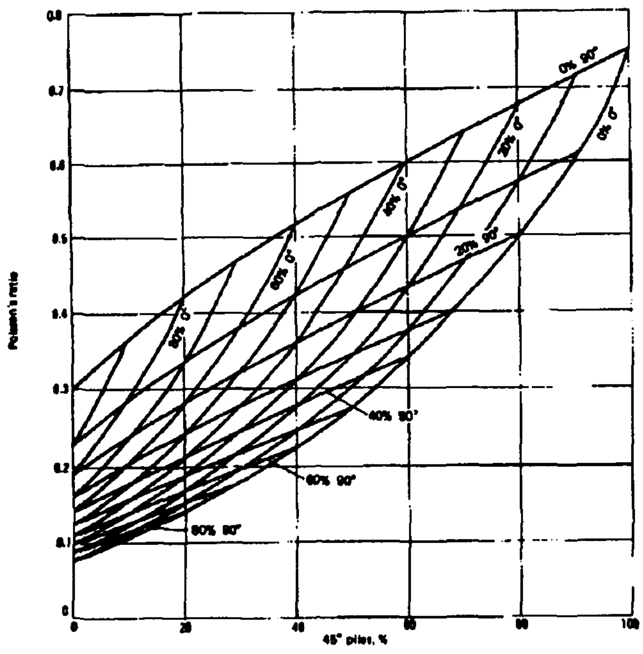


Figure 3-20 Carpet Plot Illustrating Poisson's Ratio [*ASM Engineered Materials Handbook*]

Computer Laminate Analysis

There are a number of structural analysis computer programs available for mainframe computers that use finite-element or finite-difference numerical methods and are suitable for evaluating composites. In general, these programs will address: [3-2]

- Structural response of laminated and multidirectional reinforced composites
- Changes in material properties with temperature, moisture and ablative decomposition
- Thin-shelled, thick-shelled, and/or plate structures
- Thermal-, pressure- traction-, deformation- and vibration-induced load states
- Failure modes
- Non-linearity
- Structural instability
- Fracture mechanics

The majority of these codes for mainframes are quite expensive to acquire and operate, which precludes their use for general marine structures. Specialized military applications such as a pressure hull for a torpedo or a highly stressed weight critical component might justify analysis with these sort of programs.

More useful to the marine designer, are the PC based laminate analysis programs that allow a number of variations to be evaluated at relatively low cost. The software generally costs less than $500 and can run on hardware that is probably already integrated into a design office. The better programs are based on laminated plate theory, which treats each ply as a quasi-homogeneous material. Prediction of ultimate strengths with materials that enter non-elastic regions, such as foam cores, will be of limited accuracy. Some other assumptions in laminated plate theory include: [3-2]

- The thickness of the plate is much smaller than the in-plane dimensions
- The strains in the deformed are small compared to unity
- Normals to the undeformed plate surface remain normal to the deformed plate surface
- Vertical deflection does not vary through the thickness
- Stress normal to the plate surface is negligible

For a detailed description of laminated plate theory, the reader is advised to refer to ***Introduction to Composite Materials***, by S.W. Tsai and H.T. Hahn, Technomic, Lancaster, PA (1985).

Table 3-2 illustrates a typical range of input and output variables for computer laminate analysis programs. Some programs are menu driven while others follow a spreadsheet format. Once material properties have been specified, the user can "build" a laminate by selecting materials and orientation. As a minimum, stresses and strains failure levels for each ply will be computed. Some programs will show stress and strain states versus design allowables based on various failure criteria. Most programs will predict which ply will fail first and provide some routine for laminate optimization. In-plane loads can usually be entered to compute predicted states of stress and strain instead of failure envelopes.

Table 3-2. Typical Input and Output Variables for Laminate Analysis Programs

Input		Output	
Load Conditions	**Material Properties**	**Ply Properties**	**Laminate Response**
Longitudinal In-Plane Loads	Modulus of Elasticity	Thicknesses*	Longitudinal Deflection
Transverse In-Plane Loads	Poisson's Ratio	Orientation*	Transverse Deflection
Vertical In-Plane Loads (shear)	Shear Modulus	Fiber Volume*	Vertical Deflection
Longitudinal Bending Moments	Longitudinal Strength	Longitudinal Stiffness	Longitudinal Strain
Transverse Bending Moments	Transverse Strength	Transverse Stiffness	Transverse Strain
Vertical Moments (torsional)	Shear Strength	Longitudinal Poisson's Ratio	Vertical Strain
Failure Criteria	Thermal Expansion Coefficients	Transverse Poisson's Ratio	Longitudinal Stress per Ply
Temperature Change		Longitudinal Shear Modulus	Transverse Stress per Ply
		Transverse Shear Modulus	Vertical Stress (shear) per Ply
			First Ply to Fail
			Safety Factors

*These ply properties are usually treated as input variables

Failure Criteria

Failure criteria used for analysis of composites structures are similar to those in use for isotropic materials, which include maximum stress, maximum strain and quadratic theories. [3-10] These criteria are empirical methods to predict failure when a laminate is subjected to a state of combined stress. The multiplicity of possible failure modes prohibits the use of a more rigorously derived mathematical formulation. The basic material data required for all the criteria is longitudinal and transverse tensile, and compressive as well as longitudinal shear strengths. Two-dimensional failure theory is based on these properties.

Maximum Stress Criteria

Evaluation of laminated structures using this criteria begins with a calculation of the strength/stress ratio for each stress component. This quantity expresses the relationship between the maximum, ultimate or allowable strength, and the applied corresponding stress. The lowest ratio represents the mode that controls ply failure. This criteria ignores the complexities of composites failure mechanisms and the associated interactive nature of the various stress components.

Maximum Strain Criteria

The maximum strain criteria follows the logic of the maximum stress criteria. The maximum strain associated with each applied stress field is merely the value calculated by dividing strengths by moduli of elasticity. The dominating failure mode is that which produces the highest strain level. Simply stated, failure is controlled by the ply that first reaches its elastic limit. This concept is important to consider when designing hybrid laminates that contain low strain materials, such as carbon fiber.

Both the maximum stress and maximum strain criteria can be visualized in two-dimensional space as a box with absolute positive and negative values for longitudinal and transverse axes. This failure envelope implies no interaction between the stress fields and material response.

Quadratic Criteria for Stress and Strain Space

One way to include the coupling effects (Poisson phenomena) in a failure criteria is to use a theory based on distortional energy. The resultant failure envelope is an ellipse which is very oblong. A constant, called the normalized empirical constant, which relates the coupling of strength factors, generally falls between -½ (von Mises criteria) and 0 (modified Hill criteria). [3-10] A strain space failure envelope is more commonly used for the following reasons:

- Plotted data is less oblong
- Data does not vary with each laminate
- Input properties are derived more reliably
- Axes are dimensionless

First- and Last-Ply to Failure Criteria

These criteria are probably more relevant with aerospace structures where laminates may consist of over 50 plies. The theory of first-ply failure suggests an envelope that describes the failure of the first ply. Analysis of the laminate continues with the contribution from that and successive plies removed. With the last ply to failure theory, the envelope is developed that corresponds to failure of the final ply in what is considered analogous to ultimate failure. Each of these concepts fail to take into account the contribution of a partially failed ply or the geometric coupling effects of adjacent ply failure.

Thickness Design Criteria

Many components and smaller hull structures in the marine industry are designed using purely empirical methods. The specification criteria is usually based on satisfactory in-service performance of similar structures. This method is normally only applied to production fiberglass parts that are fabricated by hand lay-up or spray-up techniques where builders have established a working criteria for minimum thickness. Owens-Corning [3-11] has developed a simple methodology for relating laminate thickness to the areal weight of fiberglass applied and the fiberglass weight percent. The following relationship based on factors from Figure 3-21 is postulated:

$$T = \frac{WZ}{100}$$

where:

T = laminate thickness in inches
W = amount of fiberglass used in ounces per square foot
Z = factor from Figure 3-21

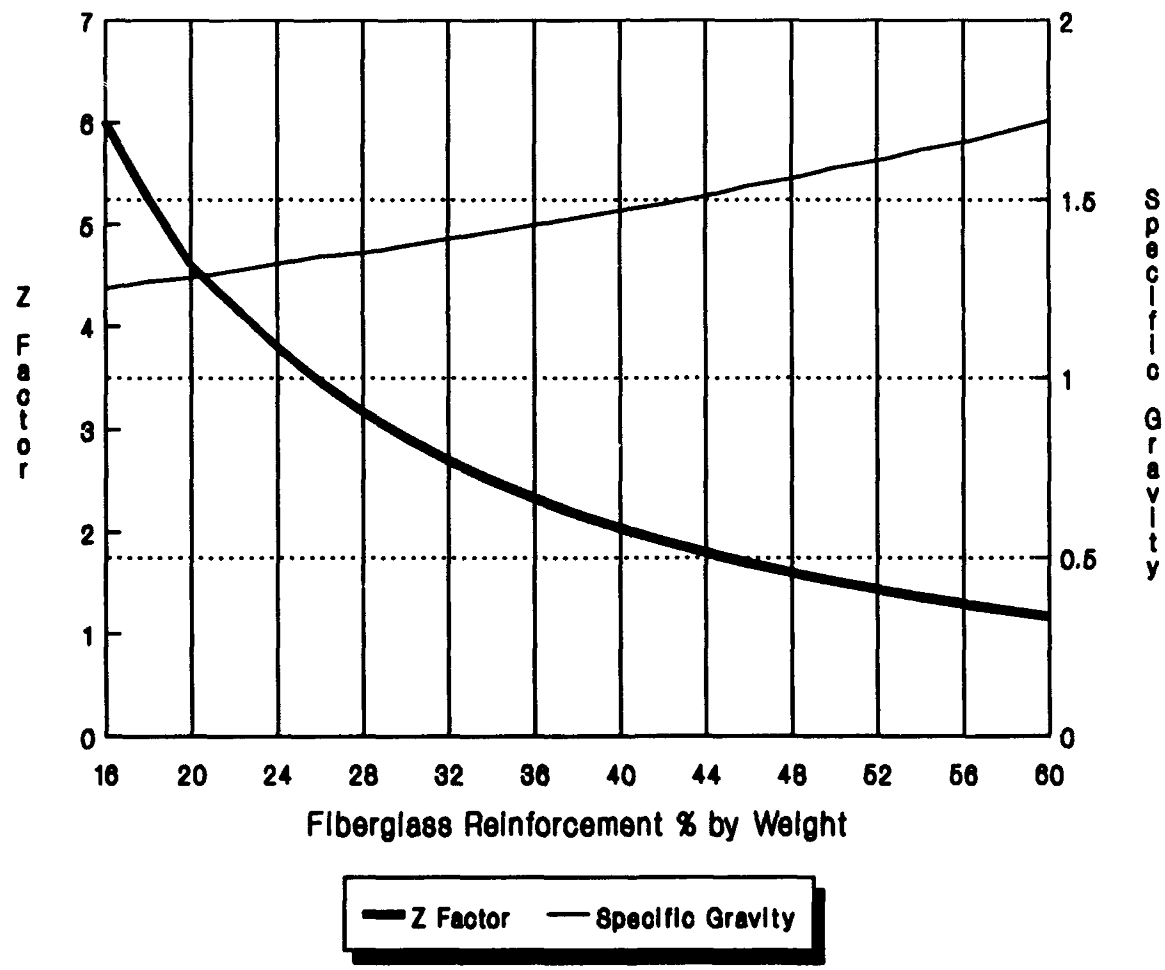


Figure 3-21 Z-Factor and Approximate Laminate Specific Gravity for Fiberglass Laminates with Unfilled Resin Systems [Owens-Corning Fiberglas, *The Hand Lay-Up and Spray-Up Guide*]

Conventional Laminate Property Data

It has been emphasized throughout this document that accurate design engineering can only be accomplished if material property data is determined from laminate testing using shipyard samples. However, the designer must have some starting point for the purposes of conducting preliminary design or trade-off studies. In the early 1970's, Owens-Corning Fiberglas in conjunction with Gibbs & Cox published a document entitled *Design Properties of Marine Grade Fiberglass Laminates.* [3-12] The laminates considered were manufactured by the hand layup method and generally utilized orthophthalic polyester resin. The following materials were considered in the study:

- Chopped Strand Mat - ¾ oz/ft^2 to 3 oz/ft^2 with data also relevant for "spray-up" laminates.
- Woven Roving - Most laminates used 24 oz/yd^2, with some data on 18 and 40 oz/yd^2 material included. Fabric construction is 5 x 4, accounting for superior performance in the warp direction. Most U.S. Navy construction uses only woven roving.
- Mat Woven Roving Laminate - Most data is for alternating layers of 24 oz/yd^2 woven roving and 1½ oz/ft^2 mat. This construction technique has traditionally been the most popular with recreational boat builders, in part because interlaminar shear strength is perceived to be better than pure woven roving laminates. The data presented here does not support this, although fabrication considerations still favor this technique.

Data for "wet strength" was used whenever possible, although the authors point out that the state-of-the-art for general purpose polyester resin at that time had reduced "wet" versus "dry" property differences to about 5 to 7%. In the twenty years that have elapsed since most of this data was collected, resins have improved further as has sizing agents on fiberglass.

The Gibbs & Cox data is being reproduced in this document not so much for the absolute material properties that can be extracted but more to show the range of data accumulated and the graphical method chosen for representation. The variety of data sources and statistical processing techniques varied to the point where the compiled data was not suitable for statistical analysis. References [3-13] through [3-20] were cited as sources for the material property data.

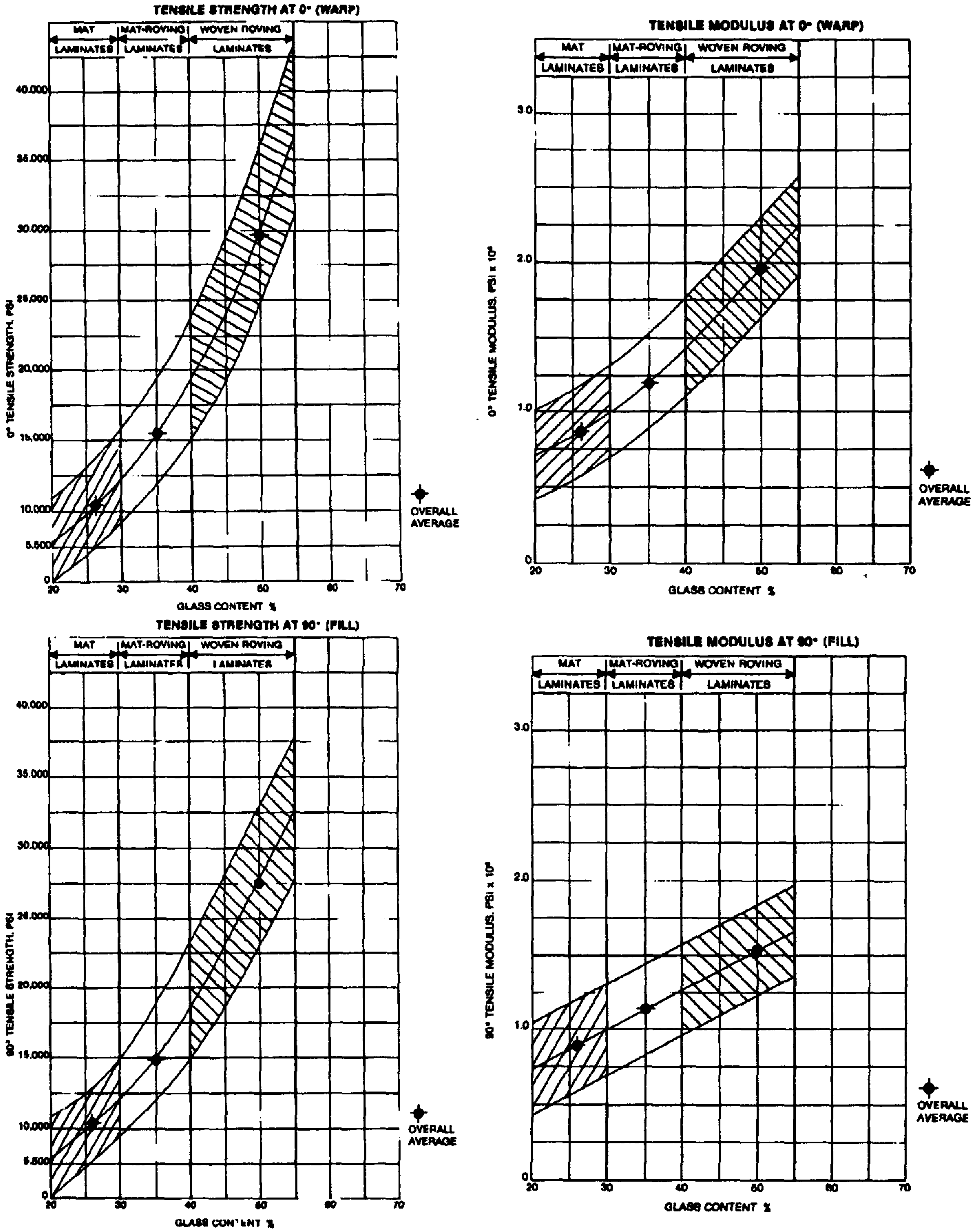


Figure 3-22 On-Axis Tensile Properties of 1½ oz Mat and 24 oz Woven Roving [Gibbs and Cox, *Design Properties of Marine Grade Fiberglass Laminates*]

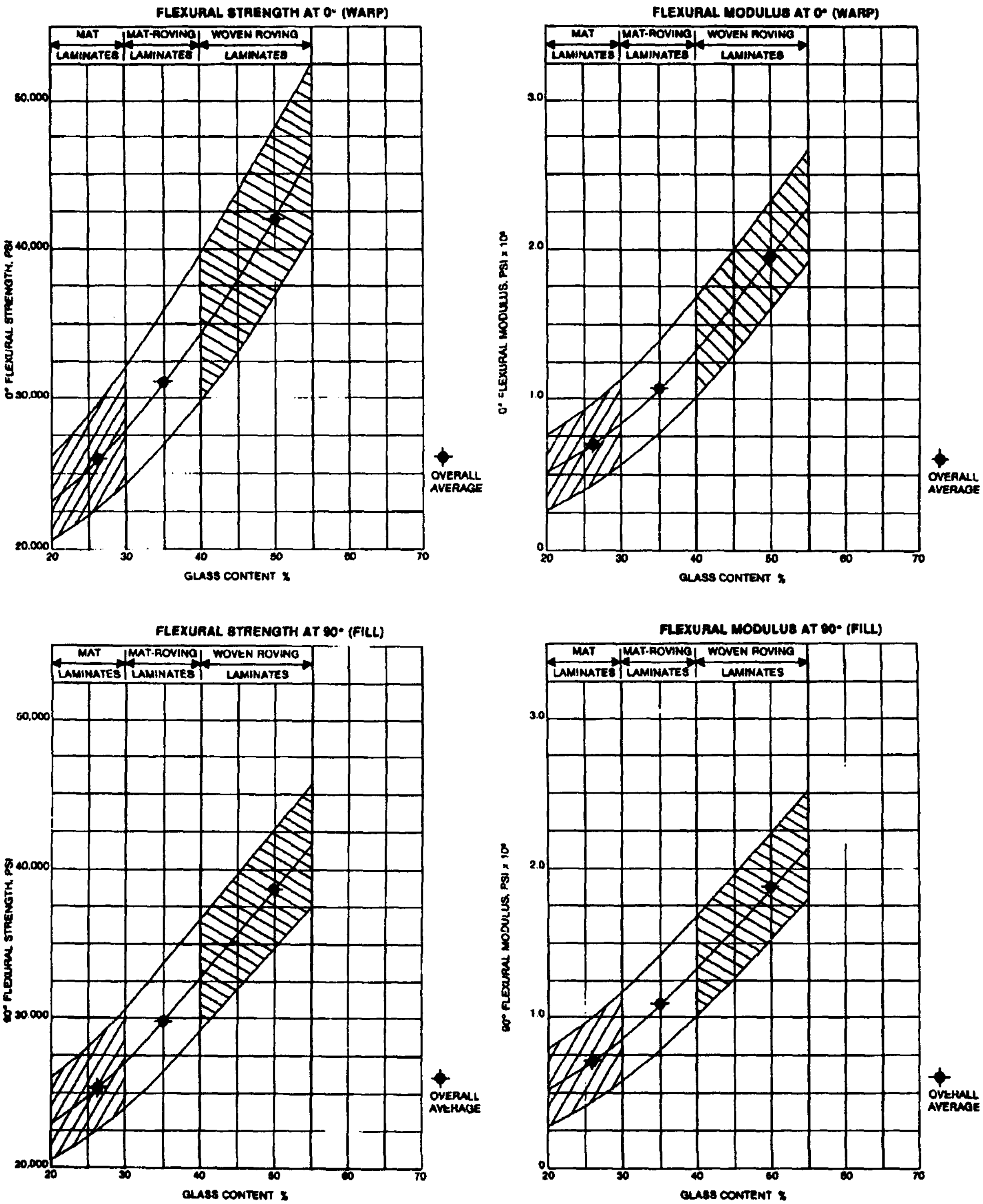


Figure 3-23 On-Axis Flexural Properties of 1½ oz Mat and 24 oz Woven Roving [Gibbs and Cox, *Design Properties of Marine Grade Fiberglass Laminates*]

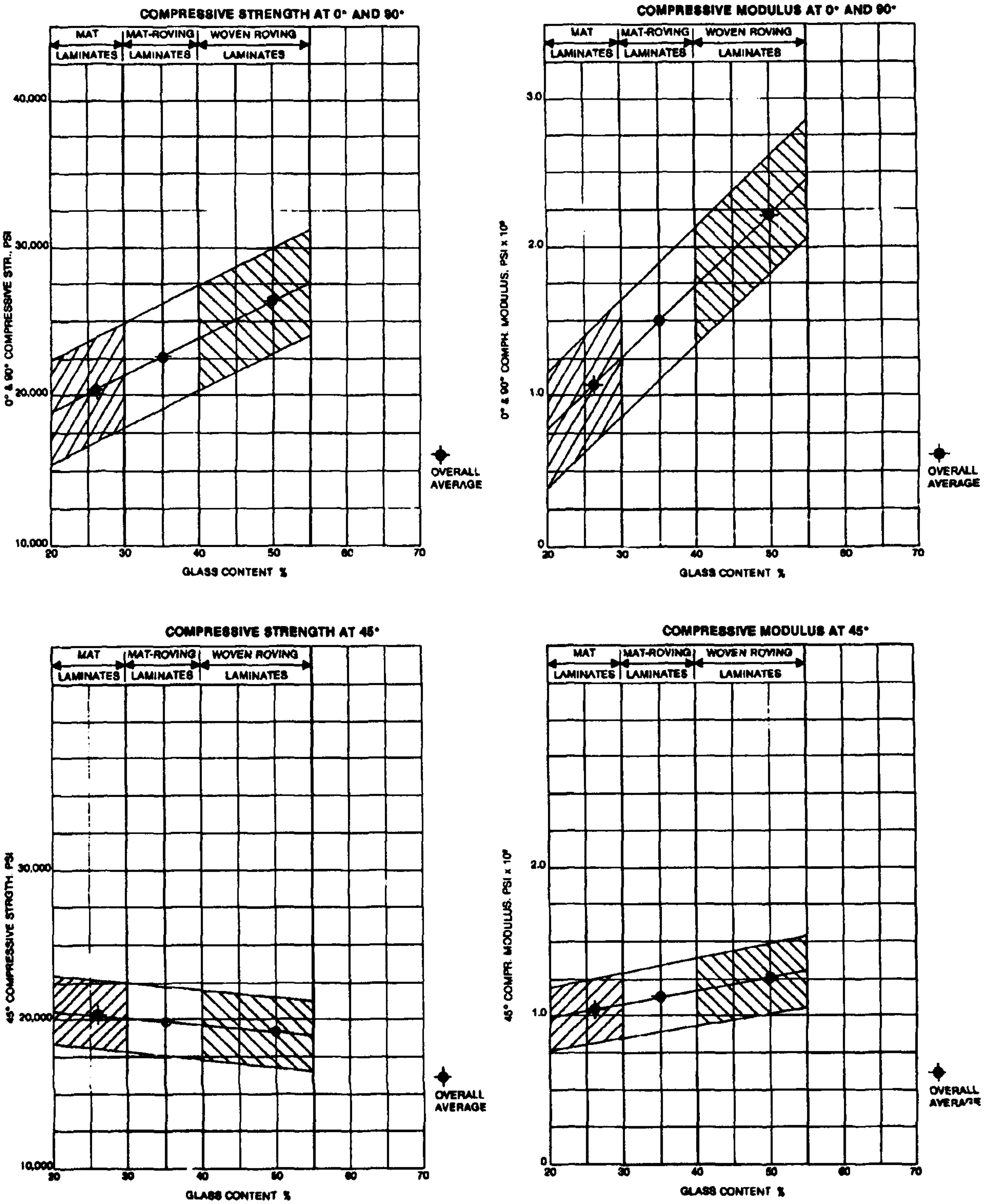


Figure 3-24 Compressive Properties of 1½ oz Mat and 24 oz Woven Roving [Gibbs and Cox, *Design Properties of Marine Grade Fiberglass Laminates*]

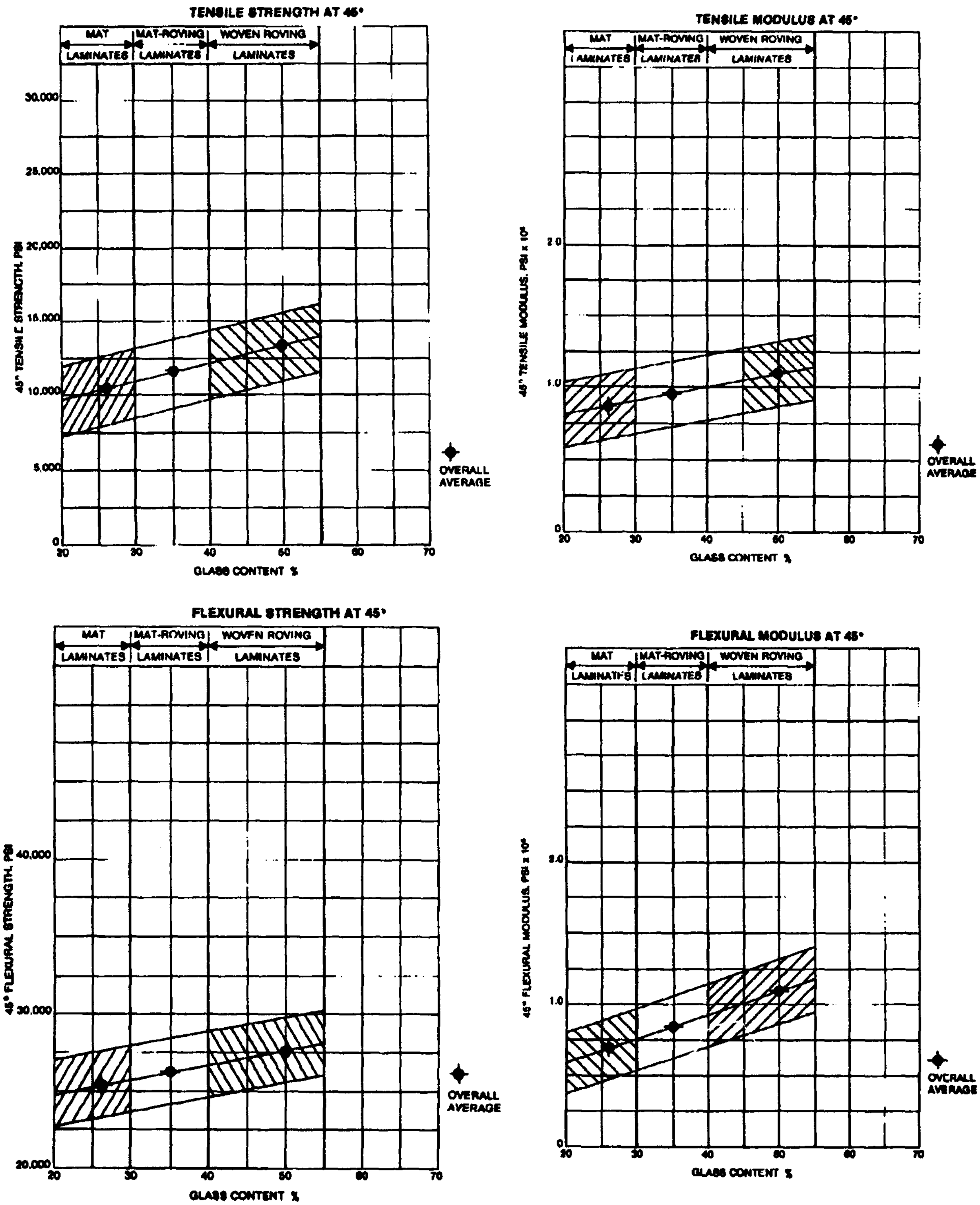


Figure 3-25 Off-Axis Properties of 1½ oz Mat and 24 oz Woven Roving [Gibbs and Cox, *Design Properties of Marine Grade Fiberglass Laminates*]

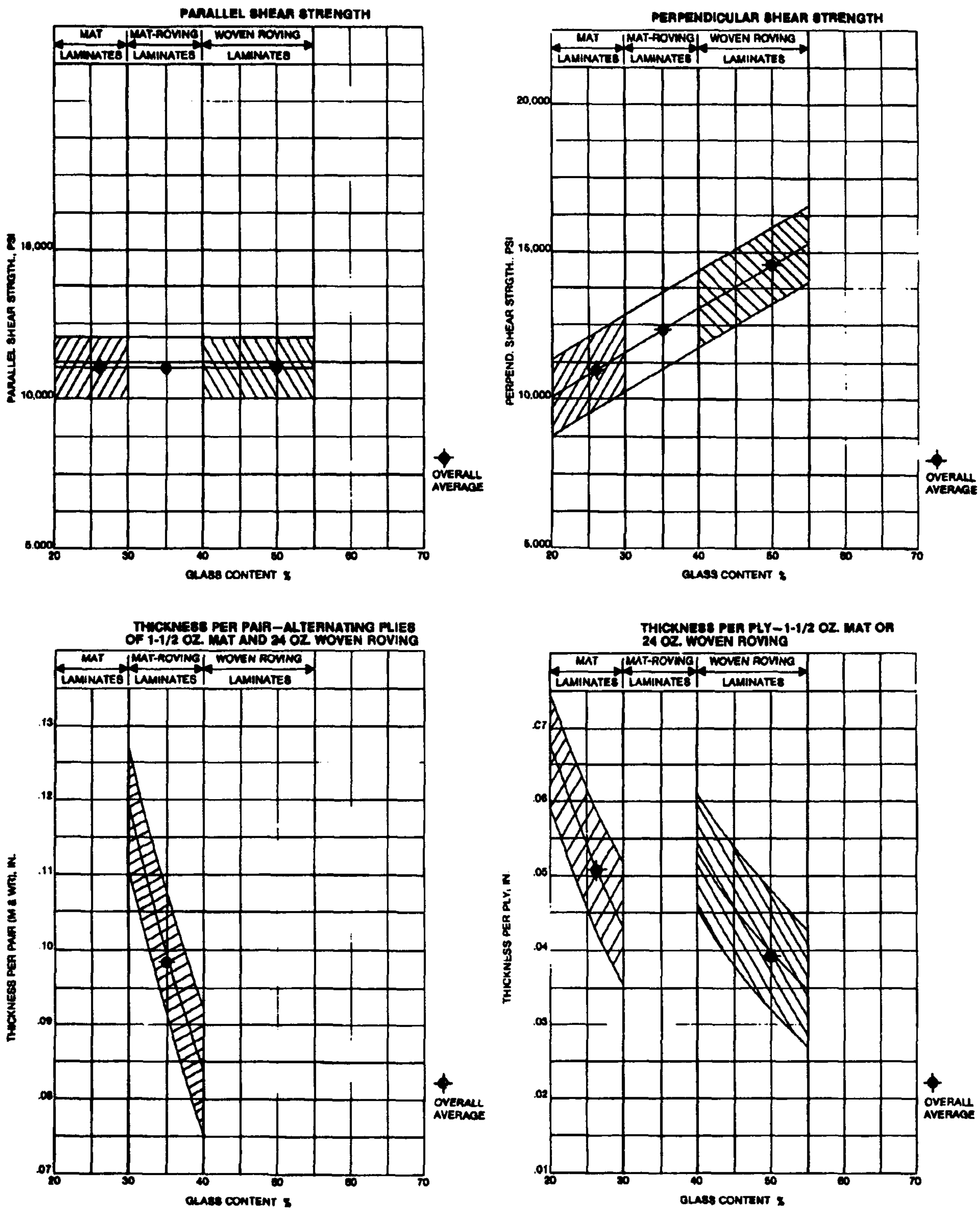
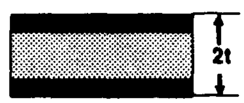
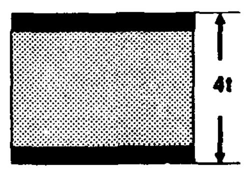


Figure 3-26 Shear and Thickness Properties of 1½ oz Mat and 24 oz Woven Roving [Gibbs and Cox, *Design Properties of Marine Grade Fiberglass Laminates*]

Sandwich Construction

The structure of most small craft is designed to withstand high localized forces normal to the hull panels, as this is the dominant loading of the structure. Therefore, the structure must be designed with relatively higher flexural stiffness and strength than in-plane stiffness and strength. This is especially true when comparing sandwich to solid laminates, along with corresponding frame spacing. Sandwich construction is often used in high performance boats because good out-of-plane flexural properties can be achieved at relatively low weights. Table 3-3 developed for honeycomb core structures illustrates the potential gains of utilizing sandwich construction.

Table 3-3. Strength and Stiffness for Cored and Solid Construction [Hexcel, *The Basics on Bonded Sandwich Construction*]

			
Relative Stiffness	100	700	3700
Relative Strength	100	350	925
Relative Weight	100	103	106

Sandwich panels consist of thin, high stiffness and strength skins over a thick, low density core material. The behavior of sandwich beams and panels is quite different from "solid" beams and panels, with higher flexural stiffness and strength relative to in-plane properties. Most designers have substantial experience with solid GRP, aluminum, or steel construction, and there are a number of widely accepted scantling rules for these materials. However, the experience base for sandwich construction is relatively small, and although there has been some work on sandwich scantling rules, there is at present no widely accepted scantling rule for sandwich construction.

Flexural Stiffness of a Beam

The flexural stiffness of a beam is a function of the elastic modulus, which is similar for the solid beam and the sandwich skins, and the moment of inertia, which is very different for solid and sandwich beams. The moment of inertia for the two types of beams are:

Solid Beam Moment of Inertia

$$I_s = \frac{bh^3}{12}$$

Approximate Sandwich Beam Skins Moment of Inertia

$$I_f = \frac{2bt^3}{12} + \frac{2btd^2}{4}$$

Approximate Sandwich Beam Core Moment of Inertia

$$I_c = \frac{b\,(d-t\,)^3}{12}$$

where:

b = the width of the beam

h = the height of the beam

t = the thickness of the sandwich skins

d = the thickness of the core, as per Figure 3-27

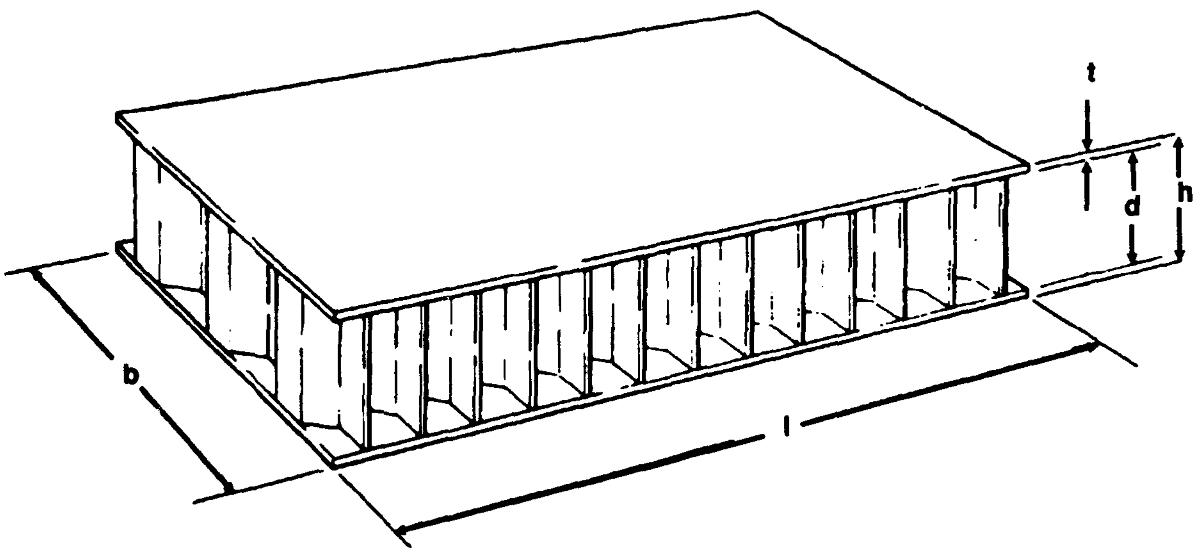


Figure 3-27 Geometry of Sandwich Beams [Hexcel, *The Basics on Bonded Sandwich Construction*]

The flexural stiffness is the product of the modulus of elasticity and the moment of inertia:

Solid Beam Flexural Stiffness

$$E_s I_s = \frac{E_f\, b\, h^3}{12}$$

Approximate Sandwich Beam Flexural Stiffness

$$E_f I_F + E_c I_c = E_f\left(\frac{2bt^3}{12} + \frac{2b\,t\,(d+t)^2}{4}\right) + E_c\,\frac{b\,d^3}{12}$$

where:

E_g = the modulus of the solid beam

E_f = the modulus of the sandwich facing material

E_c = the modulus of the core material

These expressions can be simplified by neglecting the smaller terms. The following ratios, common to sandwich construction, can be used to determine the relative magnitude of the terms:

$$\frac{t}{d} \approx 0.1$$

$$\frac{E_f}{E_c} \approx 200$$

Substituting these ratios into the expression for the flexural stiffness of a sandwich beam, it can be seen that the first and third terms contribute less than 1% of the flexural stiffness, thus they can be neglected with little error. The resulting expression is:

Simplified Sandwich Beam

$$E_f I_f = E_f \frac{bt\,(d+t)^2}{2}$$

Using this expression, the ratio of the flexural stiffnesses of a solid beam and a sandwich beam is:

$$\frac{E_f I_f}{E_g I_g} = \left(\frac{E_f}{E_g}\right)\left(\frac{(b\,t\,(d+t)^2)/2}{b\,h^3/12}\right) = \left(\frac{E_f}{E_g}\right)\frac{6\,t\,(d+t)^2}{h^3}$$

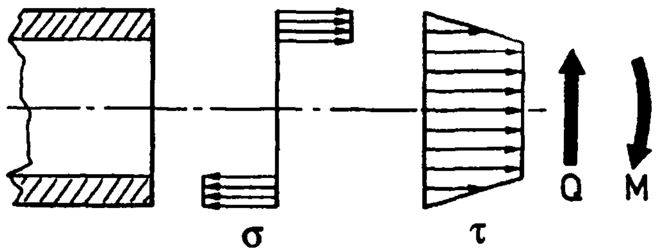
When there is no core, $t = h/2$ and when $E_f = E_g$, the bending stiffness ratio is 1.0. If the sandwich beam is at least as thick as the solid beam, and $E_f = E_g$, then this ratio is always greater than 1.0, thus for a given weight, a sandwich beam is stiffer than a solid beam. As an example, let $E_f = E_g$, $d = h = 1$, and $t = 0.2\,h$:

$$\frac{E_f I_f}{E_g I_g} = (1)\,\frac{6 \times .2h\,(h + .2h)^2}{h^3} = 1.728$$

Thus the sandwich beam, which is 20% thicker than the solid beam, has a flexural stiffness 1.73 times greater than the solid beam. If the facing density is ten times the core density, the sandwich beam would weigh only 48% of the solid beam weight.

Flexural Strength of a Beam

The flexural strength of the solid and sandwich beams is a function of the stress distribution in the beams and the limiting material strength. The general stress distribution in sandwich beams subjected to a moment M is presented in Figure 3-28. The maximum tensile/compressive stresses in the two beams are:



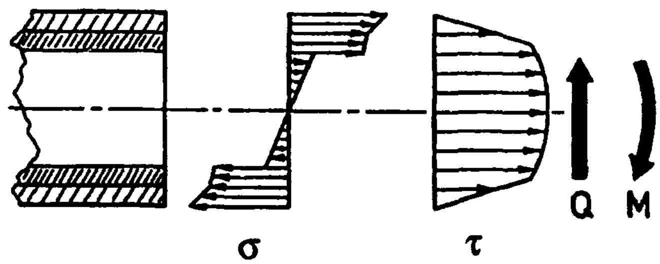
Assumed Stress Distribution in the Classical Sandwich Theory

Solid Beam

$$S_g = \frac{6M}{bh^2}$$

Sandwich Beam

$$S_f = \frac{M}{(d+t)\,bt}$$



More Realistic Stress Distribution in a Sandwich Elelment

Figure 3-28 Stress Distribution Within a Sandwich Beam [Rasmussen and Baatrup, *Rational Design of Large Sandwich Structures*]

where:

S_g = the maximum stress in the solid beam

S_f = the maximum stress in the sandwich beam

M = the applied moment

The resulting ratio of maximum stress is:

$$\frac{S_f}{S_g} = \frac{h^2}{6\,(d+t)dt}$$

When no core is present, $h = 2t$, $d = 0$ and $E_f = E_g$, the maximum stress ratio approaches ∞. This ratio should be 1.0, but the stress was assumed constant, rather than linearly varying, through the face thickness. This error is largest for the case with no core, but becomes negligible when the core thickness is much greater than the facing thickness. The same example used previously, with $t = 0.2h$ and $d = h$, yields the following maximum stress ratio:

$$\frac{S_f}{S_g} = 0.694$$

If the limiting failure mechanism is tensile/compressive strength of the facings, the sandwich beam has a flexural strength 1.44 times that of the solid beam. Thus the flexural strength of the sandwich beam is also greater than that of the solid beam for this example, although not as dramatic as the increase in flexural stiffness.

Summary of Beam Comparison

Sandwich beams can be designed to have higher flexural strength and stiffness at lower weight, but the in-plane stiffness and strength per unit weight are lower than for solid beams. The flexural stiffness of a sandwich beam is a linear function of the face thickness and the modulus of the face material, but the stiffness increases with the square of the core thickness. Thus, doubling the skin thickness or facing modulus will double the flexural stiffness, but doubling the core thickness will increase the flexural stiffness by a factor of 4.0. The flexural stiffness of a solid beam is a linear function of the modulus of the material, and a function of the cube of the beam thickness. The flexural strength of a sandwich beam is a linear function of the facing thickness, facing strength and core thickness. The strength of a solid beam is a linear function of the material strength and is proportional to the square of the beam thickness. Figure 3-29 illustrates some basic structural design concepts applicable to sandwich construction.

Sandwich Panel Flexural Stiffness

The primary use of sandwich laminates, with high flexural stiffness and strength, is for large unsupported panels, such as hulls, decks and bulkheads. Beam theory is commonly used in the design of these panels, since this type of theory is successfully utilized for steel construction. This theory does not work well for sandwich panels, however, since it does not consider membrane effects. Finite element method (FEM) analysis can be used to predict the behavior of the sandwich panels, but this method also has limitations. Deflection or strain predictions for loads where the structural response of the materials is linear are generally satisfactory, however, these predictions are usually not very good for the non-linear or plastic response region. Strength prediction, or failure analysis, is a problem when failure occurs outside the elastic response range of the materials, which is usually the situation. Also, the accuracy of the FEM predictions is highly dependent on material properties, which must be obtained from testing. Thus FEM is useful for analyzing the structural response to working or design loads, but is of limited use in predicting structural response to extreme loads.

The limitations of analytical approaches to the problem leads to a reliance on mechanical testing of both the materials and the structure. Materials testing is based on standard tests, such as ASTM tests, which are developed to provide industry wide standards. The marine industry has not played an active role in developing these standard tests, thus most of the tests which are used have been developed by and for other industries, and are not necessarily applicable to the marine industry. In particular, almost all of the material tests are uniaxial load tests, while the materials in marine structures are usually subjected to multi-axial loads. As an example, beam flexural tests are used to determine flexural stiffness and strength of sandwich laminates. This test method can lead to large errors when considering pressure loaded sandwich panels, such as those in boat hulls. Figures 3-30 through 3-33 present relative flexural stiffness and strengths of several sandwich laminates obtained by testing sandwich beams using ASTM C 393 and structural testing of sandwich panels constructed of the same laminates using distributed

1. The facings should be thick enough to withstand the tensile, compressive and shear stresses induced by the design load.

2. The core should have sufficient strength to withstand the shear stresses induced by the design loads. Core bonding material must have sufficient strength to carry shear stress in the core.

3. The core should be thick enough and have sufficient shear modulus to prevent overall buckling of the sandwich under load, and to prevent crimping.

4. Compressive modulus of the core and the compressive modulus of the facings should be sufficient to prevent wrinkling of the faces under design load.

5. With honeycomb cores, the cell structure should be small enough to prevent intracell dimpling of the facings under design load.

6. The core should have sufficient compressive strength to resist crushing by design loads acting normal to the panel facings or by compressive stresses induced through flexure.

7. The sandwich structure should have sufficient flexural and shear rigidity to prevent excessive deflections under design load.

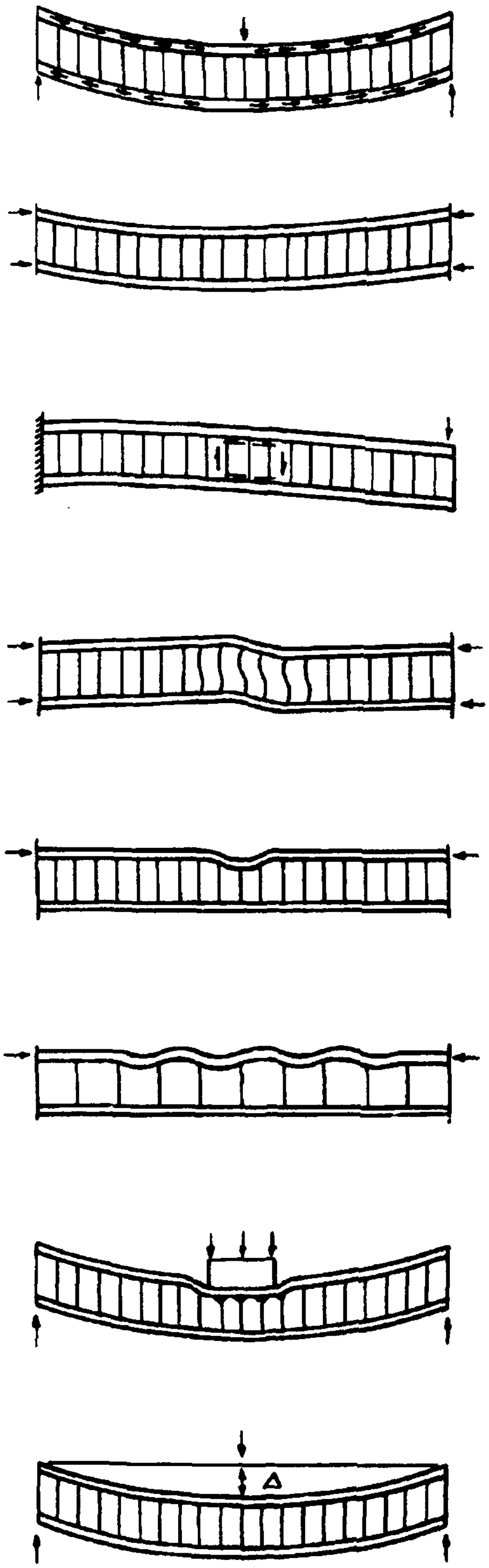


Figure 3-29 Basic Sandwich Structural Criteria [*ASM Engineered Materials Handbook*]

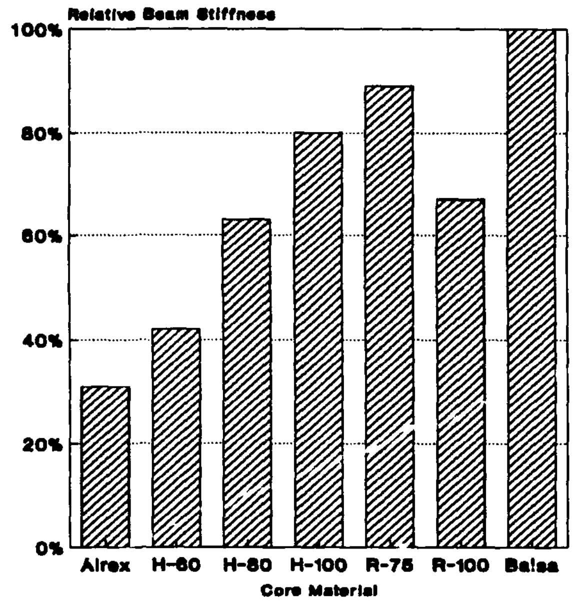


Figure 3-30 Relative Stiffness for FRP Beams with Different Cores [Reichard]

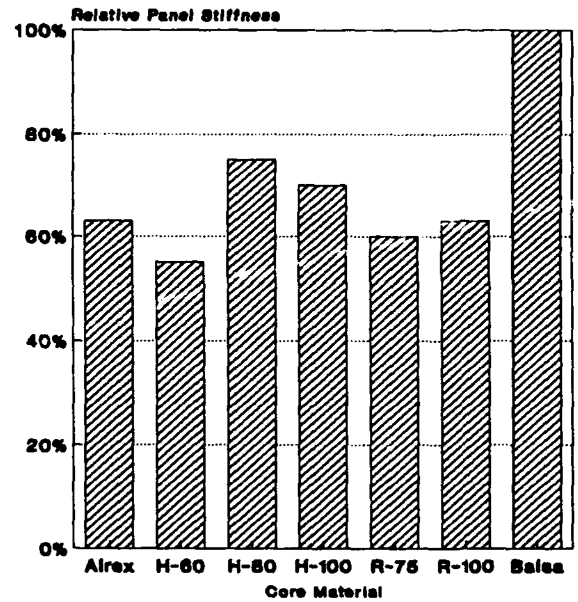


Figure 3-31 Relative Stiffness for FRP Panels with Different Cores [Reichard]

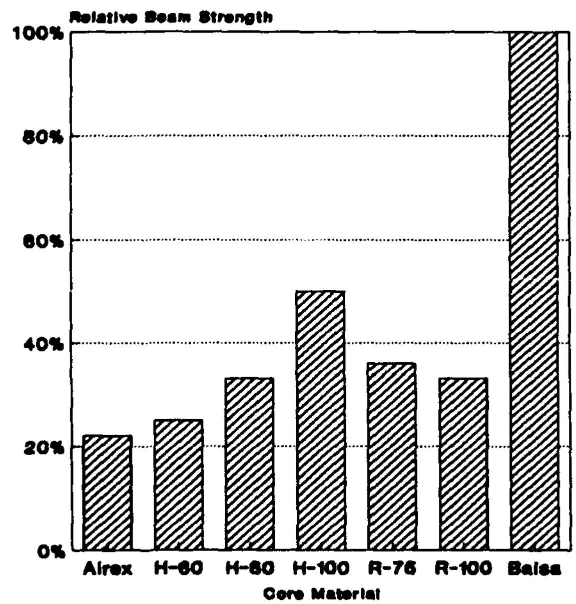


Figure 3-32 Relative Strength for FRP Beams with Different Cores [Reichard]

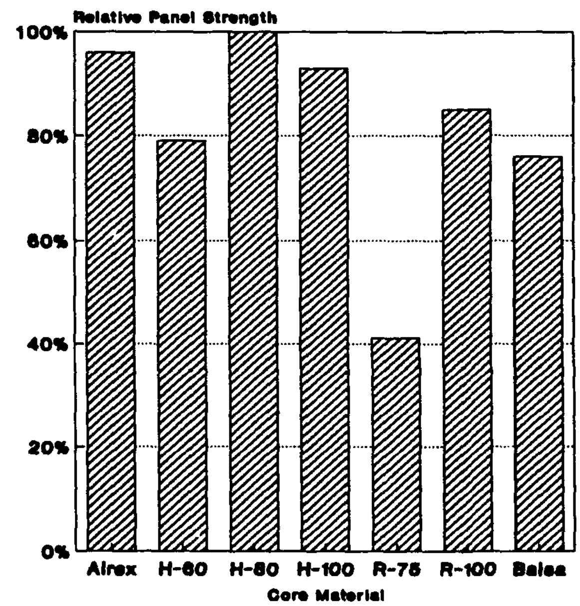


Figure 3-33 Relative Strength for FRP Panels with Different Cores [Reichard]

pressure loading. The core materials tested included products from: Airex®, Divinycell®, Klegecell® and Baltek. It is obvious that there are significant differences between beam and panel testing.

The primary obstacles to the use of sandwich construction for marine structures are the limitations of the analytical methods and the lack of appropriate test methods. Both of these areas are presently being addressed by individual researchers, but a coordinated, industry wide effort is necessary to adequately address these problems. Some formulas are presented here that relate sandwich properties to an equivalent solid skin thickness, t_{SS}.

for skins in tension:

$$t_F\left(t_C+\frac{T_F}{2}\right) \approx \frac{t_{SS}^2 \times \sigma_f}{\sigma \times \sigma_t}$$

for skins in compression:

$$t_F\left(t_C+\frac{T_F}{2}\right) \approx \frac{t_{SS}^2 \times \sigma_f}{\sigma \times \sigma_c}$$

where:

t_F = Sandwich skin thickness

t_C = Core thickness

σ_f = Single skin flexural strength

σ_t = Sandwich skin tensile strength

σ_c = Sandwich skin compressive strength

sandwich bending stiffness:

$$I_{sandwich} = \frac{t_{SS}^3 \times E_f}{12 \times 0.5\,(E_t + E_c)}$$

where:

E_f = Single skin flexural modulus

E_t = Sandwich skin tensile modulus

E_c = Sandwich skin compressive modulus

Design of Details

In reviewing the past three decades of FRP boat construction, very few failures can be attributed to the overall structural collapse of the structure due to primary hull girder loading. This is in part due to the fact that the overall size of FRP ships has been limited, but also because safety factors have been very conservative. In contrast to this, numerous failures resulting from what is termed "local phenomena" have been observed, especially in the early years of FRP development. As high-strength materials are introduced to improve vessel performance, the safety cushion associated with "bulky" laminates diminishes. As a consequence, the FRP designer must pay careful attention to the structural performance of details.

Details in FRP construction can be any area of the vessel where stress concentrations may be present. These typically include areas of discontinuity and applied load points. As an example, failures in hull panels generally occur along their edge, rather than the center. [3-21] FRP construction is particularly susceptible to local failure because of the difficulty in achieving laminate quality equal to a flat panel. Additionally, stress concentration areas typically have distinct load paths which must coincide with the directional strengths of the FRP reinforcing material. With the benefit of hindsight knowledge and a variety of reinforcing materials available today, structural detail design can rely less on "brute force" techniques.

Secondary Bonding

FRP structures will always demonstrate superior structural properties if the part is fabricated in one continuous cycle without total curing of intermediate plies. This is because interlaminar properties are enhanced when a chemical as well as mechanical bond is present. Sometimes the part size, thickness or manufacturing sequence preclude a continuous layup, thus requiring the application of wet plies over a previously cured laminate, known as secondary bonding.

Much of the test data available on secondary bonding performance dates back to the early 1970's when research was active, supporting an FRP minesweeper program. Frame and bulkhead connections were targeted as weak points when large hulls were subjected to extreme shock from detonated charges. Reports on secondary bond strength by Owens-Corning Fiberglas [3-22] and Della Rocca & Scott [3-23] are summarized below:

- Failures were generally cohesive in nature and not at the bond interface line. A clean laminate surface at the time of bonding is essential and can best be achieved by use of a peeling ply. A peeling ply consists of a dry piece of reinforcement (usually cloth) that is laid down without being wetted out. After cure, this strip is peeled away, leaving a rough bonding surface with raised glass fibers.
- Filleted joints proved to be superior to right-angle joints in fatigue tests. It was postulated that the bond angle material was stressed in more of a pure flexural mode for the radiused geometry.
- Bond strengths between plywood and FRP laminates is less than that of FRP itself. Secondary mechanical fasteners might be considered.

- In a direct comparison between plywood frames and hat-sectioned stiffeners, the stiffeners appear to be superior based on static tests.
- Chopped strand mat offers a better secondary bond surface than woven roving.

Table 3-4. Secondary Bond Technique Desirability [Della Rocca and Scott, *Materials Test Program for Application of Fiberglass Plastics to U.S. Navy Minesweepers*]

Preferable Bonding Techniques	Acceptable Bonding Techniques	Undesirable Procedures
Bond resin: either general purpose or fire retardant, resilient	*Bond resin:* general purpose or fire retardant, rigid air inhibited	
Surface treatment: roughened with a pneumatic saw tooth hammer, peel ply, or continuous cure of rib to panel; one ply of mat in way of bond	*Surface treatment:* rough sanding	No surface treatment
Stiffener faying flange thickness: minimum consistent with rib strength requirement		Excessive stiffener faying flange thickness
Bolts or mechanical fasteners are recommended in areas of high stress		

Deck Edge Connection

Since the majority of FRP vessels are built with the deck and hull coming from different molds, the builder must usually decide on a suitable technique for joining the two. Since this connection is at the extreme fiber location for both vertical and transverse hull girder loading, alternating tensile and compressive stresses are expected to be at a maximum. The integrity of this connection is also responsible for much of the torsional rigidity exhibited by the hull. Secondary deck and side shell loading shown in Figure 3-34 is often the design limiting condition. Other design considerations include: maintaining watertight integrity under stress, resisting local impact from docking, personnel footing assistance and appearance (fairing of shear). Figures 3-35 through 3-45 show some traditional deck edge connection techniques for various side shell and deck constructions. Open FRP boats generally require some stiffening at the gunwale. Figures 3-46 through 3-49 depict some variations on the treatment of small boat gunwales.

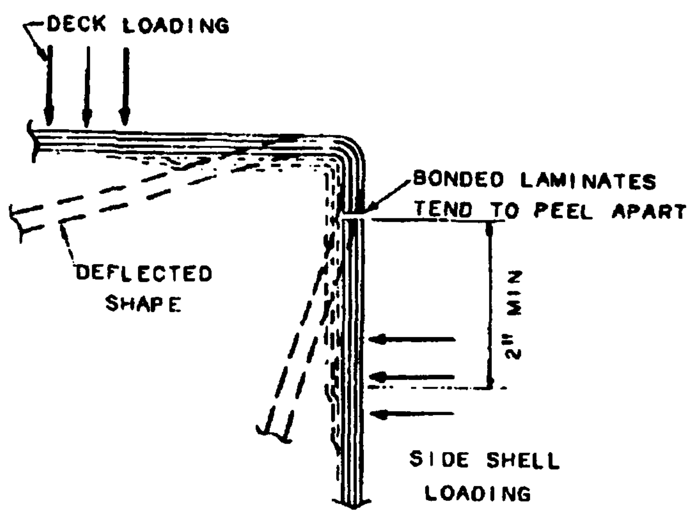


Figure 3-34 Deck Edge Connection - Normal Deck and Shell Loading Produces Tension at the Joint [Gibbs and Cox, *Marine Design Manual for FRP*]

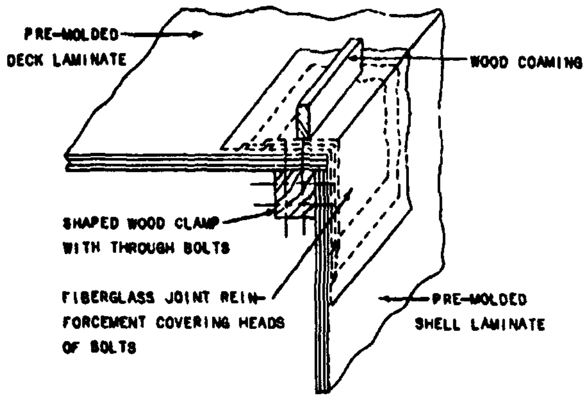


Figure 3-35 Shaped Wood Gunwale Clamp [Gibbs and Cox, *Marine Design Manual for FRP*]

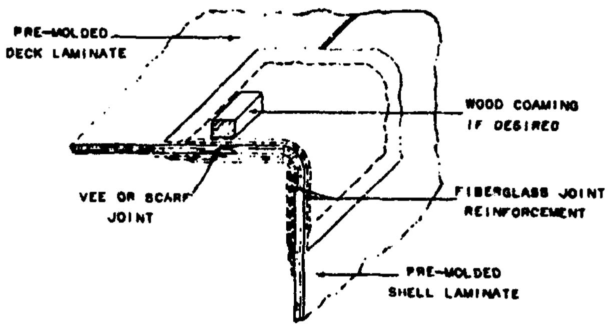


Figure 3-36 Wood Coaming and Joint in Deck [Gibbs and Cox, *Marine Design Manual for FRP*]

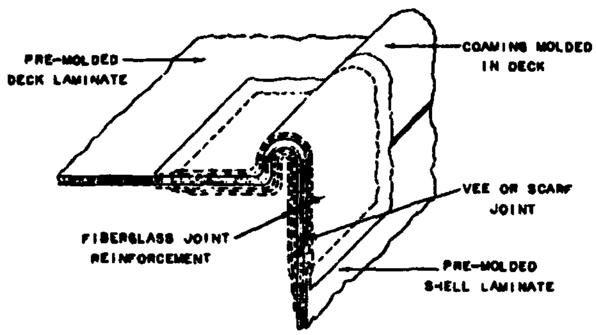


Figure 3-37 Coaming with Joint in Shell [Gibbs and Cox, *Marine Design Manual for FRP*]

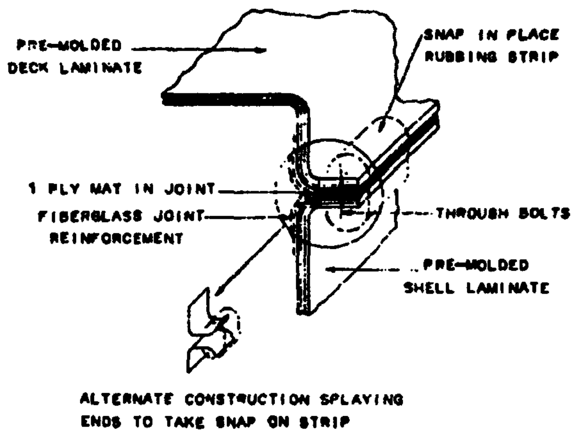


Figure 3-38 Small Boat Type with Snap in Place Rubbing Strip [Gibbs and Cox, *Marine Design Manual for FRP*]

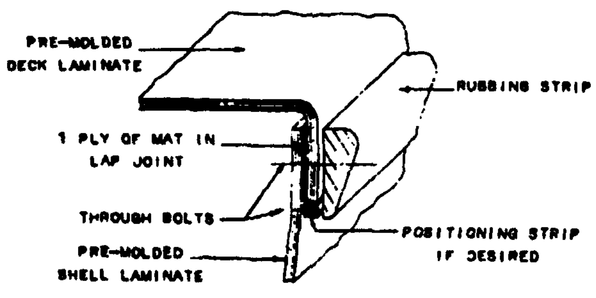


Figure 3-39 Combining Bonding & Mechanical Fastening [Gibbs and Cox, *Marine Design Manual for FRP*]

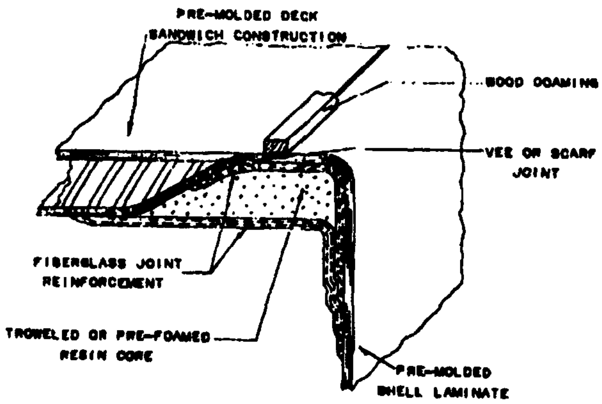


Figure 3-40 Sandwich Deck with Wood Coaming and Joint in Deck [Gibbs and Cox, *Marine Design Manual for FRP*]

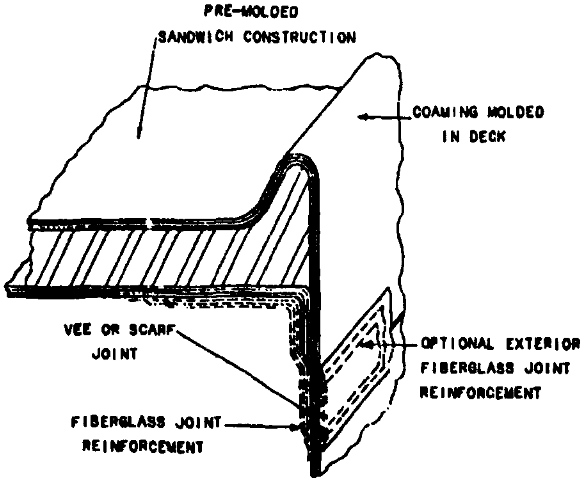


Figure 3-41 Sandwich Deck with Molded-In Coaming and Joint in Shell [Gibbs and Cox, *Marine Design Manual for FRP*]

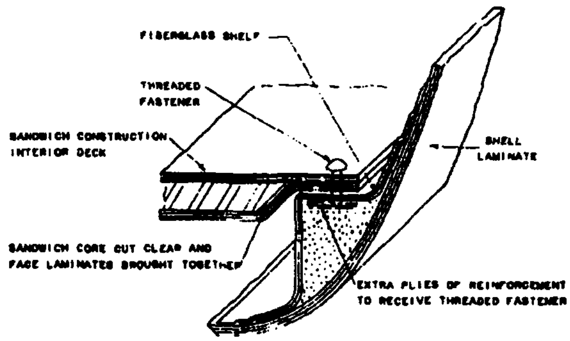


Figure 3-42 Interior Deck to Shell [Gibbs and Cox, *Marine Design Manual for FRP*]

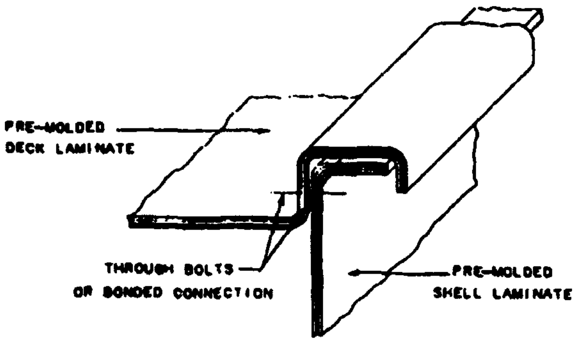


Figure 3-43 Simple Molded-In Coaming with Mechanical Fastenings [Gibbs and Cox, *Marine Design Manual for FRP*]

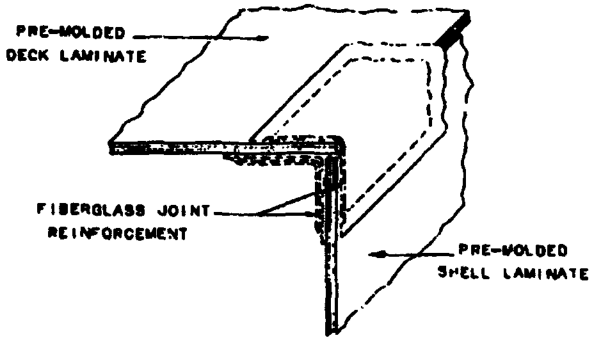


Figure 3-44 Deck Edge Connection - Simple Butt Joint [Gibbs and Cox, *Marine Design Manual for FRP*]

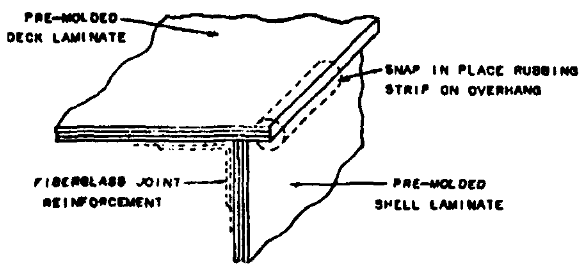


Figure 3-45 Modified Butt Joint with Overhang for Snap In Place Rubbing Strip [Gibbs and Cox, *Marine Design Manual for FRP*]

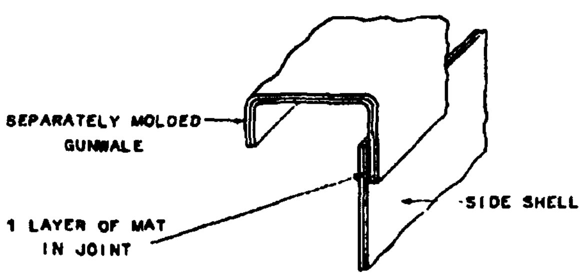


Figure 3-46 Seperately Molded Fiberglass Gunwale [Gibbs and Cox, *Marine Design Manual for FRP*]

Each builder develops their own method for deck edge connection that suits their particular needs. In lieu of specifying one particular configuration, Gibbs & Cox [3-13] offered the following guidelines that have relevance today:

- A joint should develop maximum efficiency or the full strength of the weaker of the two pieces being joined.
- A joint must be easy to fabricate to ensure quality control in areas not easily accessed for inspection.
- A joint should be compatible with molding methods used and consistent with overall hull fabrication requirements.
- Exterior reinforcement is essential to resist loads normal to the side shell and deck.
- Exposed edges, if unavoidable, should always be sealed to prevent delamination.

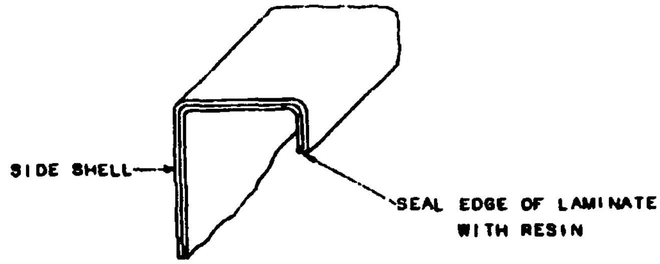


Figure 3-47 Integrally Molded Gunwale [Gibbs and Cox, *Marine Design Manual for FRP*]

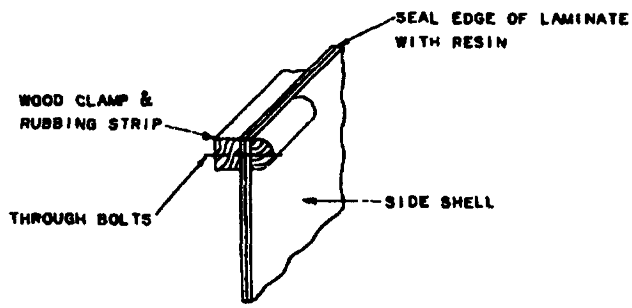


Figure 3-48 Wood Gunwale [Gibbs and Cox, *Marine Design Manual for FRP*]

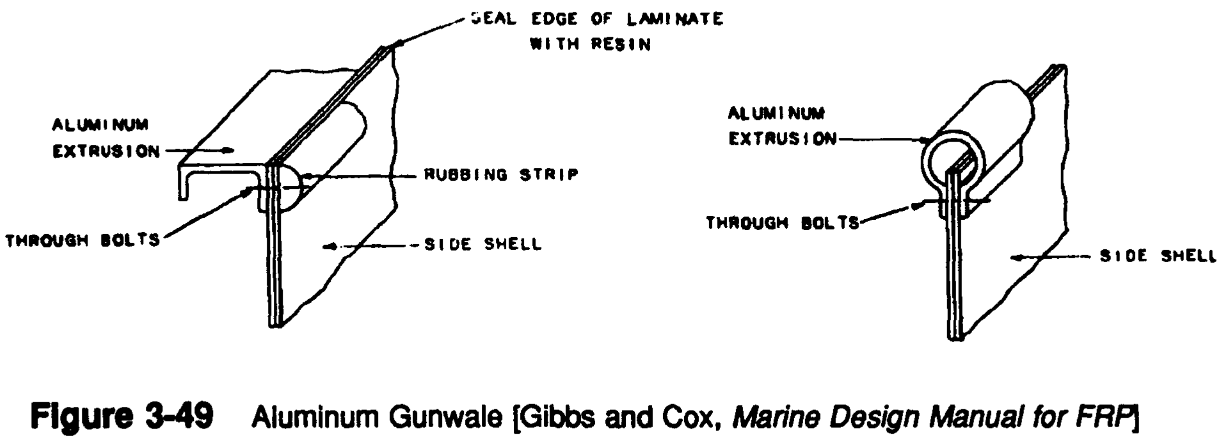


Figure 3-49 Aluminum Gunwale [Gibbs and Cox, *Marine Design Manual for FRP*]

Centerline Joints

To facilitate hand layup fabrication, some builders produce hulls from separate female molds for each side of the hull. This enables the laminators to work on a more horizontal surface. When such a technique is used, some form of butt joint must be utilized to join the two hull halves. This highly stressed portion of the hull must be fabricated with care, especially since secondary bonding is involved. Builders rarely skimp on material since this joint is low in the vessel where weight is desirable. In addition to adequate strength and good adhesion, the joining laminate should include sufficient mat reinforcements to create a superior water permeation barrier. Figures 3-50 through 3-52 show typical connection configurations for various size boats. Figure 3-53 shows a typical centerboard trunk that may be found in a small sailboat. As will be shown for bulkheads, the connection illustrated in Figure 3-53 could be improved with the addition of a radiused fillet. Figure 3-55 is a detail sketch for recommended butt joining techniques with single skin laminates.

Keel Attachment

Externally mounted ballasted keels for sailboats have traditionally been fastened to a matching FRP stub as pictured in Figure 3-54. This technique may still be valid for a few cruising type designs that sport such a fat-sectioned keel. However, performance sailboats since the 1970's have had much higher aspect ratio keels with very fine root sections.

The current go-fast theory has led to keels where the root section is thinnest at the top and meets the hull at a clean right-angle when viewed in transverse section. Needless to say, these high lift keels produce tremendous moments at the faying region that, at times, is only two to three inches wide. ABS provides good guidance [3-5] for the selection and arrangement of keel bolts associated with externally mounted fin keels. Adequate solid FRP skin thickness and internal transverse structure must be

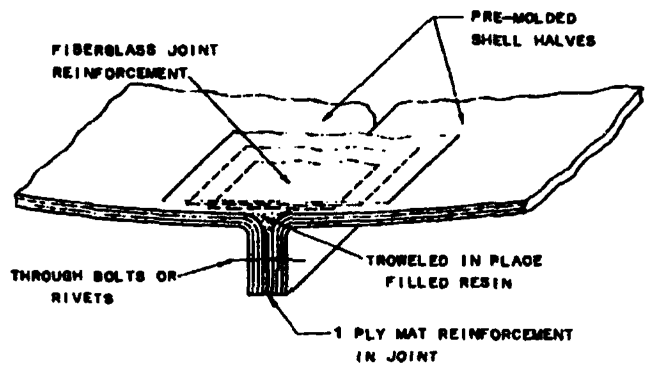


Figure 3-50 Connection of Shell Halves - Centerline Skeg [Gibbs and Cox, *Marine Design Manual for FRP*]

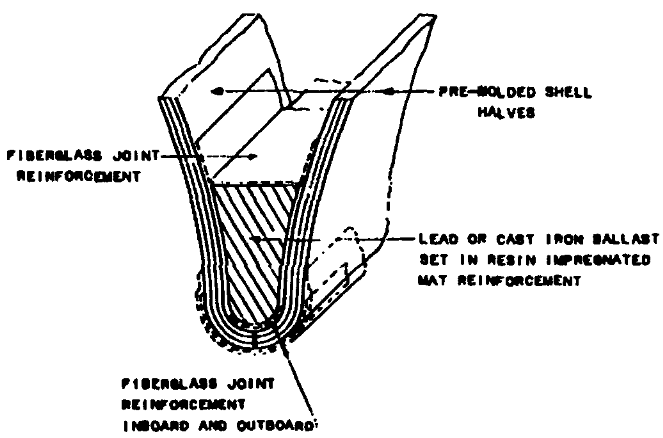


Figure 3-51 Connection of Shell Halves - Cruising Sailboat with Ballast [Gibbs and Cox, *Marine Design Manual for FRP*]

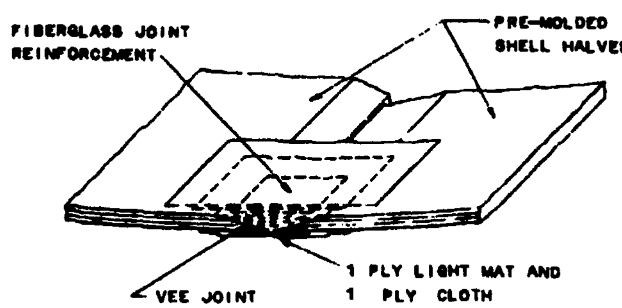


Figure 3-52 Connection of Shell Halves - Small Boats Only [Gibbs and Cox, *Marine Design Manual for FRP*]

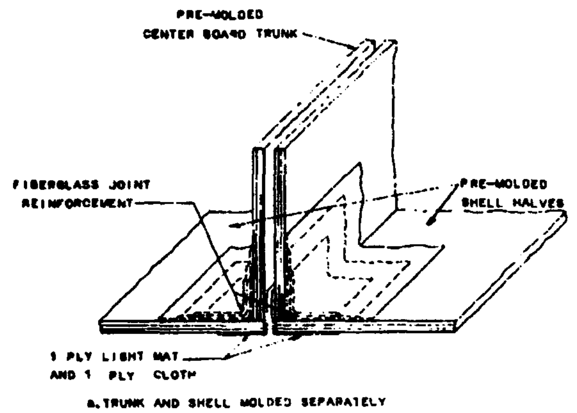


Figure 3-53 Connection of Shell and Centerboard Trunk [Gibbs and Cox, *Marine Design Manual for FRP*]

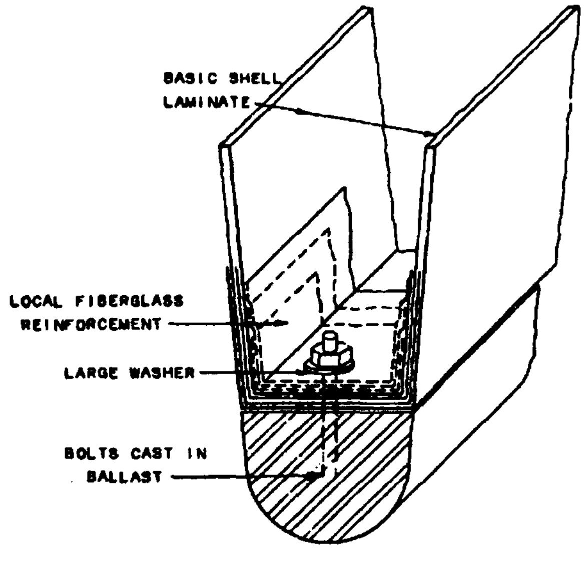


Figure 3-54 Ballast to Hull Connection [Gibbs and Cox, *Marine Design Manual for FRP*]

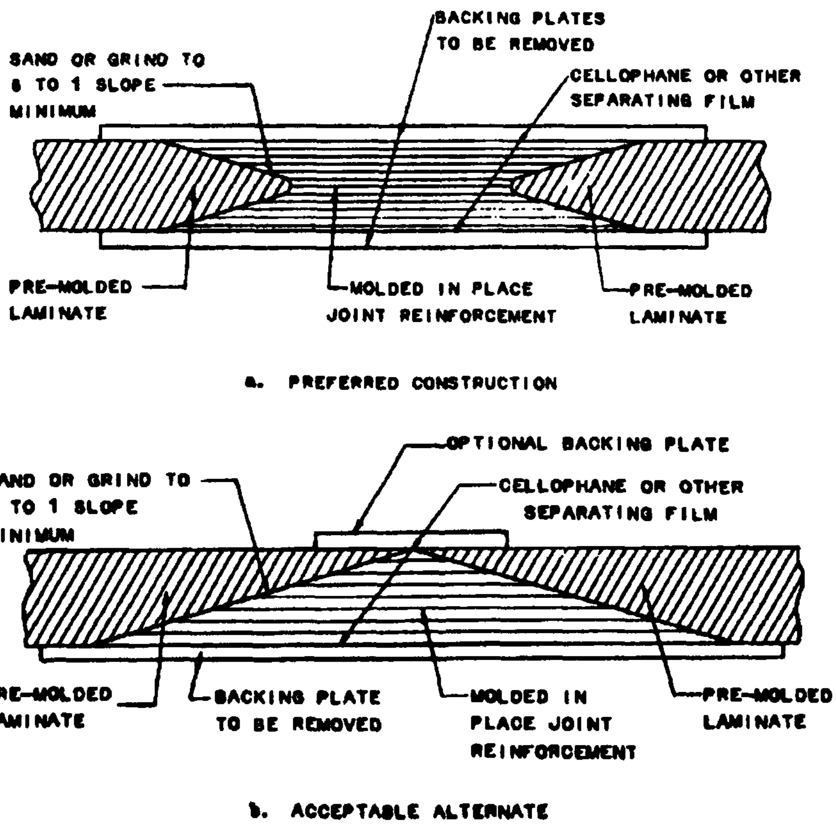


Figure 3-55 Butt Joints [Gibbs and Cox, *Marine Design Manual for FRP*]

provided to support hydrodynamic lift and grounding forces that are transmitted through the bolts. Installation of propeller struts, especially single foil types popular on sailboats and some powerboats, should be treated with similar caution as shaft or propeller imbalance, as well as lateral shaft resonances, can create large alternating moments.

Bulkheads

The scantling for actual bulkheads are usually determined from regulatory body requirements or first principals covering flooding loads and in-plane deck compression loads. Design principals developed for hull panels are also relevant for determining required bulkhead strength. Of interest in this section is the connection of bulkheads or other panel stiffeners that are normal to the hull surface. In addition to the joint strength, the strength of the bulkhead and the hull in the immediate area of the joint must be considered. Other design considerations include:

- Some method to avoid creation of a "hard" spot should be used
- Stiffness of joint should be consistent with local hull panel
- Avoid laminating of sharp, 90° corners
- Geometry should be compatible with fabrication capabilities
- Cutouts should not leave bulkhead core material exposed

An acceptable configuration for use with solid FRP hulls is shown in Figure 3-56. As a general rule, tape-in material should be at least 2 inches along each leg; have a thickness half of the solid side shell; taper for a length equal to at least three times the tape-in thickness; and include some sort of fillet material. Figure 3-57 shows an example of elastomeric support under the bulkhead in conjunction with a hull of sandwich construction. Double bias knitted tapes with or without a mat backing are excellent choices for tape-in material. With primary reinforcement oriented at ± 45°, all fiberglass adds to the strength of the joint, while at the same time affording more flexibility. Figure 3-58 shows a comparison between double-bias tape-in versus conventional woven roving tape-in.

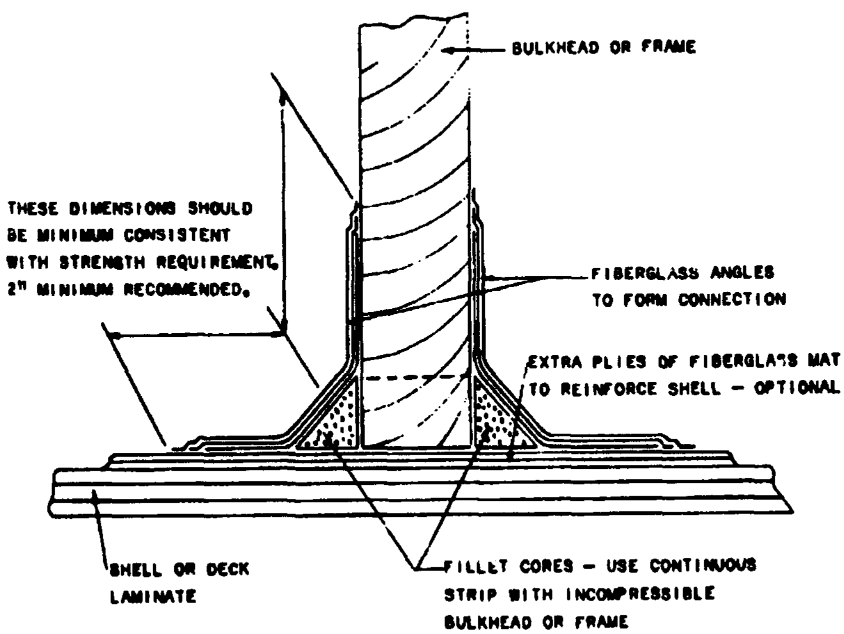


Figure 3-56 Connection of Bulkheads and Framing to Shell or Deck [Gibbs and Cox, *Marine Design Manual for FRP*]

Stiffeners

Stiffeners in FRP construction can either be longitudinal or transverse and usually have a non-structural core that serves as a form. In general, continuity of longitudinal members should be maintained with appropriate cut-outs in transverse members. These intersections should be completely bonded on both the fore and aft side of the transverse member with a schedule similar to that used for bonding to the hull.

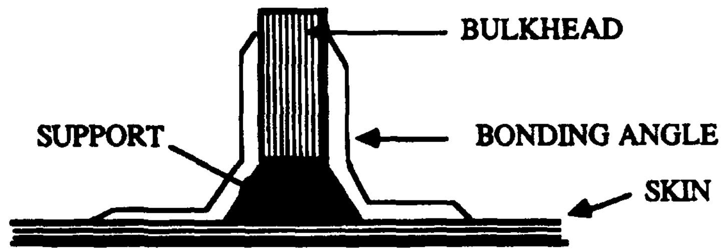


Figure 3-57 Elastomeric Bulkhead Attatchment [USCG NVIC No. 8-87]

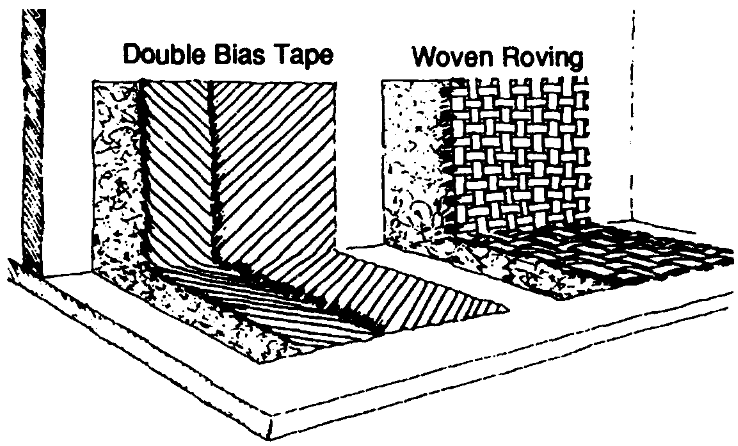


Figure 3-58 Double Bias and Woven Roving Bulkhead Tape-In [Knytex]

Traditional FRP design philosophy produced stiffeners that were very narrow and deep to take advantage of the increased section modulus and stiffness produced by this geometry. The current trend with high-performance vehicles is toward shallower, wider stiffeners that reduce effective panel width and minimize stress concentrations. Figure 3-59 shows how panel span can be reduced with a low aspect ratio stiffener. Some builders are investigating techniques to integrally mold in stiffeners along with the hull's primary inner skin, thus eliminating secondary bonding problems altogether.

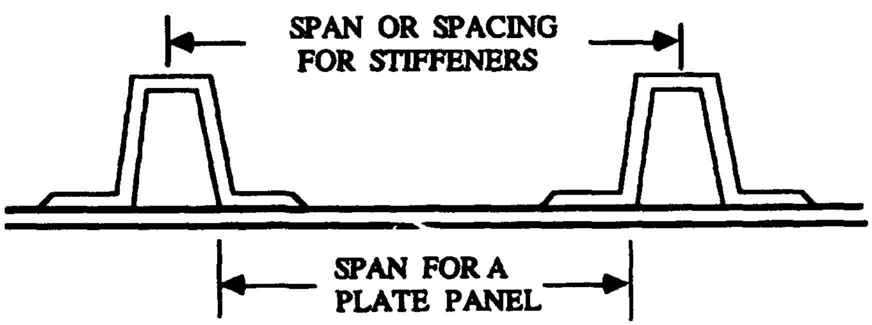


Figure 3-59 Illustration of Reference Stiffener Span Dimensions [USCG NVIC No. 8-87]

Regulatory agencies, such as ABS, typically specify stiffener scantlings in terms of required section moduli and moments of inertia. [Ref: 3-5, 3-6, 3-24] Examples of a single skin FRP stiffener and a high-strength material stiffener with a cored panel are presented along with sample property calculations to illustrate the design process. These examples are taken from USCG NVIC No. 8-87. [3-24]

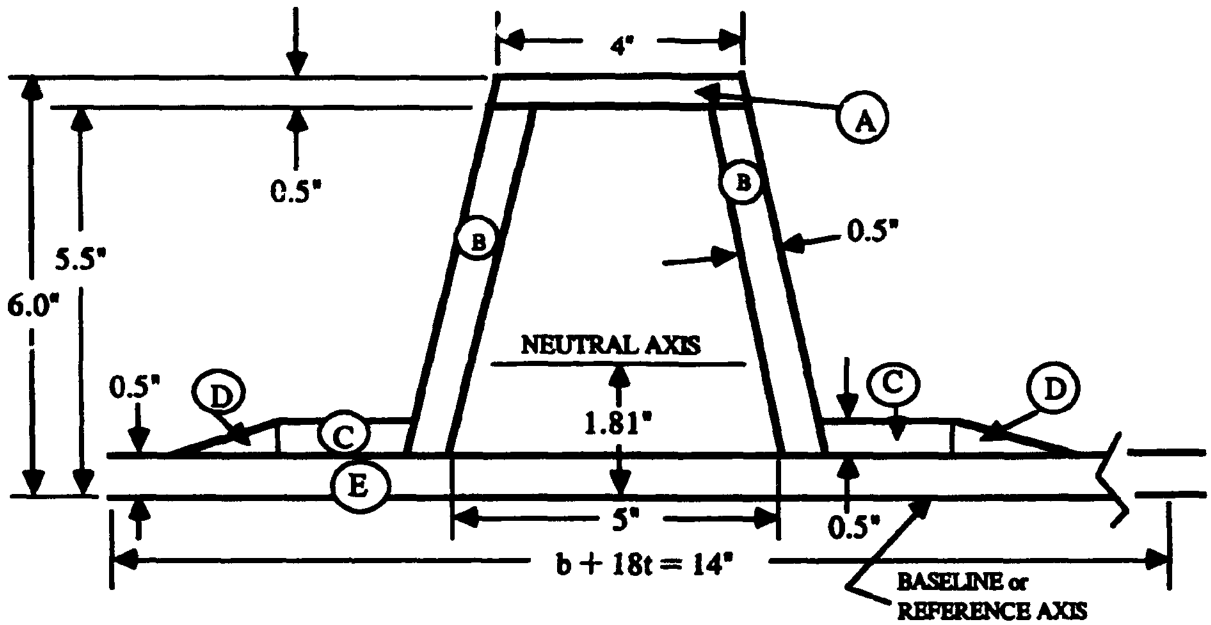


Figure 3-60 Stringer Geometry for Single Skin Construction [USCG NVIC No. 8-87]

Table 3-5. Example Calculation for Single Skin Stiffener

Item	b	h	A = b x h	d	Ad	Ad²	I_o
A	4.00	0.50	2.00	5.75	11.50	66.13	0.04
B	0.50	5.10	2.55	3.00	7.65	23.95	5.31
B	0.50	5.10	2.55	3.00	7.65	23.95	5.31
C	2.00	0.50	1.00	0.75	0.75	0.56	0.02
C	2.00	0.50	1.00	0.75	0.75	0.56	0.02
D	3.00	0.50	0.75	0.67	0.50	0.33	0.01
E	14.00	0.50	7.00	0.25	1.75	0.44	0.15
	Totals:		16.85		30.55	115.92	10.86

$$d_{NA} = \frac{\sum Ad}{\sum A} = \frac{30.55}{16.85} = 1.81 \text{ inches}$$

$$I_{NA} = \sum i_o + \sum Ad^2 - [\,Ad^2\,] = 10.86 + 115.92 - [16.85 \text{ x } (1.81)^2] = 71.58 \text{ in}^4$$

$$SM_{top} = \frac{I}{d_{NA\,top}} = \frac{71.58}{4.19} = 30.26 \text{ in}^3$$

$$SM_{bottom} = \frac{I}{d_{NA\,bottom}} = \frac{71.58}{1.81} = 39.55 \text{ in}^3$$

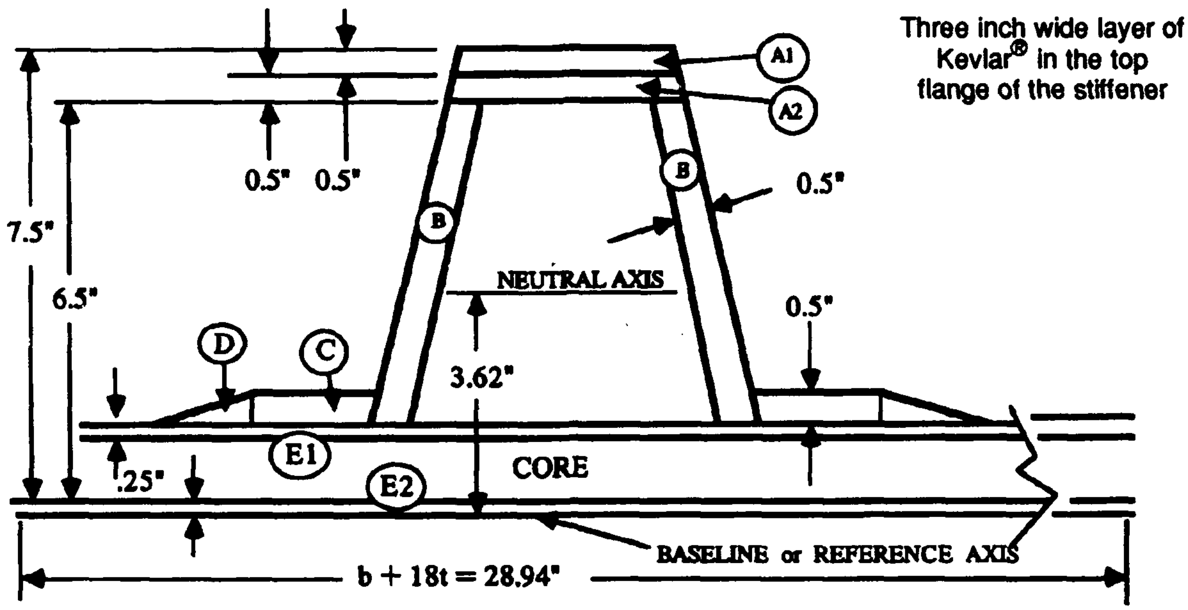


Figure 3-61 Stringer Geometry for Sandwich Construction including High-Strength Reinforcement [USCG NVIC No. 8-87]

Table 3-6. High Strength Stiffener with Sandwich Side Shell

Item	b	h	A = b x h	d	Ad	Ad^2	i_o
A1	3.70	0.50	3.29*	7.25	52.56	381.08	0.039
A2	3.80	0.50	1.90	6.75	12.83	86.57	0.040
B	0.50	5.00	2.50	4.00	10.00	40.00	5.208
B	0.50	5.00	2.50	4.00	10.00	40.00	5.208
C	2.00	0.50	1.00	1.75	1.75	3.06	0.021
C	2.00	0.50	1.00	1.75	0.75	0.56	0.021
D	3.00	0.50	0.75	0.67	0.50	0.33	0.01
E1	28.94	0.25	7.23	1.375	9.95	13.68	0.038
E2	28.94	0.25	7.23	0.125	0.90	0.11	0.038
Totals:			27.40		99.24	565.39	10.620

$$d_{NA} = \frac{\sum Ad}{\sum A} = \frac{30.55}{16.85} = 1.81 \text{ inches}$$

$$I_{NA} = \sum i_o + \sum Ad^2 - [\,Ad^2\,] = 10.86 + 115.92 - [16.85 \times (1.81)^2] = 71.58 \text{ in}^4$$

$$SM_{top} = \frac{I}{d_{NA\,top}} = \frac{71.58}{4.19} = 30.26 \text{ in}^3$$

$$SM_{bottom} = \frac{I}{d_{NA\,bottom}} = \frac{71.58}{1.81} = 39.55 \text{ in}^3$$

- SYMBOLS:
  - b = width or horizontal dimension
  - h = height or vertical dimension
  - d = height to center of A from reference axis
  - NA = neutral axis
  - i_o = item moment of inertia = $bh^3/12$
  - d_{NA} = distance from reference axis to real NA
  - I_{NA} = moment of inertia of stiffener and plate about the real neutral axis
- The assumed neutral axis is at the outer shell so all distances are positive.
- Note how the stiffened plate is divided into discreet areas and lettered.
- Items B and C have the same effect on section properties and are counted twice.
- Some simplifications were made for the vertical legs of the stiffener, item B. The item i_O was calculated using the equation for the I of an inclined rectangle. Considering the legs as vertical members would be a further simplification.
- Item D is combined from both sides of the required bonding angle taper.
- Ratio of elastic moduli $E = \frac{E_{Kevlar^{®}}}{E_{E-glass}} = \frac{9.8 \text{ msi}}{5.5 \text{ msi}}$
- * Effective area of Kevlar® compared to the E-glass = 3.7 x 0.5 x 1.78 = 3.29
- The overall required section modulus for this example must also reflect the mixed materials calculated as a modifier to the required section modulus:

$$SM_{Kevlar^{®}} = SM_{E\text{-}glass} \times \frac{E_{Kevlar^{®}}}{E_{E\text{-}glass}} \times \frac{Ultimate\ Strength_{E\text{-}glass}}{Ultimate\ Strength_{Kevlar^{®}}}$$

$$\frac{E_{Kevlar^{®}}}{E_{E\text{-}glass}} \times \frac{Ultimate\ Strength_{E\text{-}glass}}{Ultimate\ Strength_{Kevlar^{®}}} = \frac{9.8 \text{ msi}}{5.5 \text{ msi}} \times \frac{110 \text{ ksi}}{196 \text{ ksi}} = 1.0$$

Reinforcing fibers of different strengths and different moduli can be limited in the amount of strength that the fibers can develop by the maximum elongation tolerated by the resin and the strain to failure of the surrounding laminate. Therefore, the strength of the overall laminate should be analyzed, and for marginal safety factor designs or arrangements meeting the minimum of a rule, tests of a sample laminate should be conducted to prove the integrity of the design. In this example, the required section modulus was unchanged but the credit for the actual section modulus to meet the rule was significant.

Engine Beds

If properly fabricated, engine beds in FRP vessels can potentially reduce the transmission of machinery vibration to the hull. Any foundation supporting propulsion machinery should be given the same attention afforded the main engine girders.

As a general rule, engine girders should be of sufficient strength, stiffness and stability to ensure proper operation of rotating machinery. Proper bonding to the hull over a large area is essential. Girders should be continuous through transverse frames and terminate with a gradual taper. Laminated timbers have been used as a core material because of excellent damping properties and the ability to hold lag bolt fasteners. Consideration should be given to bedding lag bolts in resin to prevent water egress. Some builders include some metallic stock between the core and the laminate to accept machine screws. If this is done, proper care should be exercised to guarantee that the metal remains bonded to the core. New, high density PVC foam cores offer an attractive alternative that eliminates the concern over future wood decay. Figures 3-62 through 3-64 show some typical engine mounting configurations.

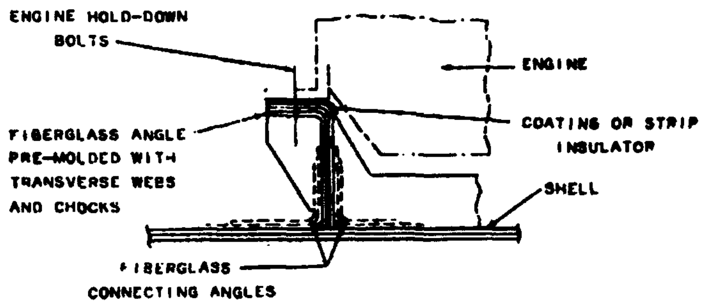


Figure 3-62 Engine Bearer - Pre-Molded Fiberglass Angle Bonded to Shell [Gibbs and Cox, *Marine Design Manual for FRP*]

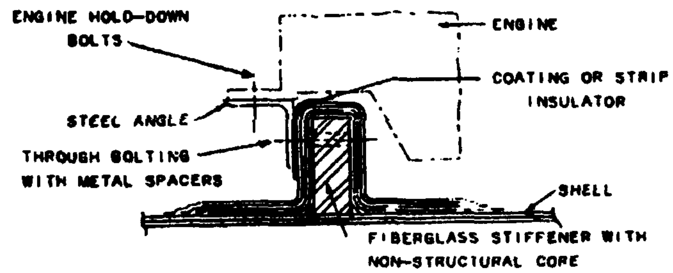


Figure 3-63 Engine Bearer - Steel Angle Bolted to Hat Stiffener [Gibbs and Cox, *Marine Design Manual for FRP*]

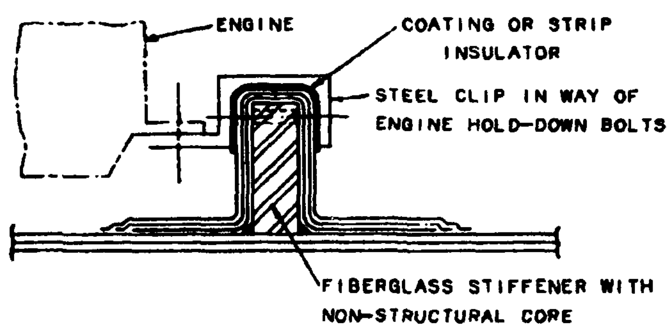


Figure 3-64 Engine Bearer - Steel Clip Bolted to Hat Stiffener [Gibbs and Cox, *Marine Design Manual for FRP*]

Hardware

Through-bolts are always more desirable than self-tapping fasteners. Hardware installations in single skin laminates is fairly straightforward. Backing plates of aluminum or stainless steel are always preferable over simple washers. If using only oversized washers, the local thickness should be increased by at least 25%. [3-25] The strength of hardware installations should be consistent with the combined load on a particular piece of hardware. In addition to shear and normal loads, applied moments with tall hardware must be considered. Winches that are mounted on pedestals are examples of hardware that produce large overturning moments.

Hardware installation in cored construction requires a little more planning and effort. Low density cores have very poor holding power with screws and tend to compress under the load of bolts. Some builders simply taper the laminate to a solid thickness in way of planned hardware installations. This technique has the drawback of generally reducing the section modulus of the deck unless a lot of solid glass is used. A more efficient approach involves the insertion of a higher density core in way of planned hardware. In the past, the material of choice was plywood, but high density PVC foam will provide superior adhesion. Figure 3-65 illustrates this technique.

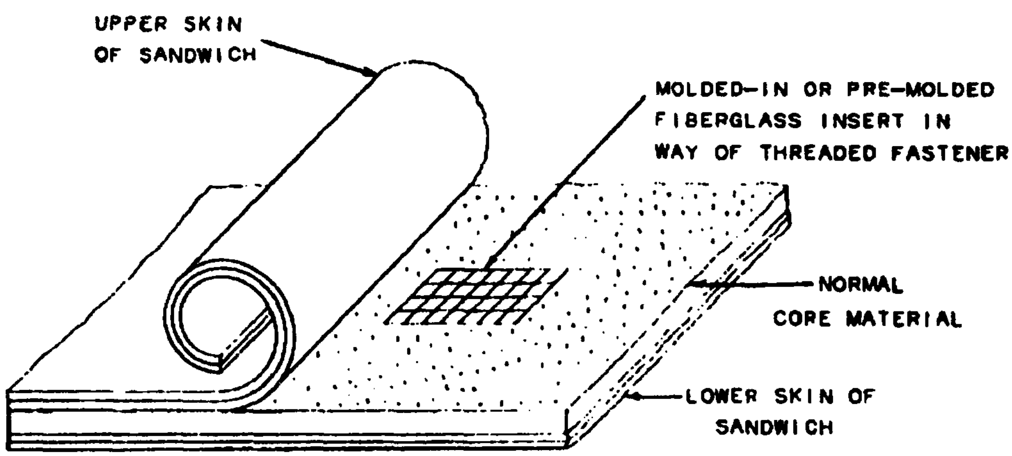


Figure 3-65 Fiberglass Insert for Threaded or Bolted Fasteners in Sandwich Construction [Gibbs and Cox, *Marine Design Manual for FRP*]

Hardware must often be located and mounted after the primary laminate is complete. To eliminate the possibility of core crushing, a compression tube as illustrated in Figure 3-66 should be inserted.

Non-essential hardware and trim, especially on small boats, is often mounted with screw fasteners. Table 3-7 is reproduced to provide some guidance in determining the potential holding force of these fasteners. This table is suitable for use with mat and woven roving type laminate with tensile strength between 6 and 25 ksi; compressive strength between 10 and 22 ksi; and shear strength between 10 and 13 ksi.

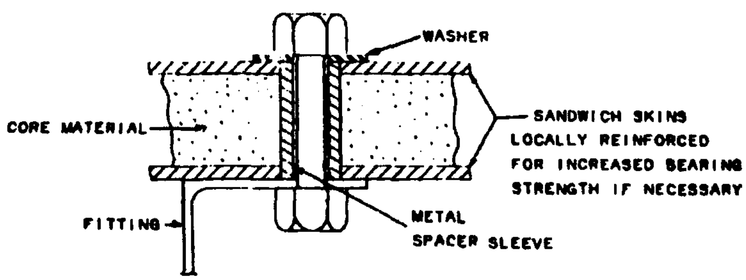


Figure 3-66 Through Bolting in Sandwich Construction [Gibbs and Cox, *Marine Design Manual for FRP*]

Table 3-7. Holding Forces of Fasteners in Mat/Polyester Laminates [Gibbs and Cox, *Marine Design Manual for FRP*]

Thread Size	Axial Holding Force				Lateral Holding Force			
	Minimum		Maximum		Minimum		Maximum	
	Depth (ins)	Force (lbs)	Depth (ins)	Force (lbs)	Depth (ins)	Force (lbs)	Depth (ins)	Force (lbs)
Machine Screws								
4 - 40	.125	40	.3125	450	.0625	150	.125	290
6 - 32	.125	60	.375	600	.0625	180	.125	380
8 - 32	.125	100	.4375	1150	.0625	220	.1875	750
10 - 32	.125	150	.5	1500	.125	560	.25	1350
1/4 - 20	.1875	300	.625	2300	.1875	1300	.3125	1900
5/16 - 18	.1875	400	.75	3600	.1875	1600	.4375	2900
3/8 - 16	.25	530	.875	5000	.25	2600	.625	4000
7/16 - 14	.25	580	1.0	6500	.3125	3800	.75	5000
1/2 - 13	.25	620	1.125	8300	.375	5500	.875	6000
9/16 - 12	.25	650	1.25	10000	.4375	6500	.9375	8000
5/8 - 11	.25	680	1.375	12000	.4375	6800	1.0	11000
3/4 - 10	.25	700	1.5	13500	.4375	7000	1.0625	17000
Self Tapping Thread Cutting Screws								
4 - 40	.125	80	.4375	900	.125	250	.1875	410
6 - 32	.125	100	.4375	1100	.125	300	.25	700
8 - 32	.25	350	.75	2300	.1875	580	.375	1300
10 - 32	.25	400	.75	2500	.1875	720	.4375	1750
1/4 - 20	.375	600	1.0625	4100	.25	1600	.625	3200
Self Tapping Thread Forming Screws								
4 - 24	.125	50	.375	500	.125	220	.1875	500
6 - 20	.1875	110	.625	850	.125	250	.25	600
8 - 18	.25	180	.8125	1200	.1875	380	.3125	850
10 - 16	.25	220	.9375	2100	.25	600	.5	1500
14 - 14	.3125	360	1.0625	3200	.25	900	.6875	2800
5/16 - 18	.375	570	1.125	4500	.3125	1800	.8125	4400
3/8 - 12	.375	700	1.125	5500	.375	3600	1.0	6800

Thickness Transition

FRP construction gives the designer the freedom to tailor skin thicknesses very precisely. The efficiency of cored structures in resisting normal loads makes this type of construction popular. These two advantages of FRP construction can lead to stress concentrations if thickness variations are not adequately tapered. Figure 3-67 illustrates a recommended taper equal to three times the core thickness. When tapering from a cored laminate to a solid area, consideration should be given to the reduced section modulus that will occur without additional reinforcement material.

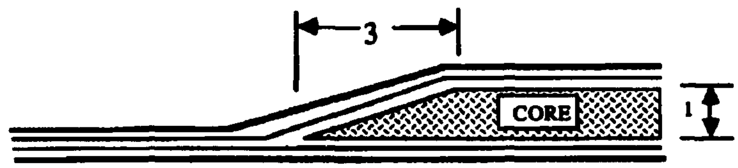


Figure 3-67 Recommended Core Taper for Transition to Single-Skin [USCG NVIC No. 8-87]

Hatches and Portlights

Stress concentrations around deck and hull openings are a problem with metal as well as FRP hulls. Ship designers are acutely aware of this problem when designing containerships with large hatch covers. The designer is expected to make allowances for the loss of longitudinal and torsional strength. Corners of openings should be radiused to relieve undue stress concentrations.

Openings in smaller craft are usually cut as the vessel nears completion. In the case of FRP constructed vessels, reinforcement fibers can be cut in a fashion that causes excessive deterioration of global strengths. Just as additional framing is usually added around an opening in a metal ship, perimeter reinforcement is required with FRP. Restoration of reinforcement in the direction that was severed is a primary goal. Unidirectional and bi-axial tapes are useful materials for local reinforcement.

Care should always be exercised in the planning phases of a deck layout, especially when high performance laminates are utilized. At a recent conference, a naval architect recounted a story of how a deck on a racing sailboat collapsed just aft of the deck partners after a pair of compasses were flush mounted. The point was made that the scantlings should not have been so marginal as to fail when two simple four inch diameter holes were drilled. It was also noted that such a modification to the deck is actually quite extreme when the amount of unidirectional fiber that was severed is considered.

Through-Hulls

Through-hull fittings represent a special case of hull opening in that they are usually located below the waterline. These fittings must exhibit the highest degree of both watertight and structural integrity. Nonmetallic fittings are gaining popularity because of their noncorrosive and inert electrical properties. Any fitting will have a flat flange and a similar mating surface should be molded or machined into the hull.

With single skin laminates, holes are normally drilled after the hull is completed. Careful attention must be paid toward the sealing of the laminate edges after the hole is drilled. Bedding and installation of the fitting is accomplished with the accompanying hardware.

Through-hull fittings in sandwich can be installed a number of ways. One involves the taper to a solid section with installation as per above. An alternative method uses a high density insert in way of the fitting. Extreme care must be taken to seal the edge of the core and potting is usually suggested. Potting is similar to encapsulating, except that steps are taken to insure complete penetration of all the voids before the resin catalyzes. The high density core can also be installed by drilling an oversize hole and laminating it in place.

Shroud Attachment

Loads at shroud and stay chainplates can be very great, especially with tall rigs. High-performance racing sailboats typically have very narrow spreader and shroud base dimensions to improve closewindedness. Extreme tensile and deck compressive loads are thus created. As a design starting point, the breaking strength of all shrouds and stays combined through vector addition should be considered. Figure 3-68 shows an installation for a cruising type sailboat where the chainplates may be mounted to the shell plating. More often than not, chainplates are located further inboard than this. Nevertheless, installation details remain similar if tying into a bulkhead or longitudinal frame.

Local reinforcement of the panel should extend both fore and aft of the mast a good distance. An effective insert capable of resisting bolt compression and shear loads should be present. Secondary stabilizing structure as well as deck strengthening in way of the mast partners are required. Bolted connections through FRP should not load the material for greater than about 20% of its ultimate strength if creep is to be avoided.

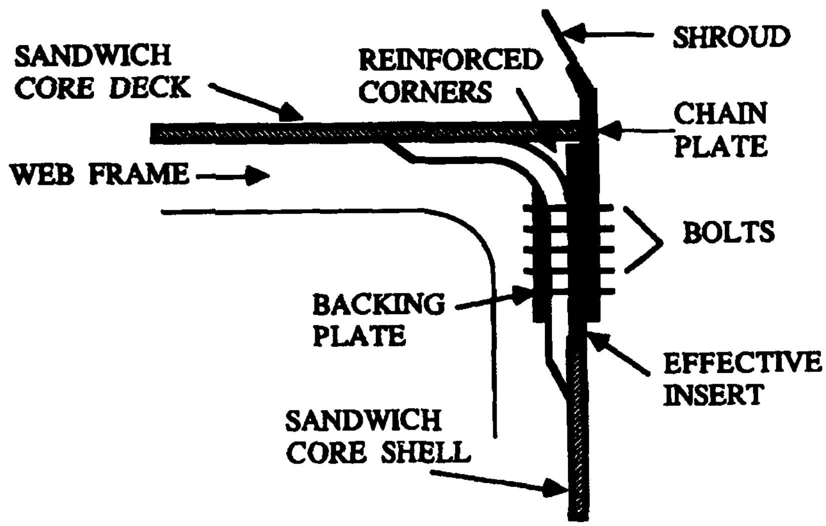


Figure 3-68 Typical Shroud Attatchment to Side Shell with Sandwich Construction [USCG NVIC No. 8-87]

Rudders

Rudders and supporting structure represent one of the most challenging design problems facing a naval architect. High aspect ratio spade rudders are an extreme example. Hydrodynamic performance criteria dictates the use of a rather narrow foil section. The high aspect ratio produces an enormous transverse moment about the lower bearing. The rudder post itself must additionally resist torsional loads and rotate freely. Figure 3-69 is included to illustrate the stress distribution resulting from bending moment and torque.

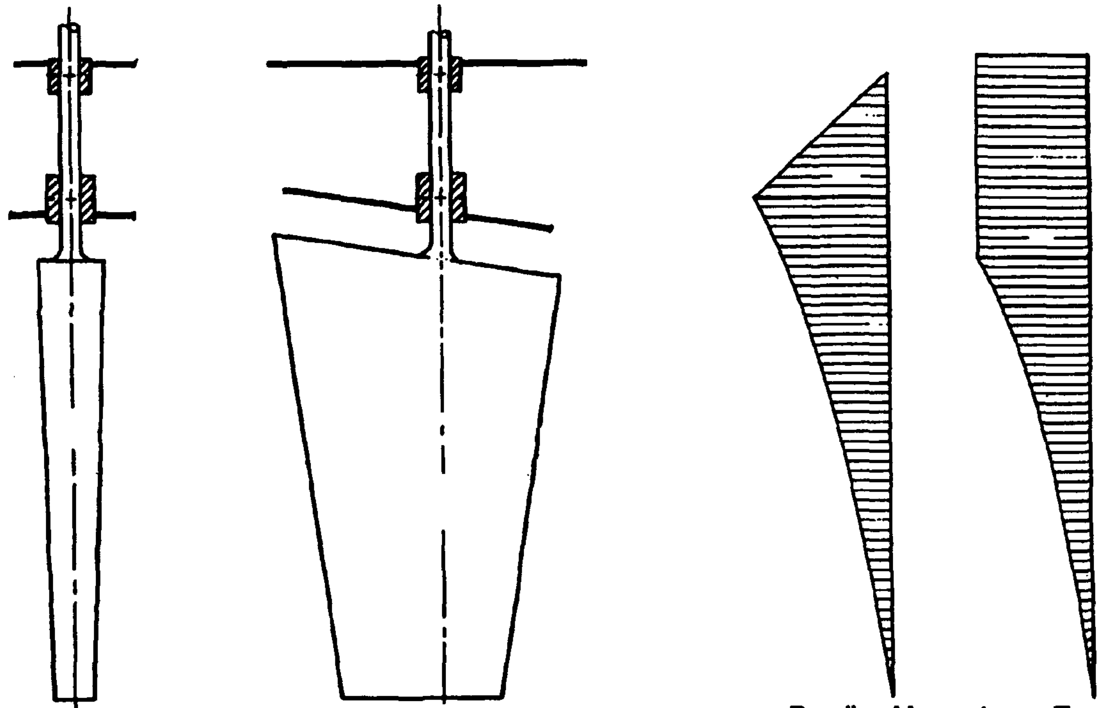


Figure 3-69 Typical Force Distribution within a Spade Rudder [*ABS Guide for Building and Classing Offshore Racing Yachts*]

Rudder weight is usually offset by its buoyancy. The mass, however, still exists and will increase the vessel's radius of gyration. Prudent design practice would strive to maintain a good safety factor for the rudder structure because even minor failures can incapacitate a vessel. The commercial marine industry recognizes this fact, but the competitive yachting market was compelled to experiment with exotic materials such as carbon fiber in the late 1970's. The failure rate in the 1979 Fastnet Race has become one of the most notorious cases of poor composite design and process engineering. Those failures were primarily due to fiber misalignment with principal stresses and manufacturing inconsistencies. More thorough engineering, greater selection of reinforcement configuration and improved manufacturing processes have virtually eliminated failures in exotic lightweight rudder posts.

Bearing foundations within the hull structure must be of sufficient strength to resist the moments transmitted through the bearings. Transverse ring frames are typically included to increase torsional stiffness. ABS rules give good guidance on rudder stock and bearing support.

This page intentionally left blank

Fatigue

A fundamental problem concerning the engineering uses of fiber reinforced plastics (FRP) is the determination of their resistance to combined states of cyclic stress. [4-1] Composite materials exhibit very complex failure mechanisms under static and fatigue loading because of anisotropic characteristics in their strength and stiffness. [4-2] Fatigue causes extensive damage throughout the specimen volume, leading to failure from general degradation of the material instead of a predominant single crack. A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals. There are four basic failure mechanisms in composite materials as a result of fatigue: matrix cracking, delamination, fiber breakage and interfacial debonding. The different failure modes combined with the inherent anisotropies, complex stress fields, and overall non-linear behavior of composites severely limit our ability to understand the true nature of fatigue. [4-3] Figure 4-1 shows a typical comparison of the fatigue damage of composites and metals over time.

Many aspects of tension-tension and tension-compression fatigue loading have been investigated, such as the effects of heat, frequency, pre-stressing samples, flawing samples, and moisture [4-5 through 4-13]. Mixed views exist as to the effects of these parameters on composite laminates, due to the variation of materials, fiber orientations, and stacking sequences, which make each composite behave differently.

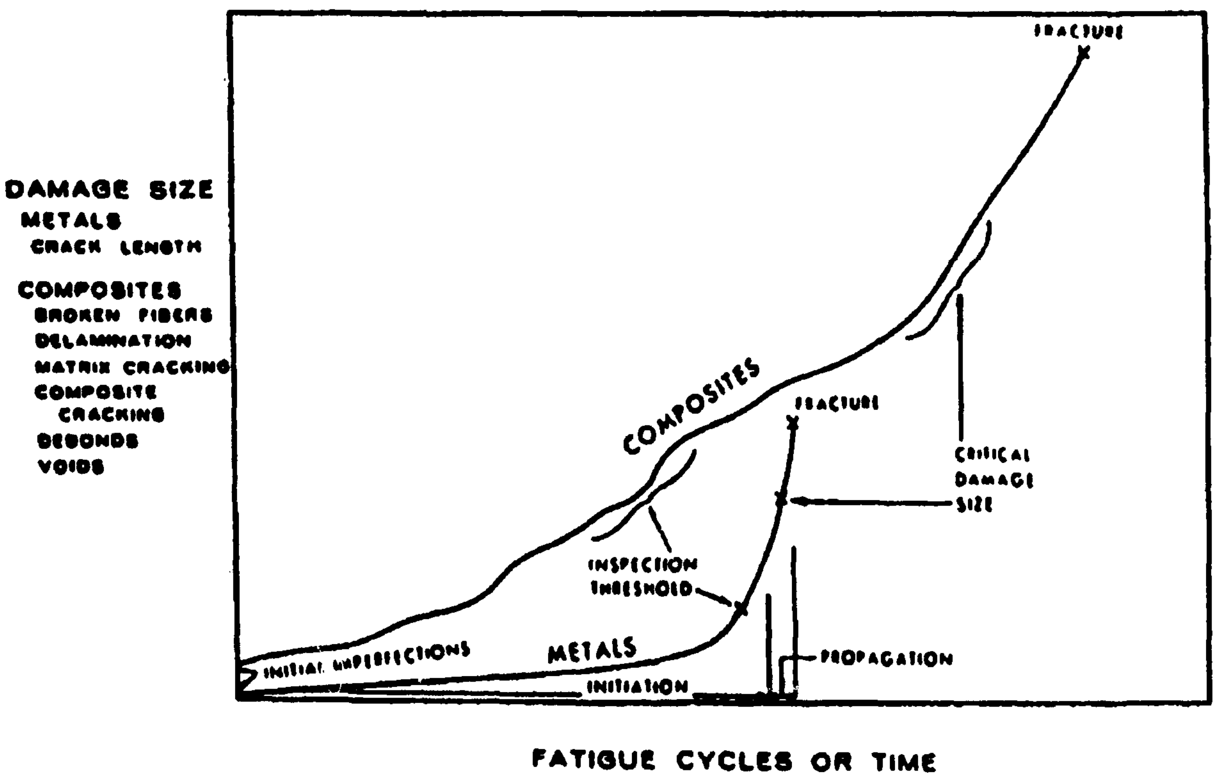


Figure 4-1 Typical Comparison of Metal and Composite Fatigue Damage [Salkind, *Fatigue of Composites*]

Extensive work has been done to establish failure criteria of composites during fatigue loading [4-1, 4-5, 4-14, 4-15]. Fatigue failure can be defined either as a loss of adequate stiffness, or as a loss of adequate strength. There are two approaches to determine fatigue life; constant stress cycling until loss of strength, and constant amplitude cycling until loss of stiffness. The approach to utilize depends on the design requirements for the laminate.

In general, stiffness reduction is an acceptable failure criterion for many components which incorporate composite materials. [4-15] Figure 4-2 shows a typical curve of stiffness reduction for composites and metal. Stiffness change is a precise, easily measured and easily interpreted indicator of damage which can be directly related to microscopic degradation of composite materials. [4-15]

In a constant amplitude deflection loading situation the degradation rate is related to the stress within the composite sample. Initially, a larger load is required to deflect the sample. This corresponds to a higher stress level. As fatiguing continues, less load is required to deflect the sample, hence a lower stress level exists in the sample. As the stress within the sample is reduced, the amount of deterioration in the sample decreases. The reduction in load required to deflect the sample corresponds to a reduction in the stiffness of that sample. Therefore, in constant amplitude fatigue the stiffness reduction is dramatic at first, as substantial matrix degradation occurs, and then quickly tapers off until only small reductions occur.

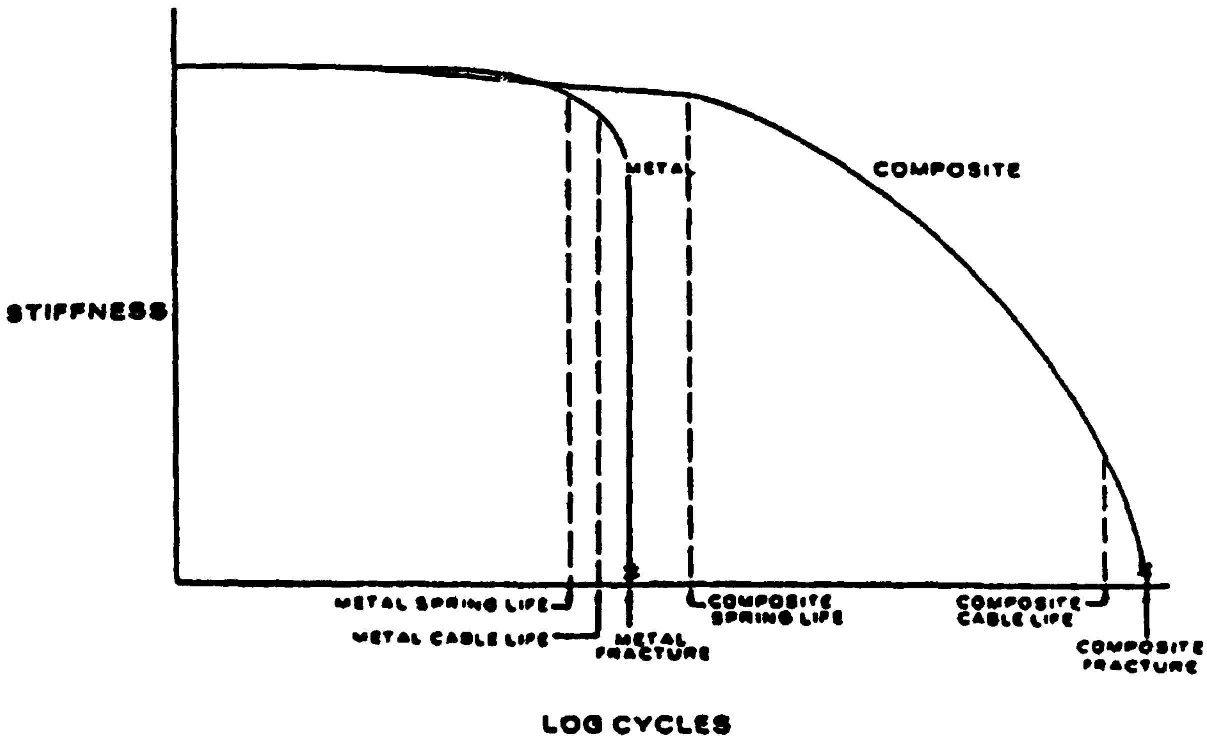


Figure 4-2 Comparison of Metal and Composite Stiffness Reduction [Salkind, *Fatigue of Composites*]

In a unidirectional fiber composite, cracks may occur along the fiber axis, which usually involves matrix cracking. Cracks may also form transverse to the fiber direction, which usually indicates fiber breakage and matrix failure. The accumulation of cracks transverse to fiber direction leads to a reduction of load carrying capacity of the laminate and with further fatigue cycling may lead to a jagged, irregular failure of the composite material. This failure mode is drastically different from the metal fatigue failure mode, which consists of the initiation and propagation of a single crack. [4-1] Hahn [4-16] predicted that cracks in composite materials propagate in four distinct modes. These modes are illustrated in Figure 4-3, where region I corresponds to the fiber and region II corresponds to the matrix.

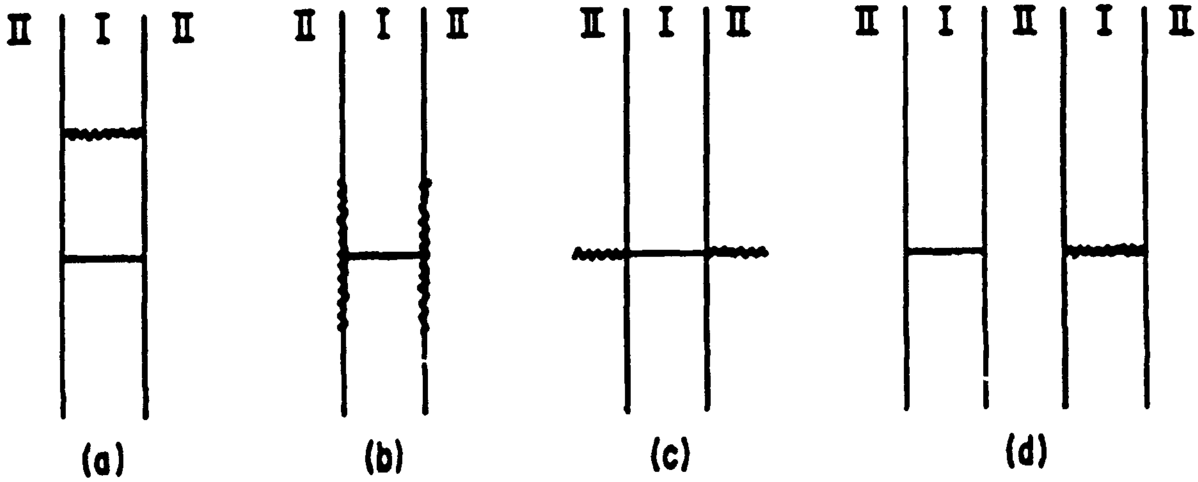


Figure 4-3 Fatigue Failure Modes for Composite Materials - **Mode (a)** represents a tough matrix where the crack is forced to propagate through the fiber. **Mode (b)** occurs when the fiber/matrix interface is weak. This is, in effect, debonding. **Mode (c)** results when the matrix is weak and has relatively little toughness. Finally, **Mode (d)** occurs with a strong fiber/matrix interface and a tough matrix. Here, the stress concentration is large enough to cause a crack to form in a neighboring fiber without cracking of the matrix. **Mode (b)** is not desirable because the laminate acts like a dry fiber bundle and the potential strength of the fibers is not realized. **Mode (c)** is also undesirable because it is similar to crack propagation in brittle materials. The optimum strength is realized in **Mode (a)** as the fiber strengths are fully utilized. [Hahn, *Fatigue of Composites*]

Minor cracks in composite materials may occur suddenly without warning and then propagate at once through the specimen. [4-1] It should be noted that even when many cracks have been formed in the resin, composite materials may still retain respectable strength properties. [4-17] The retention of these strength properties is due to the fact that each fiber in the laminate is a load-carrying member, and once a fiber fails the load is redistributed to another fiber.

Composite Fatigue Theory

There are many theories used to describe the composite material strength and fatigue life. Since no one analytical model can account for all the possible failure processes in a composite material, statistical methods to describe fatigue life have been adopted. Weibull's distribution has proven to be a useful method to describe the material strength and fatigue life. The Weibull distribution is based on three parameters; scale, shape and location. Estimating these parameters is based on one of three methods: the maximum-likelihood estimation method, the moment estimation method, or the standardized variable method. These methods of estimation are discussed in detail in references [4-18, 4-19]. It has been shown that the moment estimation method and the maximum-likelihood method lead to large errors in estimating the scale and the shape parameters, if the location parameter is taken to be zero. The standardized variable estimation gives accurate and more efficient estimates of all three parameters for low shape boundaries. [4-19]

Another method used to describe fatigue behavior is to extend static strength theory to fatigue strength by replacing static strengths with fatigue functions.

The power law has been used to represent fatigue data for metals when high numbers of cycles are involved. By adding another term into the equation for the ratio of oscillatory-to-mean stress, the power law can be applied to composite materials. [4-20]

Algebraic and linear first-order differential equations can also be used to describe the composite fatigue behavior. [4-14]

There are many different theories used to describe fatigue life of composite materials. However, given the broad range of usage and diverse variety of composites in use in the marine industry, theoretical calculations as to the fatigue life of a given composite should only be used as a first-order indicator. Fatigue testing of laminates in an experimental test program is probably the best method of determining the fatigue properties of a candidate laminate. Further testing and development of these theories must be accomplished to enhance their accuracy. Despite the lack of knowledge, empirical data suggest that composite materials perform better than metals in fatigue situations. Figure 4-4 depicts fatigue strength characteristics for some metal and composite materials. [4-21]

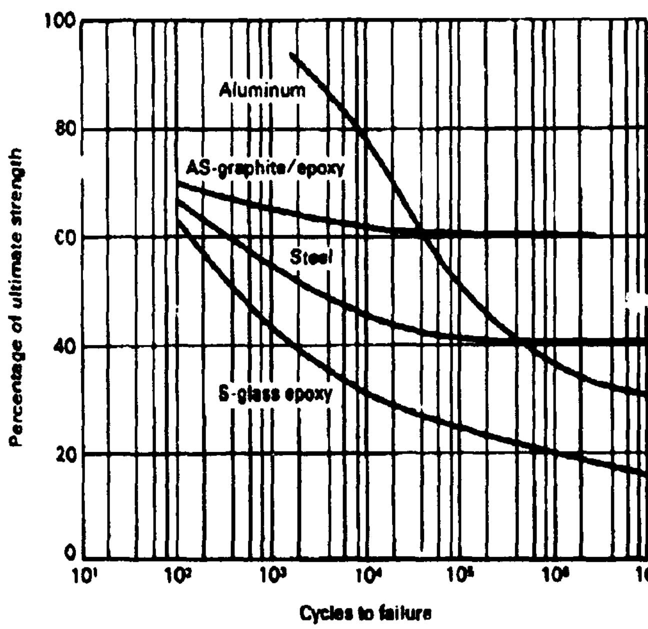


Figure 4-4 Comparison of Fatigue Strengths of Graphite/Epoxy, Steel, Fiberglass/Epoxy and Aluminum [Hercules]

Fatigue Test Data

Although precise predictions of fatigue life expectancies for FRP laminates is currently beyond the state-of-the-art of analytical techniques, some insight into the relative performance of constituent materials can be gained from published test data. The Interplastic Corporation conducted an exhaustive series of fatigue tests on mat/woven roving laminates to compare various polyester and vinyl ester resin formulations. [4-22] The conclusion of those tests is show in Figure 4-5 and is summarized as follows:

> "Cyclic flexural testing of specific polyester resin types resulted in predictable data that oriented themselves by polymer description, i.e., orthophthalic was exceeded by isophthalic, and both were vastly exceeded by vinyl ester type resins. Little difference was observed between the standard vinyl ester and the new preaccelerated thixotropic vinyl esters."

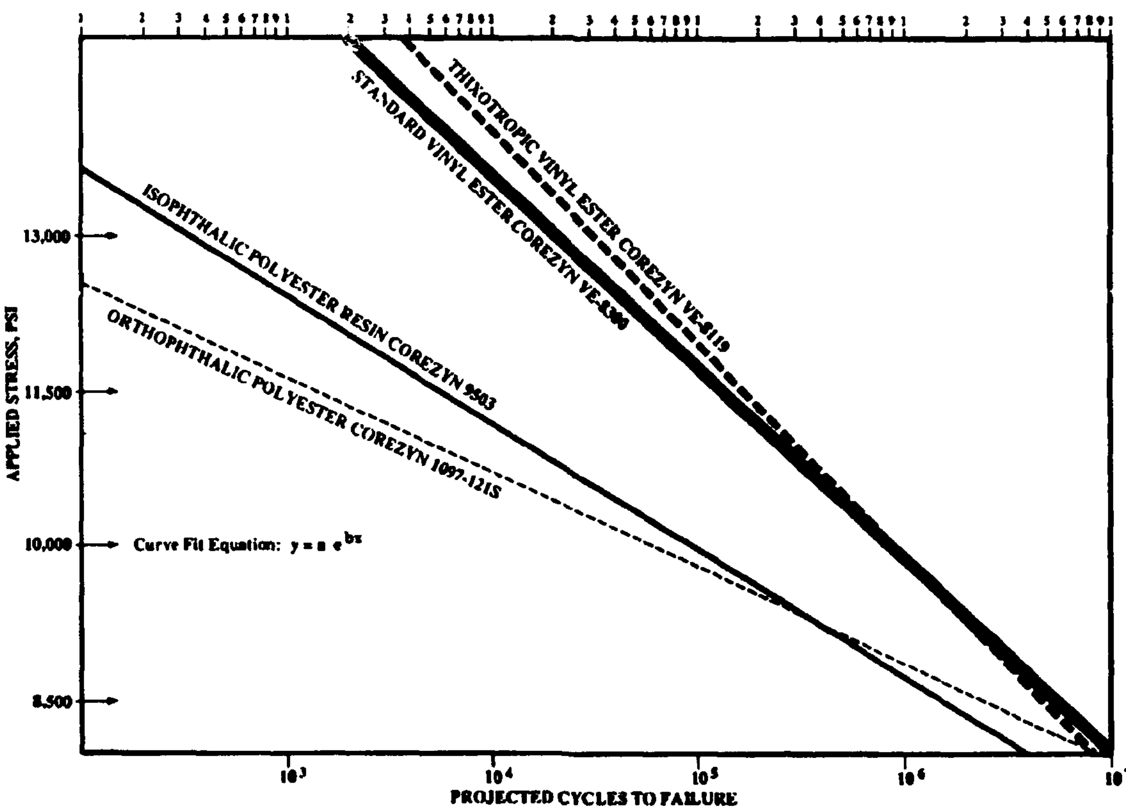


Figure 4-5 Curve Fit of ASTM D671 Data for Various Types of Unsaturated Polyester Resins [Interplastic, *Cycle Test Evaluation of Various Polyester Types and a Mathematical Model for Predicting Flexural Fatigue Endurance*]

With regards to reinforcement materials used in marine laminates, there is not a lot of comparative test data available to illustrate fatigue characteristics. It should be noted that fatigue performance is very dependent on the fiber/resin interface performance. Tests by various investigators [4-23] suggest that a ranking of materials from best to worst would look like:

- High Modulus Carbon Fiber
- High Strength and Low Modulus Carbon
- Kevlar/Carbon Hybrid
- Kevlar
- Glass/Kevlar Hybrid
- S-Glass
- E-Glass

The construction and orientation of the reinforcement also plays a critical role in determining fatigue performance. It is generally perceived that larger quantities of thinner plies perform better than a few layers of thick plies. Figure 4-23 shows a comparison of various fabric constructions with regard to fatigue performance.

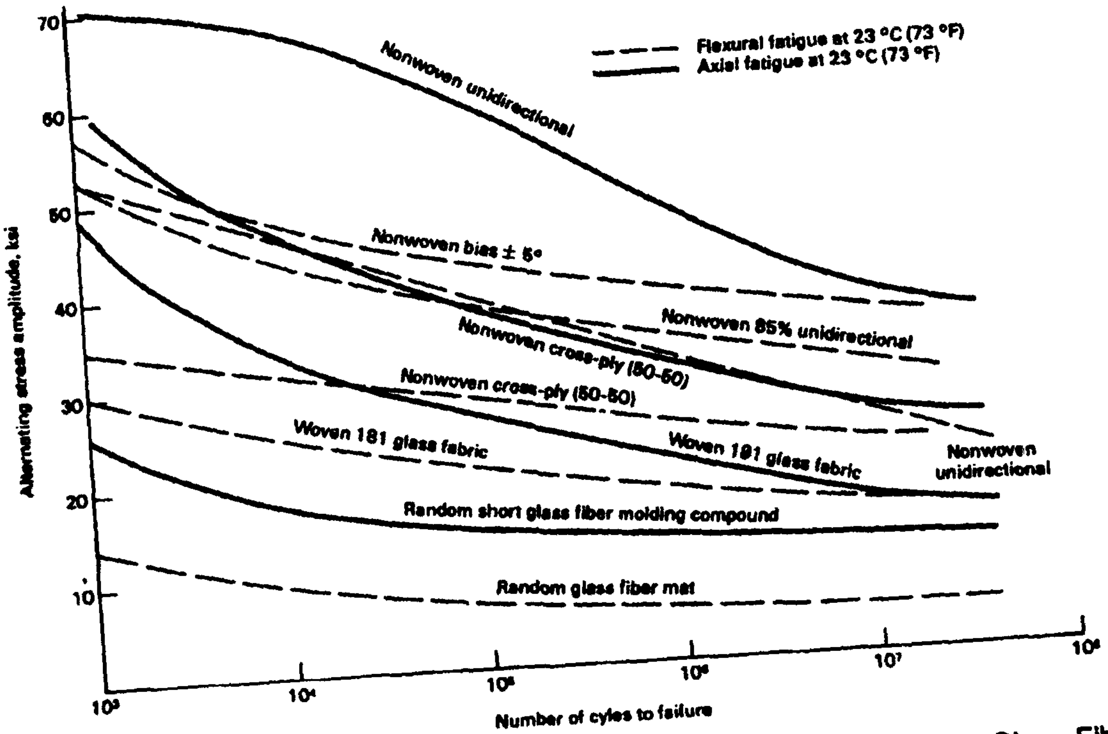


Figure 4-6 Comparitive Fatigue Strengths of Nonwoven Unidirectional Glass Fiber Reinforced Plasitc Laminates [*ASM Engineers' Guide to Composite Materials*]

Although some guidance has been provided to assist in the preliminary selection of materials to optimize fatigue performance, a thorough test program would be recommended for any large scale production effort that was fatigue performance dependent. This approach has been taken for components such as helicopter and wind turbine rotors, but is generally beyond the means of the average marine fabricator.

Impact

The introduction of FRP and FRP sandwich materials into the boating industry has led to lighter, stiffer and faster boats. This leads, in general, to reduced impact performance, since higher speeds cause impact energy to be higher, while stiffer structures usually absorb less impact energy before failure. Thus, the response of a FRP composite marine structure to impact loads is an important consideration.

The complexity and variability of boat impacts makes it very difficult to define an impact load for design purposes. There is also a lack of information on the behavior of the FRP composite materials when subjected to the high load rates of an impact, and analytical methods are, at present, relatively crude. Thus, it is difficult to explicitly include impact loads into the structural analysis and design process. Instead, basic knowledge of the principles of impact loading and structural response is used as a guide to design structures for relatively better impact performance.

The impact response of a composite structure can be divided into four categories. In the first, the entire energy of the impact is absorbed by the structure in elastic deformation, and then released when the structure returns to its original position or shape. Higher energy levels exceed the ability of the structure to absorb the energy elastically. The next level is plastic deformation, in which some of the energy is absorbed by elastic deformation, while the remainder of the energy is absorbed through permanent plastic deformation of the structure. Higher energy levels result in energy absorbed through damage to the structure. Finally, the impact energy levels can exceed the capabilities of the structure, leading to catastrophic failure. The maximum energy which can be absorbed in elastic deformation depends on the stiffness of the materials and the geometry of the structure. Damage to the structural laminate can be in the form of resin cracking, delamination between plies, debonding of the resin fiber interface, and fiber breakage for solid FRP laminates, with the addition of debonding of skins from the core in sandwich laminates. The amount of energy which can be absorbed in laminate and structural damage depends on the resin properties, fiber types, fabric types, fiber orientation, fabrication techniques and rate of impact.

Impact Design Considerations

The general principles of impact design are as follows. The kinetic energy of an impact is:

$$K.E. = \frac{m\,v^2}{2}$$

where:

v = the collision velocity and m is the mass of the boat or the impactor, whichever is smaller.

The energy that can be absorbed by an isotropic beam point loaded at mid-span is:

$$K.E. = \int_0^L \frac{M^2}{2\,E\,I}\,ds$$

where:

L = the span length

M = the moment

E = Young's Modulus

I = moment of inertia

For the small deformations of a composite panel, the expression can be simplified to:

$$K.E. = \frac{S^2 A L r^2}{6 E c^2}$$

where:

S = the stress

A = cross-sectional area

r = the depth of the beam

c = the depth of the outermost fiber of the beam

From this relationship, the following conclusions can be drawn:

- Increasing the skin laminate modulus E causes the skin stress levels to increase. The weight remains the same and the flexural stiffness is increased.
- Increasing the beam thickness r decreases the skin stress levels, but it also increases flexural stiffness and the weight.
- Increasing the span length L decreases the skin stress levels. The weight remains the same, but flexural stiffness is decreased.

Therefore, increasing the span will decrease skin stress levels and increase impact energy absorption, but the flexural stiffness is reduced, thus increasing static load stress levels.

For a sandwich structure:

$$M = \frac{S I}{d}$$

$$I \approx \frac{b t d^2}{2}$$

where:

S = skin stress

d = core thickness

b = beam width

t = skin thickness

Thus the energy absorption of a sandwich beam is:

$$K.E. = \frac{S^2 b t L}{4 E}$$

From this relationship, the following conclusions can be drawn:

- Increasing the skin laminate modulus *E* causes the skin stress levels to increase. The weight remains the same and the flexural stiffness is increased.
- Increasing the skin thickness *t* decreases the skin stress levels, but it also increases flexural stiffness and the weight.
- Increasing the span length *L* decreases the skin stress levels. The weight remains the same, but flexural stiffness is decreased.
- Core thickness has no effect on impact energy absorption.

Therefore, increasing the span will decrease skin stress levels and increase impact energy absorption, while the flexural stiffness can be maintained by increasing the core thickness.

An impact study investigating sandwich panels with different core materials, different fiber types and different resins supports some of the above conclusions. [4-24] This study found that panels with higher density foam cores performed better than identical panels with lower density foam cores, while rigid cores such as balsa and Nomex® did not fare as well as the foam. This indicates that strength is a more important property than modulus for impact performance of core materials. The difference in performance between panels constructed of E-glass, Kevlar®, and carbon fiber fabrics was small, with the carbon fiber panels performing slightly better than the other two types. The reason for these results is not clear, but the investigator felt that the higher flexural stiffness of the carbon fiber skin distributed the impact load over a greater area of the foam core, thus the core material damage was lower for this panel. Epoxy, polyester and vinyl ester resins were also compared. The differences in performance were slight, with the vinyl ester providing the best performance, followed by polyester and epoxy. Impact performance for the different resins followed the strength/stiffness ratio, with the best performance from the resin with the highest strength to stiffness ratio.

General impact design concepts can be summarized as follows:

- Impact Energy Absorption Mechanisms
- Elastic deformation
- Matrix cracking
- Delamination
- Fiber breakage
- Interfacial debonding
- Core shear

The failure mechanism is usually that of the limiting material in the composite, however, positive synergism between specific materials can dramatically improve impact performance. General material relationships are as follows:

- Kevlar® and S-glass are better than E-glass and carbon fibers.
- Vinyl ester is better than epoxy and polyester.
- Foam core is better than Nomex® and Balsa.
- Quasi-isotropic laminates are better than Orthotropic laminates.
- High fiber/resin ratios are better than low.
- Many thin plies of reinforcing fabric are better than a few thicker plies.

Theoretical Developments

Theoretical and experimental analysis have been conducted for ballistic impact (high speed, small mass projectile) to evaluate specific impact events. The theory can be applied to lower velocity, larger mass impacts acting on marine structures as summarized in Figure 4-7 and below.

1. Determine the surface pressure and its distribution induced by the impactor as a function of impact parameters, laminate and structure properties, and impactor properties.

2. Determine the internal three dimensional stress field caused by the surface pressure.

3. Determine the failure modes of the laminate and structure resulting from the internal stresses, and how they interact to cause damage.

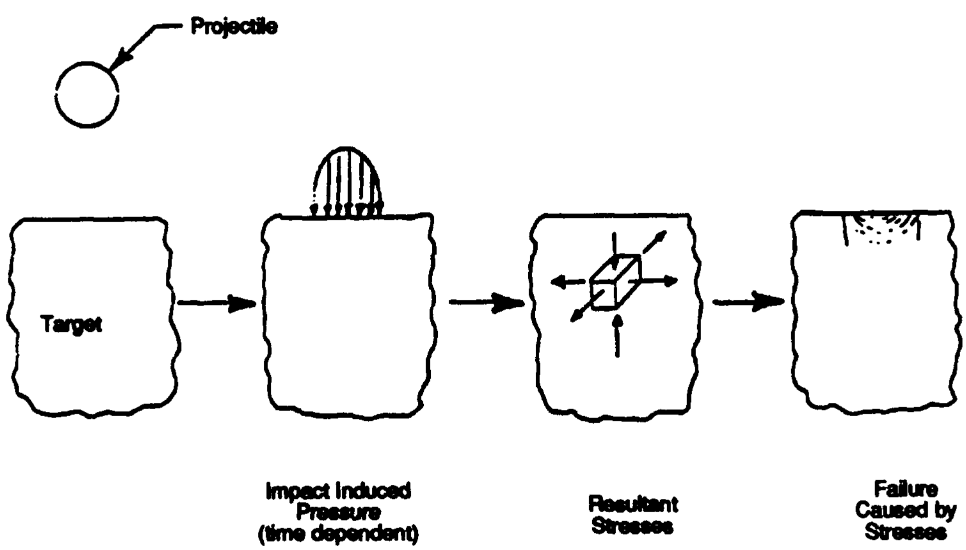


Figure 4-7 Impact Initiation and Propagation [Jones, *Impact Analysis of Composite Sandwich Panels as a Function of Skin, Core and Resin Materials*]

Delamination

Interlaminar stress in composite structures usually results from the mismatch of engineering properties between plies. These stresses are the underlying cause of delamination initiation and propagation. Delamination is defined as the cracking of the matrix between plies. The aforementioned stresses are out-of-plane and occur at structural discontinuities, as shown in Figure 4-8. In cases where the primary loading is in-plane, stress gradients can produce an out-of-plane load scenario because the local structure may be discontinuous.

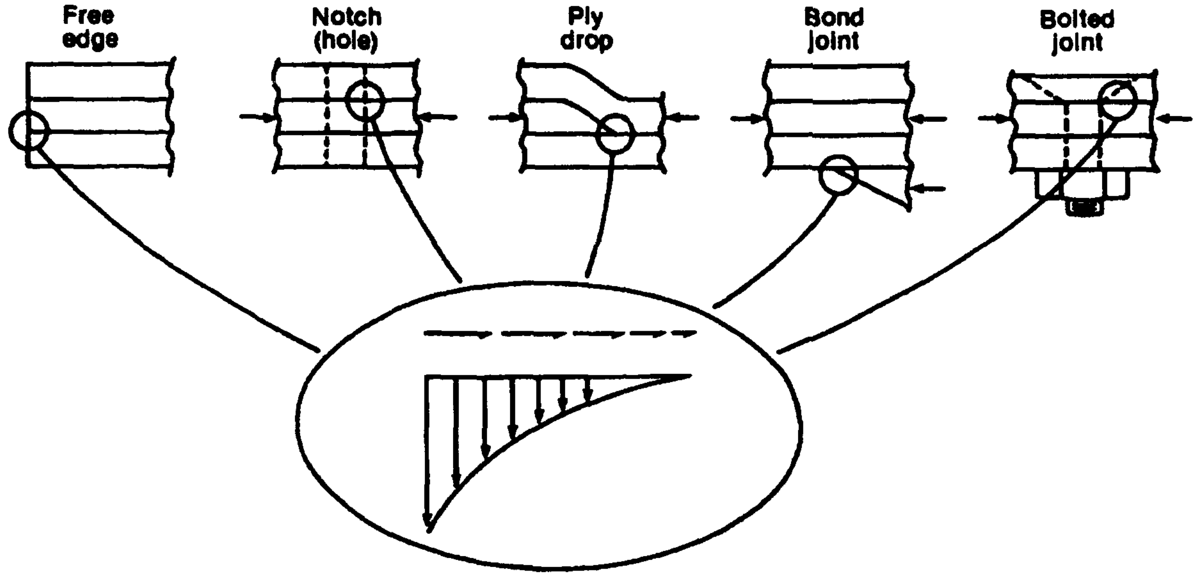


Figure 4-8 Sources of Out-of-Plane Loads from Load Path Discontinuities [ASM, *Engineered Materials Handbook*]

Analysis of the delamination problem has identified the strain energy release rate, G, as a key parameter for characterizing failures. This quantity is independent of layup sequence or delamination source. [4-25] NASA and Army investigators have shown from finite element analysis that once a delamination is modeled a few ply thicknesses from an edge, G reaches a plateau given by the equation shown in Figure 4-9.

where:

t = laminate thickness

ε = remote strain

E_{LAM} = modulus before delamination

E^* = modulus after delamination

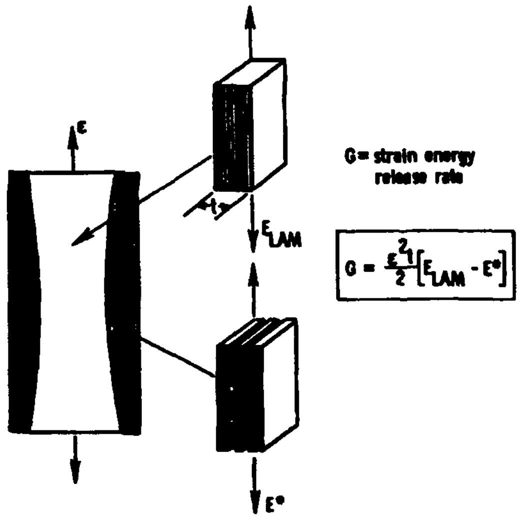


Figure 4-9 Strain Energy Release Rate for Delamination Growth [O'Brien, *Delamination Durability of Composie Materials for Rotorcraft*]

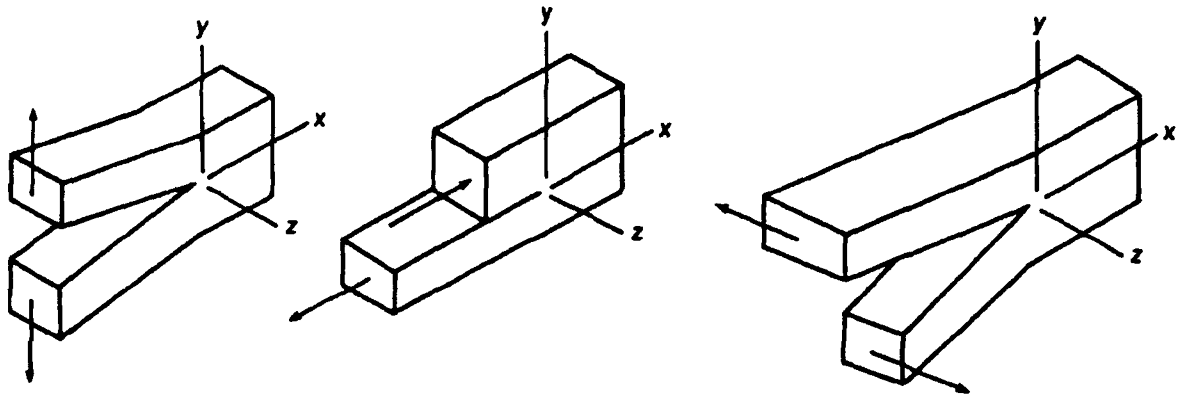


Figure 4-10 Basic Modes of Loading Involving Different Crack Surface Displacements [ASM, *Engineered Materials Handbook*]

Linear elastic fracture mechanics identifies three distinct loading modes that correspond to different crack surface displacements. Figure 4-10 depicts these different modes as follows:

- **Mode I** - Opening or tensile loading where the crack surfaces move directly apart
- **Mode II** - Sliding or in-plane shear where the crack surfaces slide over each other in a direction perpendicular to the leading edge of the crack
- **Mode III** - Tearing or antiplane shear where the crack surfaces move relative to each other and parallel to the leading edge of the crack (scissoring)

Mode I is the dominant form of loading in cracked metallic structures. With composites, any combination of modes may be encountered. Analysis of mode contribution to total strain energy release rate has been done using finite element techniques, but this method is too cumbersome for checking individual designs. A simplified technique has been developed by Georgia Tech for NASA/Army whereby Mode II and III strain energy release rates are calculated by higher order plate theory and then subtracted from the total G to determine Mode I contribution.

Delamination in tapered laminates is of particular interest because the designer usually has control over taper angles. Figure 4-11 shows delamination initiating in the region "A" where the first transition from thin to thick laminate occurs. This region is modeled as a flat laminate with a stiffness discontinuity in the outer "belt" plies and a continuous stiffness in the inner "core" plies. The belt stiffness in the tapered region, E_2, was obtained from a tensor transformation of the thin region, E_1, transformed through the taper angle, beta. As seen in the figure's equation, G will increase as beta increases, because the belt stiffness is a function of the taper angle. [4-25]

Lately, there has been much interest in the aerospace industry in the development of "tough" resin systems that resist impact damage. The traditional, high-strength epoxy systems are

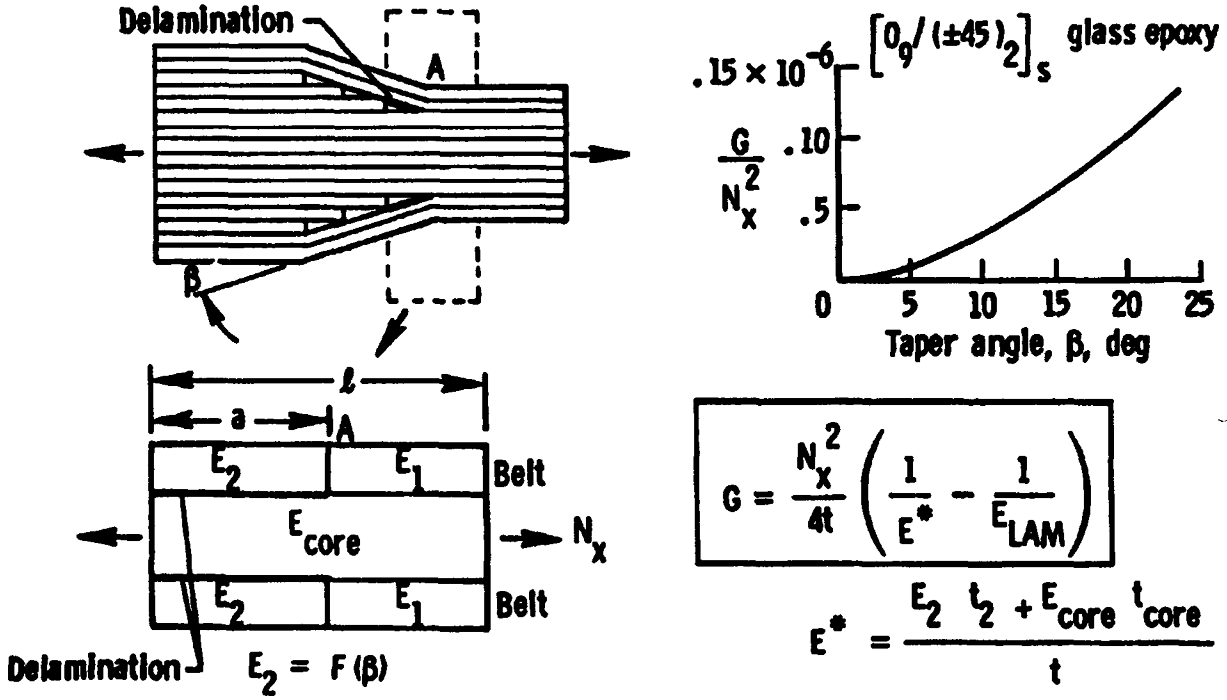


Figure 4-11 Strain Energy Release Rate Analysis of Delamination in a Tapered Laminate [O'Brien, *Delamination Durability of Composie Materials for Rotorcraft*]

typically characterized as brittle when compared to systems used in the marine industry. In a recent test of aerospace matrices, little difference in delamination durability showed up. However, the tough matrix composites did show slower delamination growth. Figure 4-12 is a schematic of a log-log plot of delamination growth rate, da/dN,

where:

G_c = cyclic strain energy release rate

G_{th} = cyclic threshold

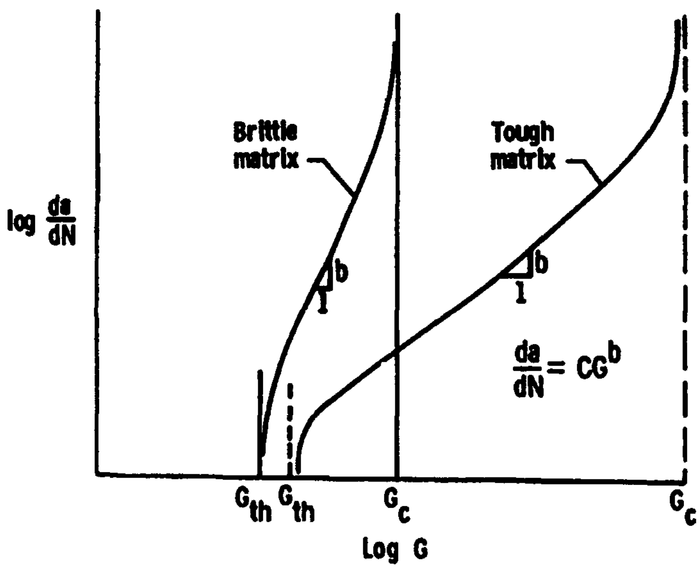


Figure 4-12 Comparison of Delamination Growth Rates for Composites with Brittle and Tough Matrices [O'Brien, *Delamination Durability of Composie Materials for Rotorcraft*]

Water Absorption

When an organic matrix composite is exposed to a humid environment or liquid, both the moisture content and material temperature may change with time. These changes usually degrade the mechanical properties of the laminate. The study of water absorption within composites is based on the following parameters as a function of time: [4-26]

- The temperature inside the material as a function of position
- The moisture concentration inside the material
- The total amount (mass) of moisture inside the material
- The moisture and temperature induced "hygrothermal" stress inside the material
- The dimensional changes of the material
- The mechanical, chemical, thermal or electric changes

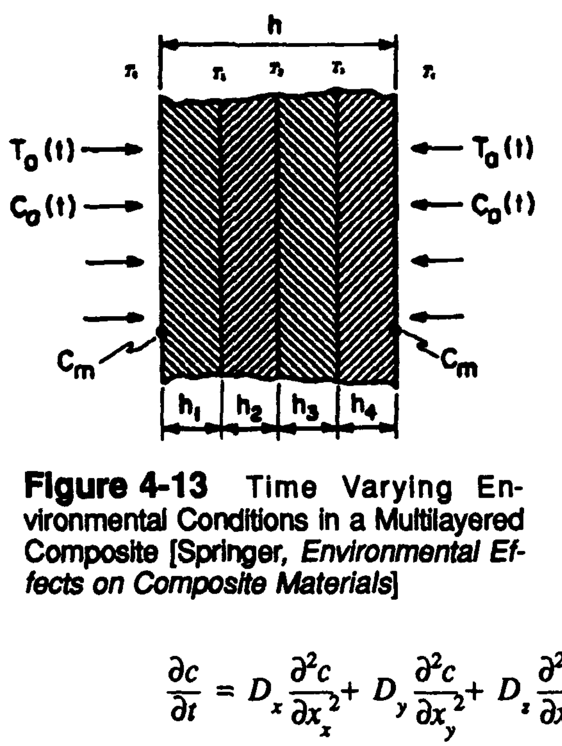


Figure 4-13 Time Varying Environmental Conditions in a Multilayered Composite [Springer, *Environmental Effects on Composite Materials*]

To determine the physical changes within a composite laminate, the temperature distribution and moisture content must be determined. When temperature varies across the thickness only and equilibrium is quickly achieved, the moisture and temperature distribution process is called "Fickian" diffusion, which is analogous to Fourier's equation for heat conduction. Figure 4-13 illustrates some of the key parameters used to describe the Fickian diffusion process in a multilayered composite. The letter *T* refers to temperature and the letter *C* refers to moisture concentration.

Fick's second law of diffusion can be represented in terms of three principal axes by the following differential equation: [4-27]

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x_x^2} + D_y \frac{\partial^2 c}{\partial x_y^2} + D_z \frac{\partial^2 c}{\partial x_z^2}$$

Figure 4-14 shows the change in moisture content, *M*, versus the square root of time. The apparent plateau is characteristic of Fickian predictions, although experimental procedures have shown behavior that varies from this. Additional water absorption has been attributed to the relaxation of the polymer matrix under the influence of swelling stresses. [4-28] Figure 4-15 depicts some experimental results from investigations conducted at elevated temperatures.

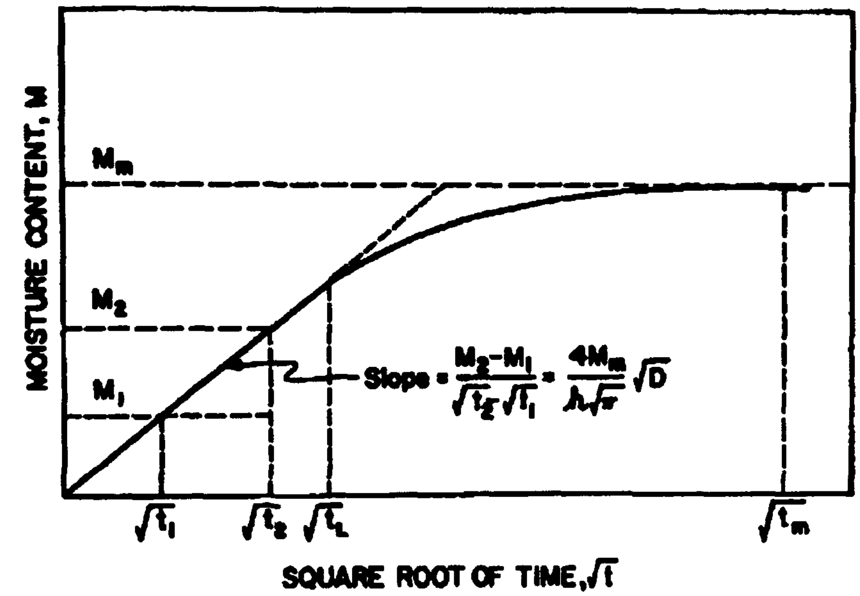


Figure 4-14 Change of Moisture Content with the Square Root of Time for "Fickian" Diffusion [Springer, *Environmental Effects on Composite Materials*]

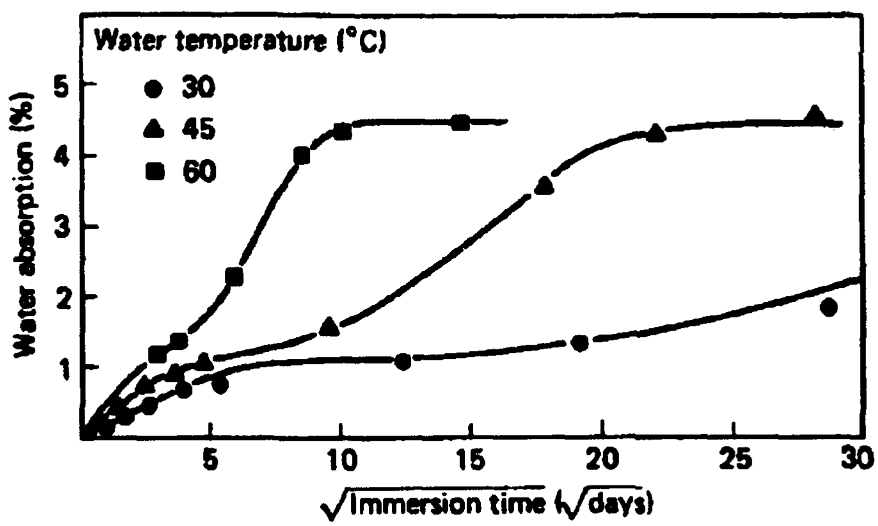


Figure 4-15 Laminate Water Absorbtion Kinetics for Experimental Laminate Specimens [Pritchard, *The Use of Water Absorbtion Kinetic Data to Predict Laminate Property Changes*]

Structural designers are primarily interested in the long term degradation of mechanical properties when composites are immersed in water. By applying curve-fitting programs to experimental data, extrapolations about long term behavior can be postulated. [4-28] Figure 4-16 depicts a 25 year prediction of shear strength for glass polyester specimens dried after immersion. Strength values eventually level off at about 60% of their original value, with the degradation process accelerated at higher temperatures. Figure 4-17 shows similar data for wet tensile strength. Experimental data at the higher temperatures is in relative agreement for the first three years.

Table 4-1 shows the apparent maximum moisture content and the transverse diffusivities for two polyester and one vinyl ester E-glass laminate. The numerical designation refers to fiber content by weight.

Laminate water contents cannot be compared directly with cast resin water contents, since the fibers do not absorb water and the water is concentrated in the resin (approximately 75% by volume for bidirectional laminates and 67% by volume for unidirectional ones). [4-28]

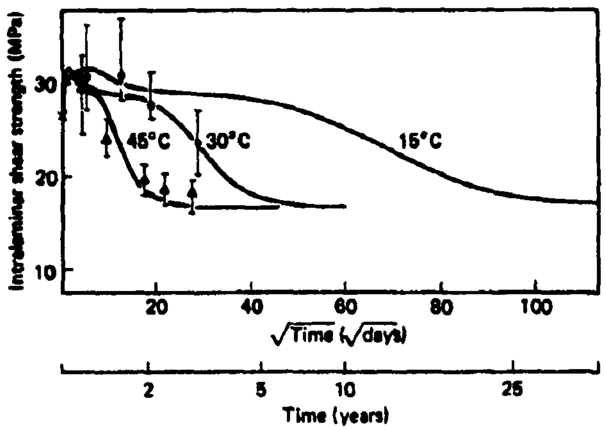


Figure 4-16 Predicted Dry Shear Strength versus Square Root of Immersion Time [Pritchard, *The Use of Water Absorbtion Kinetic Data to Predict Laminate Property Changes*]

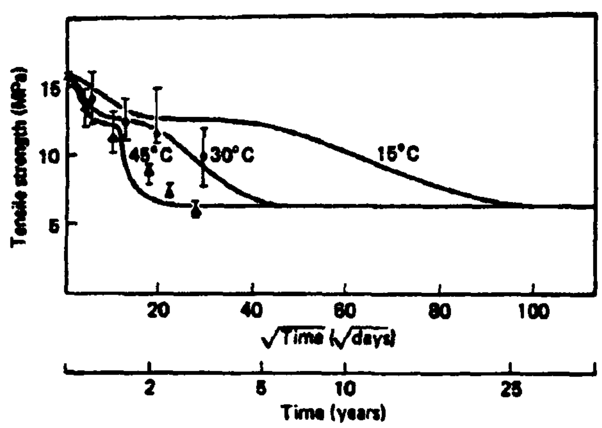


Figure 4-17 Predicted Wet Tensile Strength versus Square Root of Immersion Time [Pritchard, *The Use of Water Absorbtion Kinetic Data to Predict Laminate Property Changes*]

Table 4-1. Apparent Maximum Moisture Content and Transverse Diffusivities of Some Polyester E-Glass and Vinyl Ester Laminates [Springer, *Environmental Effects on Composite Materials*]

Substance	Temp (°C)	Maximum Moisture Content*			Transverse Diffusivity†		
		SMC-R25	VE SMC-R50	SMC-R50	SMC-R25	VE SMC-R50	SMC-R50
50% Humidity	23	0.17	0.13	0.10	10.0	10.0	30.0
	93	0.10	0.10	0.22	50.0	50.0	30.0
100% Humidity	23	1.00	0.63	1.35	10.0	5.0	9.0
	93	0.30	0.40	0.56	50.0	50.0	50.0
Salt Water	23	0.85	0.50	1.25	10.0	5.0	15.0
	93	2.90	0.75	1.20	5.0	30.0	80.0
Diesel Fuel	23	0.29	0.19	0.45	6.0	5.0	5.0
	93	2.80	0.45	1.00	6.0	10.0	5.0
Lubricating Oil	23	0.25	0.20	0.30	10.0	10.0	10.0
	93	0.60	0.10	0.25	10.0	10.0	10.0
Antifreeze	23	0.45	0.30	0.65	50.0	30.0	20.0
	93	4.25	3.50	2.25	5.0	0.8	10.0

*Values given in percent

†Values given are $D_{22} \times 10^7$ mm^2/sec

Blisters

The blistering of gel coated, FRP structures has received much attention in recent years. The defect manifests itself as a localized raised swelling of the laminate in an apparently random fashion after a hull has been immersed in water for some period of time. When blisters are ruptured, a viscous acidic liquid is expelled. Studies have indicated that one to three percent of boats surveyed in the Great Lakes and England, respectively, have appreciable blisters. [4-29]

There are two primary causes of blister development. The first involves various defects introduced during fabrication. Air pockets can cause blisters when a part is heated under environmental conditions. Entrapped liquids are also a source of blister formation. Table 4-2 lists some liquid contaminate sources and associated blister discriminating features.

Table 4-2. Liquid Contaminate Sources During Spray-Up That Can Cause Blistering [Cook, *Polycor Polyester Gel Coats and Resins*]

Liquid	Common Source	Distinguishing Characteristics
Catalyst	Overspray, drips due to leaks of malfunctioning valves.	Usually when punctured, the blister has a vinegar-like odor; the area around it, if in the laminate, is browner or burnt color. If the part is less than 24 hours old, wet starch iodine test paper will turn blue.
Water	Air lines, improperly stored material, perspiration.	No real odor when punctured; area around blister is whitish or milky.
Solvents	Leaky solvent flush system, overspray, carried by wet rollers.	Odor; area sometimes white in color.
Oil	Compressor seals leaking.	Very little odor; fluid feels slick and will not evaporate.
Uncatalyzed Resin	Malfunctioning gun or ran out of catalyst.	Styrene odor and sticky.

Even when the most careful fabrication procedures are followed, blisters can still develop over a period of time. These type of blisters are caused by osmotic water penetration, a subject that has recently been examined by investigators. The osmotic process allows smaller water molecules to penetrate through a particular laminate, which react with polymers to form larger molecules, thus trapping the larger reactants inside. A pressure or concentration gradient develops, which leads to hydrolysis within the laminate. Hydrolysis is defined as decomposition of a chemical compound through the reaction with water. Epoxide and polyurethane resins exhibit better hydrolytic stability than polyester resins. In addition to the contaminants listed in Table 4-2, the following substances act as easily hydrolyzable constituents: [4-30]

- Glass mat binder
- Pigment carriers
- Mold release agents

- Stabilizers
- Promoters
- Catalysts
- Uncross-linked resin components

Blisters can be classified as either coating blisters or those located under the surface at substrate interfaces (see Figure 4-18). The blisters under the surface are more serious and will be of primary concern. Some features that distinguish the two types include:

- Diameter to height ratio of sub-gel blister is usually greater than 10:1 and approaches 40:1 whereas coating blisters have ratios near 2:1.

  Sub-gel blisters are much larger than coating blisters.
- The coating blister is more easily punctured than the sub-gel blister.
- Fluid in sub-gel blisters is acidic (pH 3.0 to 4.0), while fluid in coating blisters has a pH of 6.5 to 8.0.

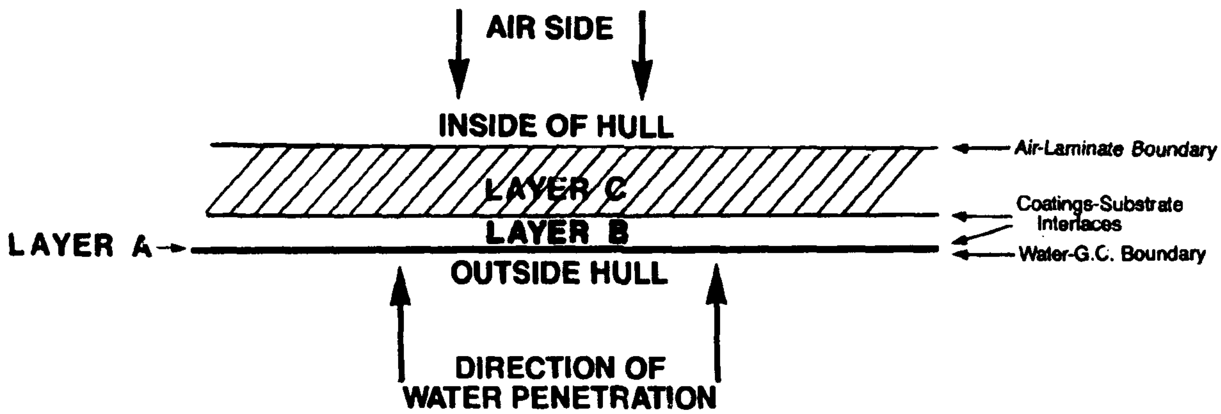


Figure 4-18 Structure Description for a Skin Coated Composite with: **Layer A** = Gel Coat, **Layer B** = Interlayer and **Layer C** = Laminate Substrate [Interplastic, *A Study of Permeation Barriers to Prevent Blisters in Marine Composites and a Novel Technique for Evaluating Blister Formation*]

Both types of blisters are essentially cosmetic problems, although sub-gel blisters do have the ability to compromise the laminate's integrity through hydrolytic action. A recent theoretical and experimental investigation [4-31] examined the structural degradation effects of blisters within hull laminates. A finite element model of the blister phenomena was created by progressively removing material from the surface down to the sixth layer, as shown in Figure 4-19. Strain gage measurements were made on sail and power boat hulls that exhibited severe blisters. The field measurements were in good agreement with the theoretically determined values for strength and stiffness. Stiffness was relatively unchanged, while strength values degraded 15% to 30%, well within the margin of safety used for the laminates.

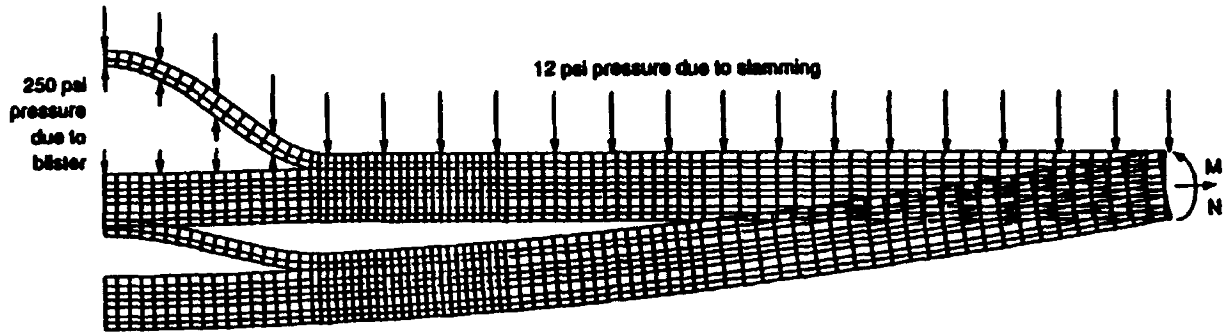


Figure 4-19 Internal Blister Axisymetric Finite Element Model [Kokarakis and Taylor, *Theoretical and Experimental Investigation of Blistered Fiberglass Boats*]

The fact that the distribution of blisters is apparently random has precluded any documented cases of catastrophic failures attributed to blistering. The repair section of this document will deal with corrective measures to remove blisters.

As was previously mentioned, recent investigations have focused on what materials perform best to prevent osmotic blistering. Referring to Figure 4-18, Layer A is considered to be the gel coat surface of the laminate. Table 4-3 lists some permeation rates for three types of polyester resins that are commonly used as gel coats.

Table 4-3. Composition and Permeation Rates for Some Polyester Resins used in Gel Coats [Crump, *A Study of Blister Formation in Gel Coated Laminates*]

Resin	Glycol	Saturated Acid	Unsaturated Acid	Permeation Rate*	
				H_2O @ 77°F	H_2O @ 150°F
NPG Iso	Neopentyl glycol	Isophthalic acid	Maleic anhydride	0.25	4.1
NPG Ortho	Neopentyl glycol	Phthalic anhydride	Maleic anhydride	0.24	3.7
General Purpose	Propylene glycol	Phthalic anhydride	Maleic anhydride	0.22	3.6
*grams/cubic centimeter per day x 10^{-4}					

Investigators at the Interplastic Corporation concentrated their efforts on determining an optimum barrier ply, depicted as Layer B in Figure 4-18. Their tests involved the complete submersion of edge-sealed specimens that were required to have two gel coated surfaces. The conclusion of this study was that a vinyl ester cladding applied on an orthophthalic laminating resin reinforced composite substantially reduced blistering

Investigators at the University of Rhode Island, under the sponsorship of the U.S. Coast Guard, conducted a series of experiments to test various coating materials and methods of application. Table 4-4 summarizes the results of tests performed at 65°C. Blister severity was subjectively evaluated on a scale of 0 to 3. The polyester top coat appeared to be the best performing scheme.

Table 4-4. Results from URI Coating Investigation [Marino, *The Effects of Coating on Blister Formation*]

Coating Scheme	Surface Treatment	Blister Initiation Time (days)	Blister Severity	Blisters Present?
Epoxy top coat	none	5	3	Yes
	sanding	5	1	Yes
	acetone wipe	5	1	Yes
	both	5	1	Yes
Polyurethane top coat	none	5	2	Yes
	sanding	14	1	Yes
	acetone wipe	?	1	Yes
	both	?	1	Yes
Polyester top coat	none	-	0	No
	sanding	-	0	No
	acetone wipe	-	0	No
	both	-	0	No
Epoxy top coat over epoxy	none	8	3	Yes
	sanding	8	1	Yes
	acetone wipe	8	2-3	Yes
	both	8	2	Yes
Polyurethane top coat over polyurethane	none	7	1	Yes
	sanding	7	1	Yes
	acetone wipe	7	1	Yes
	both	7	1	Yes
Polyester top coat over polyester	none	8	3	No
	sanding	-	0	No
	acetone wipe	8	2	No
	both	8	1	No
Epoxy top coat over polyurethane	none	8	3	Yes
	sanding	8	2	Yes
	acetone wipe	17	1-2	?
	both	19	2	Yes
Polyurethane top coat over epoxy	none	11	3	Yes
	sanding	-	0	Yes
	acetone wipe	11	1-3	Yes
	both	-	1	Yes

Coating Scheme	Surface Treatment	Blister Initiation Time (days)	Blister Severity	Blisters Present?
Polyurethane top coat over polyester	none	6	3	Yes
	sanding	6	3	Yes
	acetone wipe	6	3	Yes
	both	6	1	Yes
Epoxy top coat over polyester	none	9	3	Yes
	sanding	9	3	Yes
	acetone wipe	9	3	Yes
	both	9	3	Yes

Blister Severity Scale

0 no change in the coated laminate
1 questionable presence of coating blisters; surface may appear rough, with rare, small pin size blisters
2 numerous blisters are present
3 severe blistering over the entire laminate surface

Case Histories

Advocates of fiberglass construction have often pointed to the long term maintenance advantages of FRP materials. Wastage allowances and shell plating replacement associated with corrosion and galvanic action in metal hulls is not a consideration when designing fiberglass hulls. However, concern over long term degradation of strength properties due to in-service conditions prompted several studies in the 60's and 70's. The results of those investigations along with some case histories that illustrate common FRP structural failures are presented in this section. It should be noted that documented failures are usually the result of one of the following:

- Inadequate design
- Improper selection of materials
- Poor workmanship

US Coast Guard 40 foot Patrol Boats

These multipurpose craft were developed in the early 1950's for law enforcement and search and rescue missions. The boats were 40 feet overall with an 11 foot beam and displaced 21,000 pounds. Twin 250 horsepower diesel engines produced a top speed of 22 knots. Single skin FRP construction was reinforced by transverse aluminum frames, a decidedly conservative approach at the time of construction. Laminate schedules consisted of alternating plies of 10 ounce boat cloth and 1½ ounce mat to thicknesses of ¾ inch for the bottom and ⅜ inch for the sides.

In 1962, Owens-Corning Fiberglass and the US Coast Guard tested panels cut from three boats that had been in service 10 years. In 1972, more extensive tests were performed on a larger population of samples taken from CG Hull 40503, which was being retired after 20 years in service. It should be noted that service included duty in an extremely polluted ship channel where contact with sulfuric acid was constant and exposure to extreme temperatures during one fire fighting episode. Total operating hours for the vessel was 11,654. Visual examination of sliced specimens indicated that water or other chemical reactants had not entered the laminate. The comparative physical test data is presented in Table 4-5.

Table 4-5. Physical Property Data for 10 Year and 20 Year Tests of USCG Patrol Boat [Owens-Corning Fiberglas, *Fiber Glass Marine Laminates, 20 Years of Proven Durability*]

Hull CG 40503		10 Year Tests	20 Year Tests
Tensile Strength	Average psi	5990	6140
	Number of samples	1	10
Compressive Strength	Average psi	12200	12210
	Number of samples	2	10
Flexural Strength	Average psi	9410	10850
	Number of samples	1	10
Shear Strength	Average psi	6560	6146
	Number of samples	3	10

Submarine Fairwater

In the early 1950's, the U.S. Navy developed a fiberglass replacement for the aluminum fairwaters that were fitted on submarines. The fairwater is the hydrodynamic cowling that surrounds the submarine's sail, as shown in Figure 4-20. The motivation behind this program was electrolytic corrosion and maintenance problems. The laminate used consisted of style 181 Volan glass cloth in a general purpose polyester resin that was mixed with a flexible resin for added toughness. Vacuum bag molding was used and curing took place at room temperature.

The fairwater installed on the U.S.S. Halfbeak was examined in 1965 after 11 years in service. The tested material's physical properties are shown in Table 4-6. After performing the tests, the conclusion that the materials were not adversely affected by long term exposure to weather was reached. It should be noted that a detailed analysis of the component indicated that a safety factor of four was maintained throughout the service life of the part. Thus, the mean stress was kept below the long term static fatigue strength limit, which at the time was taken to be 20 to 25 percent of the ultimate strength of the materials mentioned.

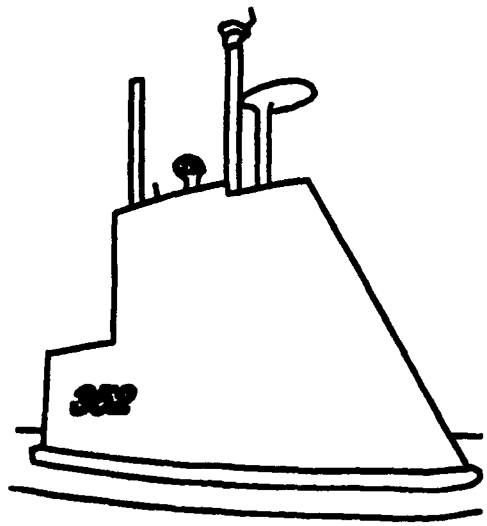


Figure 4-20 Submarine Fairwater for the U.S.S. Halfbeak [Lieblein, *Survey of Long-Term Durability of Fiberglass-Reinforced Plastic Structures*]

Table 4-6. Property Tests of Samples from Fairwater of U.S.S. Halfbeak [Fried & Graner, *Durability of Reinforced Plastic Structural Materials in Marine Service*]

Property	Condition	Original Data (1954)*	1965 Data 1st Panel	2nd Panel	Average
Flexural Strength, psi	Dry	52400	51900	51900	51900
	Wet†	54300	46400	47300	46900
Flexural Modulus, psi x 10^{-6}	Dry	2.54	2.62	2.41	2.52
	Wet	2.49	2.45	2.28	2.37
Compressive Strength, psi	Dry	—	40200	3800	39100
	Wet	—	35900	35200	35600
Barcol Hardness	Dry	55	53	50	52
Specific Gravity	Dry	1.68	1.69	1.66	1.68
Resin Content	Dry	47.6%	47.4%	48.2%	47.8%

* Average of three panels
† Specimen boiled for two hours, then cooled at room temperature for one hour prior to testing

Gel Coat Cracking

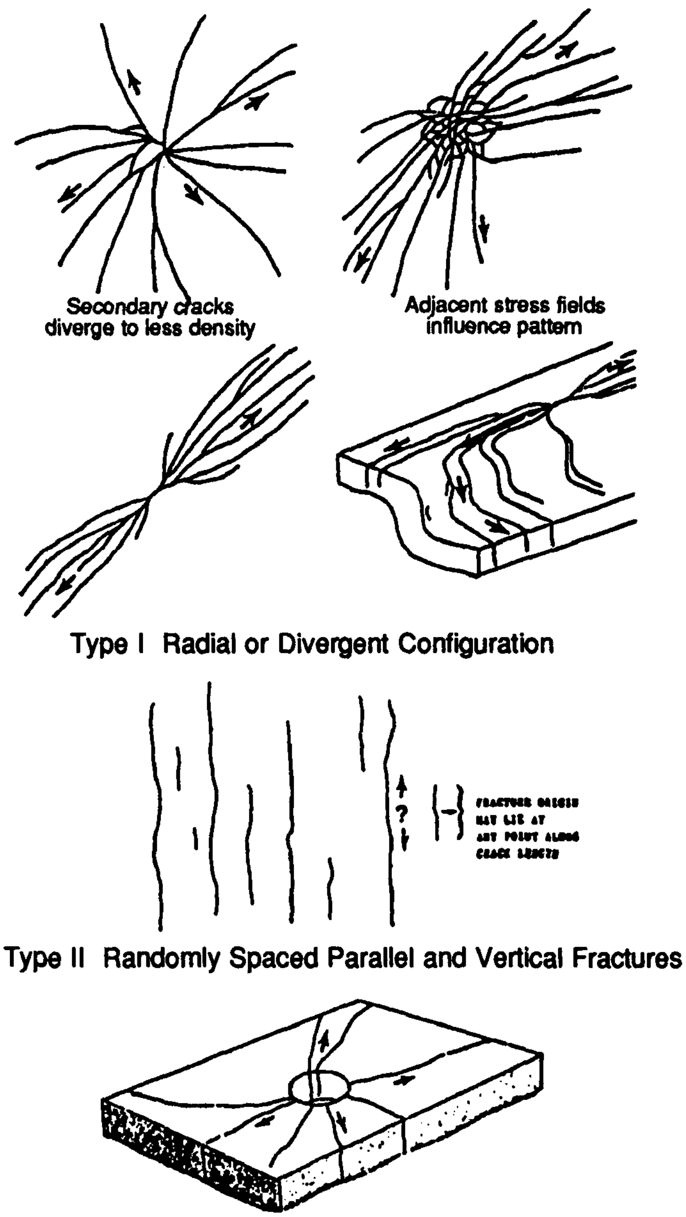
Hairline cracks in exterior gel coat surfaces are traditionally treated as a cosmetic problem. However, barring some deficiency in manufacturing, such as thickness gauging, catalyzation or mold release technique, gel coat cracks often are the result of design inadequacies and can lead to further deterioration of the laminate.

Gel coat formulations represent a fine balance between high gloss properties and material toughness. Designers must be constantly aware that the gel coat layer is not reinforced, yet it can experience the highest strain of the entire laminate because it is the farthest away from the neutral axis.

This section will attempt to classify types of get coat cracks and describe the stress field associated with them. [4-32] Figure 4-21 shows a schematic representation of three types of gel coat cracks that were analyzed by Smith using microscopic and fractographic techniques. That investigation lead to the following conclusions:

Type I

These are the most prevalent type of cracks observed by marine surveyors and have traditionally been attributed to overly thick gel coat surface or impact from the opposite side of the laminate. Although crack patterns can become rather complex, the source can usually be traced radially to the area of highest crack density. The dominant stress field is one of highly localized tensile stresses, which can be the result of internal braces (stiffener hard spots) or overload in bending and flexing (too large a panel span for laminate). Thermal stresses created by different thermal expansion coefficients of materials within a laminate can create cracks. This problem is especially apparent when plywood is used as a core. Residual stress can also influence the growth of Type I cracks.



Type I Radial or Divergent Configuration

Type II Randomly Spaced Parallel and Vertical Fractures

Type III Cracks at Hole of Other Stress Concentration

Figure 4-21 Schematic Representations of Gel Coat Crack Patterns [Smith, *Cracking of Gel Coated Compositos*]

Cracks tend to initiate at points of non-uniformity in the laminate, such as voids or areas that are resin rich or starved. The propagation then proceeds in a bilateral fashion, finally into the laminate itself.

Type II

Type II cracks are primarily found in hull structures and transoms, although similar fractures have been noted along soles and combings [4-33]. In the latter instance, insufficient support has been cited as the contributing cause, with the pattern of cracking primarily attributable to the geometry of the part. The more classical Type II cracks are the result of thermal fatigue, which is the dominant contributing factor for crack nucleation. The parallel nature of the cracks makes it difficult to pinpoint the exact origin of the failure, although it is believed that cracks nucleate at fiber bundles perpendicular to the apparent stress fields. Other factors contributing to this type of crack growth are global stress fields and high thermal gradients.

Type III

Cracking associated with holes drilled in the laminate are quite obvious. The hole acts as a notch or stress concentrator, allowing cracks to develop with little externally applied stress. Factors contributing to the degree of crack propagation include:

- Global stress field
- Method of machining the hole
- Degree of post cure

Core Separation in Sandwich Construction

It has been shown that sandwich construction can have tremendous strength and stiffness advantages for hull panels, especially when primary loads are out of plane. As a rule, material costs will also be competitive with single-skin construction, because of the reduced number of plies in a laminate. However, construction with a core material requires additional labor skill to ensure proper bonding to the skins. Debonding of skins from structural cores is probably the single most common mode of laminate failure seen in sandwich construction. The problem may either be present when the hull is new or manifest itself over a period of time under in-service load conditions.

Although most reasons for debonding relate to fabrication techniques, the designer may also be at fault for specifying too thin a core, which intensifies the interlaminar shear stress field when a panel is subject to normal loads. Problems that can be traced to the fabrication shop include:

- Insufficient preparation of core surface to resist excessive resin absorption
- Improper contact with first skin, especially in female molds
- Application of second skin before core bedding compound has cured
- Insufficient bedding of core joints
- Contamination of core material (dirt or moisture)

Selection of bonding resin is also critical to the performance of this interface. Some transition between the "soft" cores and relatively stiff skins is required. This can be achieved if a resin with a reduced modulus of elasticity is selected.

Load sources that can exacerbate a poorly bonded sandwich panel include wave slamming, dynamic deck loading from gear or personnel, and global compressive loads that tend to seek out instable panels. Areas that have been shown to be susceptible to core debonding include:

- Stress concentrations will occur at the face to core joint of scrim-cloth or contoured core material if the voids are not filled with a bonding agent, as shown in Figure 4-22
- Areas with extreme curvature that can cause difficulties when laying the core in place
- Panel locations over stiffeners
- Centers of excessively large panels
- Cockpit floors
- Transoms

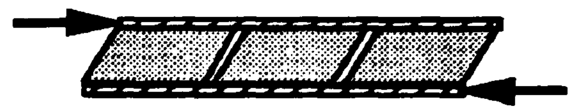


Figure 4-22 Illustration of Stress Concentration Areas in Unfilled Contoured Core Material [Morgan, *Design to the Limit: Optimizing Core and Skin Properties*]

Failures in Secondary Bonds

Secondary bond failures are probably the most common structural failure on FRP boats. For reasons outlined in the Detail Design section of this document, complete chemical bonding strength is not always obtained. Additionally, geometries of secondarily bonded components usually tend to create stress concentrations at the bond line. Some specific areas where secondary bond failures have been noted include:

- Stiffeners and bulkhead attachments
- Furniture and floor attachment
- Rudder bearing and steering gear support

Ultraviolet Exposure

The three major categories of resins that are used in boat building, polyester, vinyl ester and epoxy, have different reactions to exposure to sunlight. Sunlight consists of ultraviolet rays and heat.

Epoxies are generally very sensitive to ultraviolet (UV) light and if exposed to UV rays for any significant period of time the resins will degrade to the point where they have little, if any, strength left to them. The vinyl esters, because there are epoxy linkages in them, are also sensitive to UV and will degrade with time, although in general not as rapidly as an epoxy. Polyester, although it is somewhat sensitive to UV degradation, is the least sensitive of the three to UV light.

The outer surface of most boats is covered with a gel coat. Gel coats are based on ortho or isopolyester resin systems that are heavily filled and contain pigments. In addition, often there is a UV screen added to help protect the resin, although for most gel coats the pigment itself serves as the UV protector.

In general, the exposure of the gel coats to UV radiation will cause fading of the color which is associated with the pigments themselves and their reaction to sunlight, but also on white or off-white gel coats UV exposure can cause yellowing. The yellowing, in general, is a degradation of the resin rather than the pigments and will finally lead to the phenomenon known as "chalking." Chalking occurs when the very thin outer coating of resin degrades under the UV light to the point where it exposes the filler and some of the pigment in the gel coat. The high gloss finish that is typical of gel coats is due to that thin layer. Once it degrades and disappears the gloss is gone, and what's left is still a colored surface but it is no longer shiny. Because the pigments are no longer sealed by the thin outer coating of resin, they actually can degrade and lose some of their color and they eventually loosen up from the finish to give a kind of a chalky surface effect.

There are some gel coats that are based on vinyl ester resin. These are not generally used in the marine industry, but some boat manufacturers are starting to use them below the water line to prevent blistering, since vinyl ester resins are not typically susceptible to blistering. However, if these resins are used on the top side or the decks of a boat, they will suffer yellowing and chalking very quickly as compared to a good ortho or isopolyester gel coat.

Temperature Effects

In addition to this type of degradation caused by sunlight, the other problem that must be considered is the effects of heat. The sun will actually heat up the gel coat and the laminate beneath it. The amount of damage that can be done depends on a number of factors. First, the thermal expansion coefficient of fiberglass is very different from that of resin. Thus, when a laminate with a high glass content is heated significantly the fiberglass tends to be relatively stable, whereas the resin tries to expand but can't because it's held in place by the glass. The result of this is that the pattern of the fiberglass will show through the gel coat in many cases, a phenomenon known as "print through." Of course, if reinforcing fibers are used which have thermal expansion coefficients similar to the resins, it is less likely that print through will occur.

Another consideration in addition to the thermal coefficient of expansion is the temperature at which the resin was cured. Most polyester resins have a heat distortion temperature of around 150-200°F. This means that when the resin becomes heated to that temperature it has gone above the cure temperature, and the resin will become very soft. When resin becomes soft the laminate becomes unstable. The resin can actually cure further when it's heated to these temperatures. When it cools down the resin will try to shrink, but since it's been set at the higher temperature and the glass doesn't change dimensions very much, the resin is held in place by the glass, thereby creating very large internal stresses solely due to these thermal effects. This can happen also in a new laminate when it's cured, but this is also something that can happen to a laminate that's exposed to the sun and is heated higher than its heat distortion temperature. This can be a problem with all room temperature thermosetting resins, polyester vinyl ester and epoxies, although it is less likely to be a problem with vinyl ester and epoxy than with polyester, because the vinyl esters and epoxies usually cure at a higher exotherm temperature.

As mentioned above, the heat distortion temperature of polyester resins can range from about 150°-200°. In Florida or the tropics it's not uncommon to get temperatures in excess of 150° on boats with white gel coats. Temperatures have been measured as high as 180° on the decks of boats with red gel coat, close to 200° on the decks of boats with dark blue gel coat and well over 200° on the decks of boats with black gel coat. That's one of the reasons why there are very few boats with black gel coat. Some sport fishing boats or other boats are equipped with a wind screen which, rather than being clear, is actually fiberglass coated with black gel coat for a stylish appearance. This particular part of these boats suffers very badly from print through problems because the heat distortion temperature or the resin in the gel coat is exceeded. Obviously, during each day and night much temperature cycling occurs; the laminate will get hot in the day, cool off at night, get hot again the next day, etc. The resin will already be postcured to some extent, however it will still suffer from this cyclic heating and cooling. These temperature cycles tend to produce internal stresses which then cause the laminate to fatigue more rapidly than it normally would.

Another thermal effect in fatigue is caused by shadows moving over the deck of a boat that's *sitting in the sun.* As the sun travels overhead, the shadow will progress across the deck. At the edge of the shadow there can be a very large temperature differential on the order of 20°-30°. As a result, as that shadow line travels there is a very sharp heating or cooling at the edge, and the differential causes significant stress right at that point. That stress will result in fatigue of the material. Boats that are always tied up in the same position at the dock, so that the same areas of the boat get these shadows traveling across them, can actually suffer fatigue damage with the boat not even being used.

Another environmental effect, which sometimes is considered by boat designers and sometimes is not heat, but cold. Most resins will absorb some amount of moisture, some more than others. A laminate which has absorbed a significant amount of moisture will experience severe stresses if the laminate becomes frozen, since water expands when it freezes. This expansion can generate significant pressures in a laminate and can actually cause delamination or stress cracking.

Another problem with cold temperatures concerns the case of a laminate over plywood. Plywood is relatively stable thermally and has a low coefficient of thermal expansion as compared to the resins in the fiberglass laminated over it. If the fiberglass laminate is relatively thin and the plywood fairly thick, the plywood will dominate. When the resin tries to contract in cold temperatures, the plywood will try to prevent it from contracting and local cracking will occur in the resin because the plywood is not homogeneous. There is a grain to the wood, so some areas won't restrain the contracting resin and other areas will. As a result, spiderweb cracking can occur. This effect has been noted on new boats that have been built in warmer climates and sent to northern regions.

Repair

Failures in FRP constructed vessels fall into one of two categories. First, the failure can be the result of a collision or other extreme force. Secondly, the failure may have occurred because of design inadequacies. In the case of the latter, the repair should go beyond restoring the damaged area back to its original strength. The loads and stress distributions should be reexamined to determine proper design alterations. When the failure is caused by an unusual event, it should be kept in mind that all repair work relies on secondary bonding, which means that stronger or additional replacement material is needed to achieve the original strength. In general, repair to FRP vessels can be easier than other materials. However, proper preparation and working environment are critical.

Major Single-Skin Damage

Damage to the hull or deck structure is considered major when the structural integrity of the vessel is compromised. If the damage is extensive, provisions must be made to adequately support the vessel to insure the restoration of the original form. The as-built laminate schedule should be determined in order to reproduce strength and orientation properties. The following general repair procedure should be followed: [4-34]

Edge and Surface Preparation: The area to be repaired should be defined by a thorough survey of the damage. The laminate should be cut back to an area that has been determined to be sound. The edges of the sound laminate should be tapered back to a slope of 1:12 as shown in Figure 4-23b. Surface preparation with coarse sandpaper is recommended to produce a roughened area for secondary bond adhesion.

Molding: The method of creating a female mold for repairing a damaged area depends greatly on the extent of the damage. In the case of a 75 foot Gulf Shrimper that collided with a barge, the entire bow section of the vessel was replaced using a female mold taken from a sistership. [4-35] When damage to an area is not too extensive, the general form can be temporarily recreated using auto body filler, thus enabling a mold to be fabricated in place. The area is subsequently cut back to sound laminate, as outlined above. Large molds may require stiffeners to maintain their form.

Laminating: Laminated repairs have traditionally been done using a ply taper sequence illustrated in Figure 4-23a. It has been determined that this technique produces relatively weak resin rich areas at the repair interface. As an alternative, it is recommended to first apply a layer that completely covers the work area, followed by successively tapered layers. The plies should be slightly larger then necessary when laminated to allow for subsequent grinding. Also note the extension of the first and last layers over the sound laminate illustrated in Figure 4-23b.

Finishing: When fairing the repair job in preparation for gel coat or paint application, extreme care should be exercised to insure that the laminated skins of the repair reinforcements are not compromised.

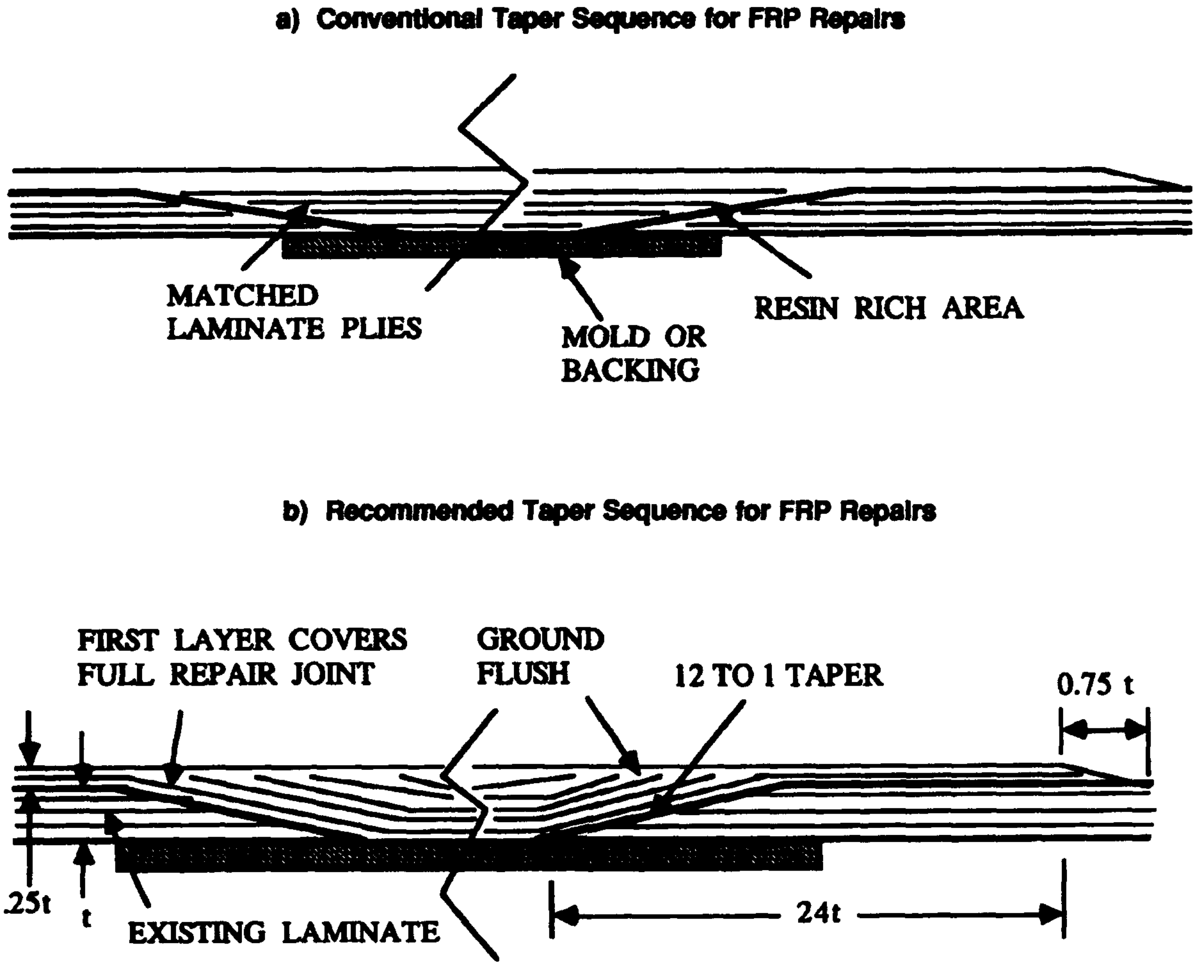


Figure 4-23 Illustrations of Conventional and Preferred FRP Hole Repair Techniques for Single-Skin Construction [USCG NVIC No. 8-87]

Major Damage in Sandwich Construction

Determining the extent of damage with sandwich construction is a bit more difficult because debonding may extend far beyond the area of obvious visual damage. The cut back area should be increasingly larger proceeding from the outer to the inner skin as shown in Figure 4-24. Repair to the skins is generally similar to that for single-skin construction. The new core will necessarily be thinner than the existing one to accommodate the additional repair laminate thickness. Extreme care must be exercised to insure that the core is properly bonded to both skins and the gap between new and old core is filled.

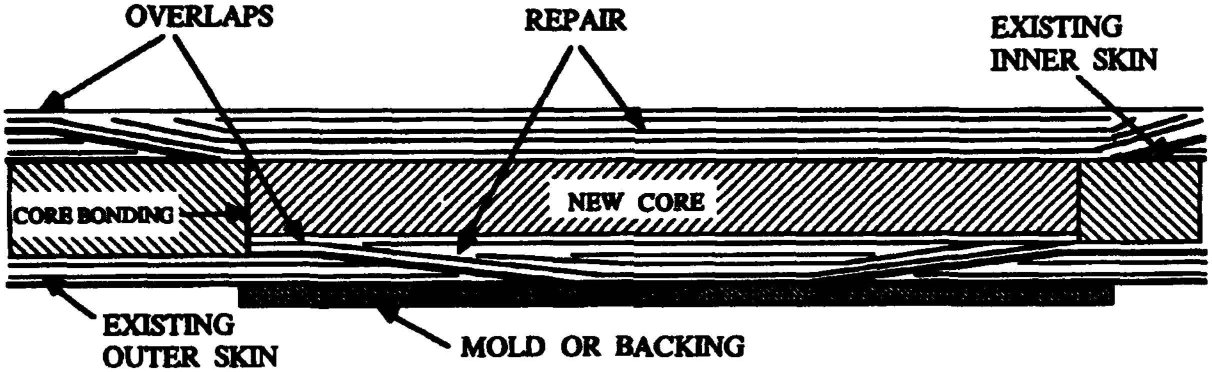


Figure 4-24 Technique for Repairing Damage to Sandwich Construction [USCG NVIC No. 8-87]

Core Debonding

Repairing large sections of laminate where the core has separated from the skin is costly and will generally result in a structure that is inferior to the original design, both from a strength and weight standpoint. Pilot holes must be drilled throughout the structure in the areas suspected to be debonded. These holes will also serve as ports for evacuation of any moisture and injection of resin, which can restore the mechanical aspects of the core bond to a certain degree. In most instances, the core never was fully bonded to the skins as a result of manufacturing deficiencies.

Small Non-Penetrating Holes

If the structural integrity of a laminate has not been compromised, a repair can be accomplished using a "structural" putty. This mixture usually consists of resin or a gel coat formulation mixed with milled fibers or other randomly oriented filler that contributes to the mixture's strength properties.

For minor surface damage, filler is only required to thicken the mixture for workability. The following general procedure [4-36] can be followed:

- Clean surface with acetone to remove all wax, dirt and grease.
- Remove the damaged material by sanding or with a putty knife or razor blade. Wipe clean with acetone, being careful not to saturate the area.
- Formulate the putty mixture using about 1% MEKP catalyst.
- Apply the putty mixture to the damaged area to a thickness of about 1/16".
- If a gel coat mixture is used, a piece of cellophane should be placed over the gel coat and spread out with a razor's edge. After about 30 minutes, the cellophane can be removed.
- Wet-sand and buff gel coated surface or sand and paint when matching a painted finish.

Blisters

The technique used to repair a blistered hull depends on the extent of the problem. Where blisters are few and spaced far apart, they can be repaired on an individual basis. If areas of the hull have a cluster of blisters, gel coat should be removed from the vicinity surrounding the problem. In the case where the entire bottom is severely blistered, gel coat removal over the entire surface is recommended. The following repair procedure [4-37] is advised:

> **Gel Coat Removal:** Sand blasting is not recommended because it shatters the underlying laminate, thus weakening the structure. Also, the gel coat is harder than the laminate, which has the effect of quickly eroding the laminate once the gel coat is removed. Grinding or sanding until the laminate has a "clear" quality is the preferred approach.
>
> **Laminate Preparation:** It is essential that the laminate is clean. If the blister can not be completely removed, the area should be thoroughly washed with water and treated with a water soluble silane wash. A final wash to remove excess silane is recommended. The laminate is then required to be thoroughly dried. Vacuum bagging is an excellent way to accomplish this. In lieu of this, moderate heat application and fans can work.
>
> **Resin Coating:** The final critical element of the repair procedure is the selection of a resin to seal the exposed laminate and create a barrier layer. As illustrated in the Blisters section, vinyl ester resins are superior for this application and are chemically compatible with polyester laminates, which to date are the only materials to exhibit blistering problems. Epoxy resin in itself can provide the best barrier performance, but the adhesion to other materials will not be as good. Epoxy repair might be most appropriate for isolated blisters, where the increased cost can be justified.

Manufacturing Processes

The various fabrication processes applicable to marine composite structures are summarized in the tables at the end of this section. The most common technique used for large structures such as boat hulls, is the open mold process. Specifically, hand lay-up or spray-up techniques are used. Spray-up of chopped fibers is generally limited to smaller hulls and parts. Figure 5-1 shows the results of an industry survey indicating the relative occurrence of various manufacturing processes within the marine industry.

The most popular forms of open molding in the marine industry are single-skin from female molds, cored construction from female molds and cored construction from male mold. Industry survey results showing the popularity of these techniques is shown in Figure 5-2.

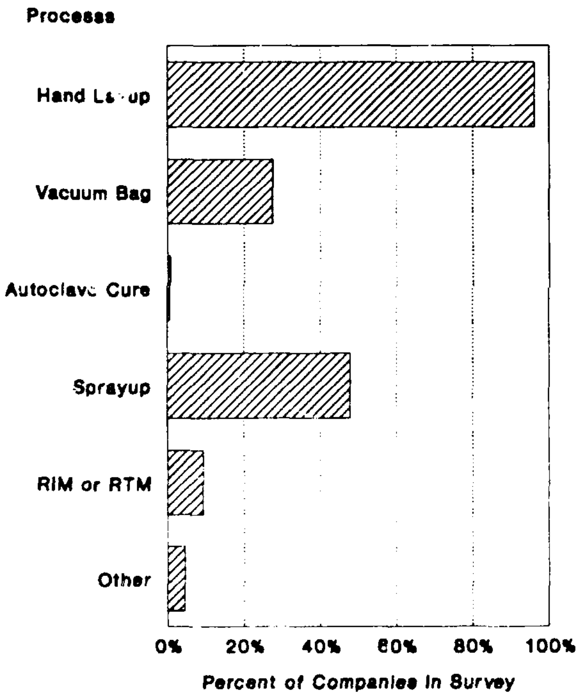


Figure 5-1 Marine Industry Manufacturing Processes [EGA Survey]

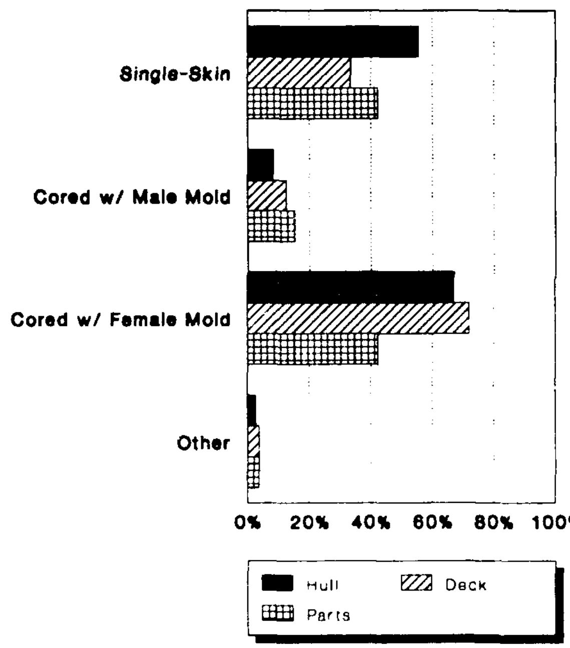


Figure 5-2 Marine Industry Construction Techniques [EGA Survey]

Mold Building

Almost all production hull fabrication is done with female molds that enable the builder to produce a number of identical parts with a quality exterior finish. It is essential that molds are carefully constructed using the proper materials if consistent finish quality and dimensional control are desired.

Plugs

A mold is built over a plug that geometrically resembles the finished part. The plug is typically built of non-porous wood, such as oak, mahogany or ash. The wood is then covered with about three layers of 7.5 to 10 ounce cloth or equivalent thickness of mat. The surface is faired and finished with a surface curing resin, with pigment in the first coat to assist in obtaining a uniform surface. After the plug is wet-sanded, three coats of carnauba wax and a layer of PVA parting film can be applied by hand.

Molds

The first step of building a mold on a male plug consists of gel coat application, which is a critical step in the process. A non-pigmented gel coat that is specifically formulated for mold applications should be applied in 10 mil layers to a thickness of 30 to 40 mils. The characteristics of tooling gel coats include: toughness, high heat distortion, high gloss and good glass retention. A back-up layer of gel that is pigmented to a dark color is then applied to enable the laminator to detect air in the production laminates and evenly apply the production gel coat surfaces.

After the gel coat layers have cured overnight, the back-up laminate can be applied, starting with a surfacing mat or veil to prevent print-through. Reinforcement layers can consist of either mat and cloth or mat and woven roving to a minimum thickness of ¼ inch. Additional thickness or coring can be used to stiffen large molds. Framing and other stiffeners are required to strengthen the overall mold and permit handling.

The mold should be post cured in a hot-air oven at 100°F for 12 to 24 hours. After this, wet-sanding and buffing can be undertaken. The three layers of wax and PVA are applied in a manner similar to the plug. [5-1]

Single Skin Construction

Almost all marine construction done from female molds is finished with a gel coat surface, therefore, this is the first procedure in the fabrication sequence. Molds must first be carefully waxed and coated with a parting agent. Gel coat is sprayed to a thickness of 20 to 30 mils and allowed to cure. A back-up reinforcement, such as a surfacing mat, veil or polyester fabric is then applied to reduce print-through. Recent testing has shown that the polyester fabrics have superior mechanical properties while possessing thermal expansion coefficients similar to common resin systems. [5-2]

Resin can be delivered either by spray equipment or in small batches via buckets. If individual buckets are used, much care must be exercised to ensure that the resin is properly catalyzed. Since the catalyzation process is very sensitive to temperature, ambient conditions should be maintained between 60° and 85°F. Exact formulation of catalysts and accelerators is required to match the environmental conditions at hand.

Reinforcement material is usually precut outside the mold on a flat table. Some material supply houses are now offering precut kits of reinforcements to their customers. [5-3] After a thin layer of resin is applied to the mold, the reinforcement is put in place and resin is drawn up by rolling the surface with mohair or grooved metal rollers, or with squeegees. This operation is very critical in hand lay-up fabrication to ensure complete wet-out, consistent fiber/resin ratio, and to eliminate entrapped air bubbles.

After the hull laminating process is complete, the installation of stringers and frames can start. The hull must be supported during the installation of the interior structure because the laminate will not have sufficient stiffness to properly support themselves. Secondary bonding should follow the procedures outlined in the section on Details.

Cored Construction from Female Molds

Cored construction from female molds follows much the same procedure as that for single skin construction. The most critical phase of this operation, however, is the application of the core to the outer laminate. The difficulty stems from the following:

- Dissimilar materials are being bonded together
- Core materials usually have some memory and resist insertion into concave molds
- Bonding is a "blind" process once the core is in place
- Contoured core material will produce voids as the material is bent into place
- Moisture contamination of surfaces

Investigators have shown that mechanical properties can be severely degraded if voids are present within the sandwich structure. [5-4] Most suppliers of contoured core material also supply a viscous bedding compound that is specially formulated to bond these cores.

Whenever possible, non-contoured core material is preferable. In the case of PVC foams, preheating may be possible to allow the material to more easily conform to a surface with compound curves. Vacuum bag assistance is recommended to draw these cores down to the outer laminate and to pull resin up into the surface of the core.

Cored Construction over Male Plugs

When hulls are fabricated on a custom basis, boat builders usually do not go through the expense of building a female mold. Instead, a male plug is constructed, over which the core material is placed directly. Builders claim that a better laminate can be produced over a convex rather than a concave surface.

Figure 5-5 shows the various stages of one-off construction from a male plug. (A variation of the technique shown involves the fabrication of a plug finished to the same degree as described above under Mold Making. Here, the inner skin is laminated first while the hull is upside-down. This technique is more common with balsa core materials.) A detail of the core and outer skin on and off of the mold is shown in Figure 5-3.

With linear PVC foam, the core is attached to the battens of the plug with either nails from the outside or screws from the inside, as illustrated in Figure 5-4. If nails are used, they are pulled through the foam after the outside laminate has cured. Screws can be reversed out from inside the mold.

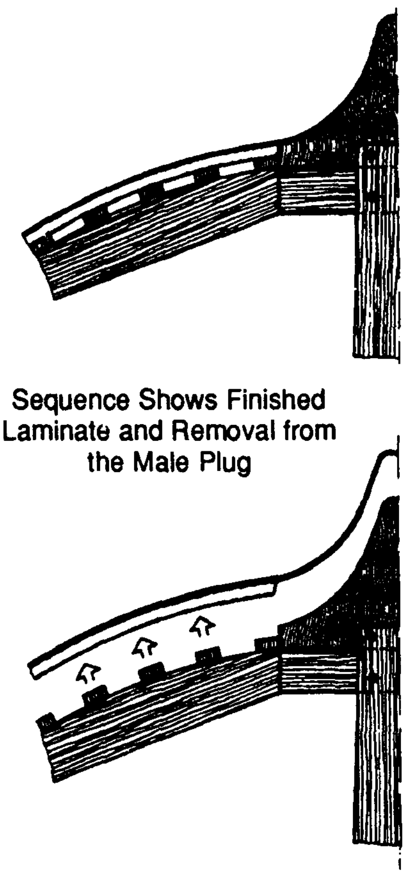


Figure 5-3 Detail of Sandwich Construction over Male Plug [Johannsen, *One-Off Airex Fiberglass Sandwich Construction*]

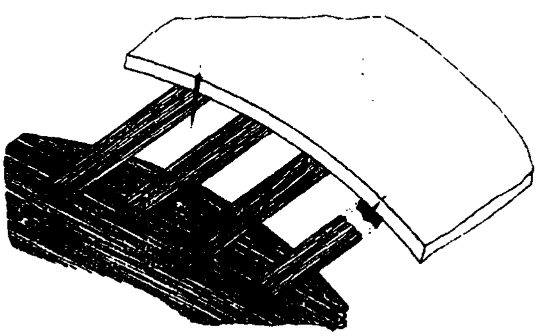


Figure 5-4 Detail of Foam Placement on Plugs Showing Both Nails from the Outside and Screws from the Inside [Johannsen, *One-Off Airex Fiberglass Sandwich Construction*]

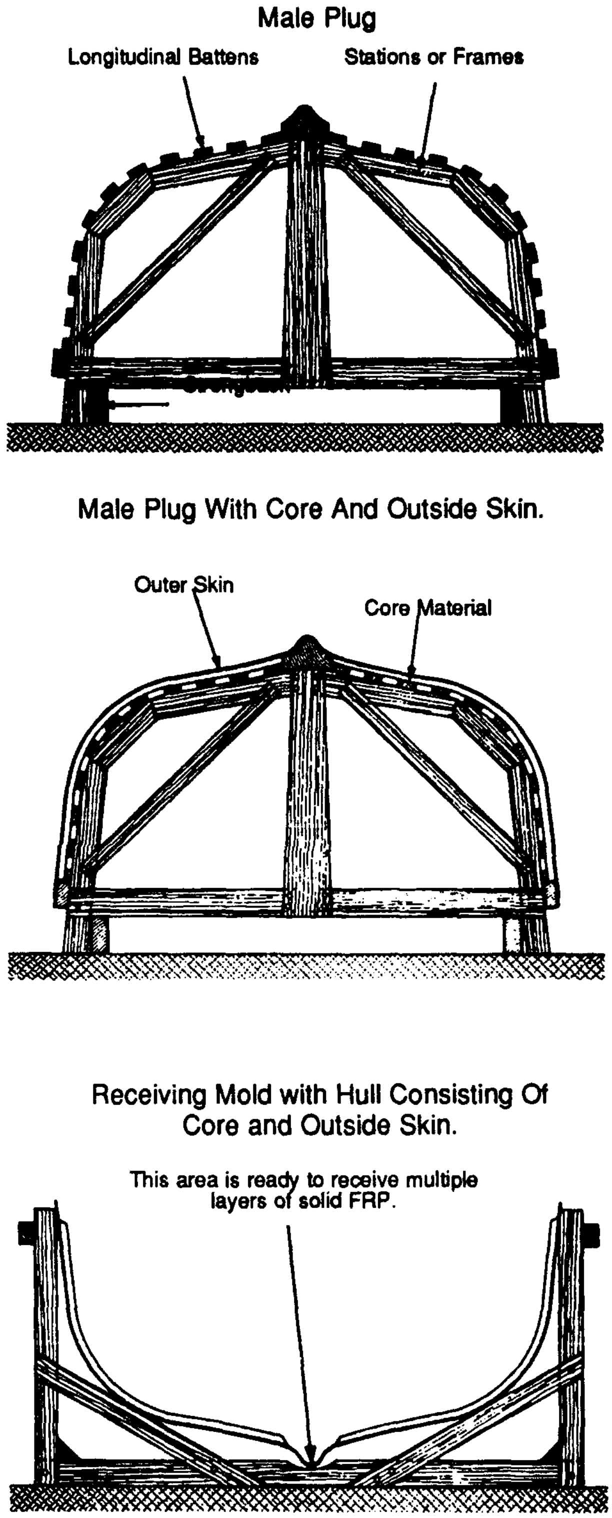


Figure 5-5 Simple, Wood Frame Male Plug used in Sandwich Construction [Johannsen, *One-Off Airex Fiberglass Sandwich Construction*]

Equipment

Various manufacturing equipment is used to assist in the laminating process. Most devices are aimed at either reducing man-hour requirements or improving manufacturing consistency. Figure 5-6 gives a representation of the percentage of marine fabricators that use the equipment described below.

Chopper Gun and Spray-Up

A special gun is used to deposit a mixture of resin and chopped strands of fiberglass filament onto the mold surface that resembles chopped strand mat. The gun is called a "chopper gun" because it draws continuous strands of fiberglass from a spool through a series of whirling blades that chop it into strands about two inches long. The chopped strands are blown into the path of two streams of atomized liquid resin, one accelerated and one catalyzed (known as the two-pot gun). When the mixture reaches the mold, a random pattern is produced.

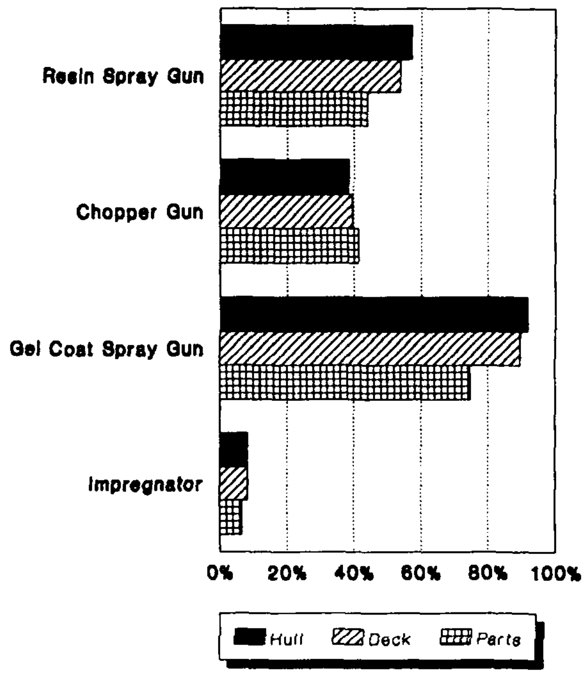


Figure 5-6 Marine Industry Manufacturing Equipment [EGA Survey]

Alternately, catalyst can be injected into a stream of promoted resin with a catalyst injector gun. Both liquids are delivered to a single-head, dual nozzle gun in proper proportions and are mixed either internally or externally. Control of gel times with this type of gun is accomplished by adjusting the rate of catalyst flow.

Spray systems may also be either airless or air-atomized. The airless systems use hydraulic pressure to disperse the resin mix. The air atomized type introduces air into the resin mix to assist in the dispersion process. Figures 5-7 and 5-8 illustrate the operation of air-atomizing and airless systems.

Resin and Gel Coat Spray Guns

Volume production shops apply resin to laminates via resin spray guns. A two-part system is often used that mixes separate supplies of catalyzed and accelerated resins with a gun similar to a paint sprayer. Since neither type of resin can cure by itself without being added to the other, this system minimizes the chances of premature cure of the resin. This system provides uniformity of cure as well as good control of the quantity and dispersion of resin. Resin spray guns can also be of the catalyst injection type described above. Table 5-1 provides a summary of the various types of spray equipment available. Air atomized guns can either be the internal type illustrated in Figure 5-9 or the external type shown in Figure 5-10.

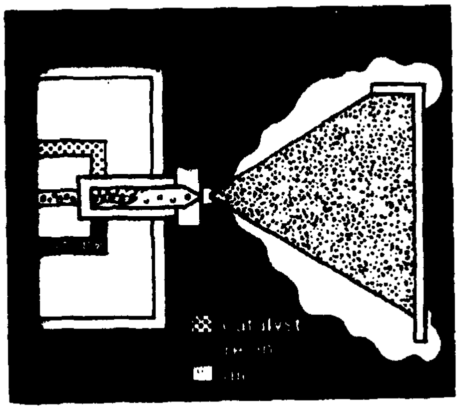


Figure 5-7 Air Atomizing Gun Showing Possible "Fog" Effect at Edge of Spray Pattern [Venus-Gusmer]

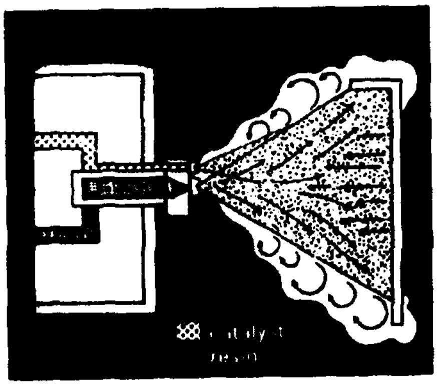


Figure 5-8 Airless Spray Gun Showing Possible Bounce Back from the Mold [Venus-Gusmer]

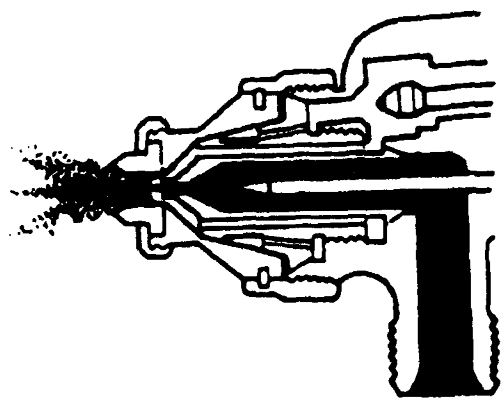


Figure 5-9 Internal Atomization Spray Gun [Binks Mfg.]

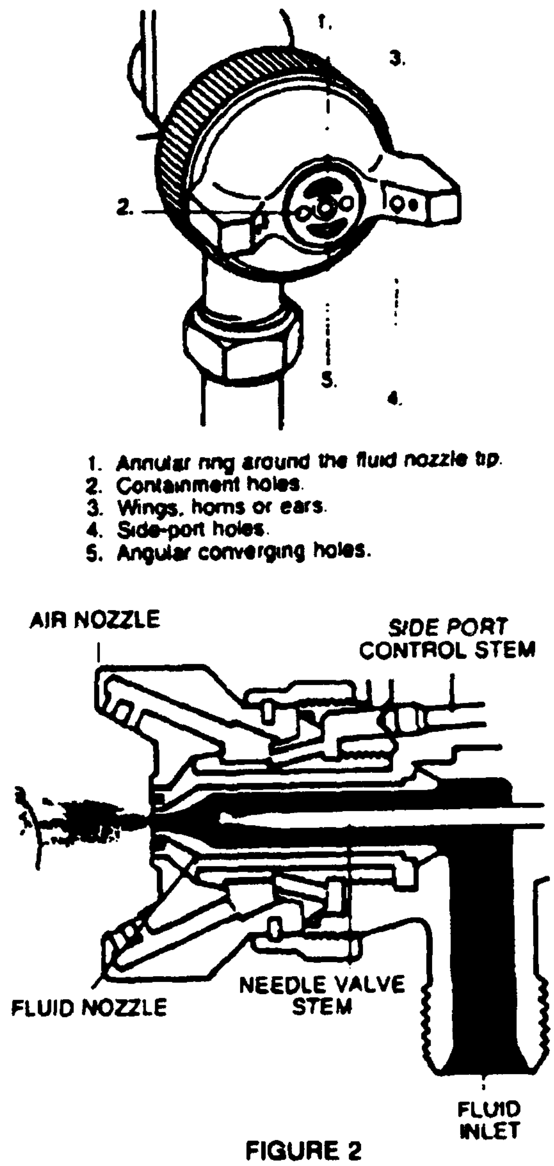


Figure 5-10 External Atomization Spray Gun [Binks Mfg.]

Table 5-1. Description of Spray Equipment [Cook, *Polycor Polyester Gel Coats and Resins*]

Process	Technique	Description
Material Delivery	Gravity	The material is above the gun and flows to the gun (not commonly used for gel coats - sometimes used for more viscous materials).
	Suction	The material is picked up by passing air over a tube inserted into the material (no direct pressure on the material). Not commonly used for making production parts due to slow delivery rates.
	Pressure	The material is forced to the gun by direct air pressure or by a pump. Pressure feed systems - mainly pumps - are the main systems used with gel coats.
Method of Catalyzation	Hot Pot	Catalyst is measured into a container (pressure pot) and mixed by hand. This is the most accurate method but requires the most clean up.
	Catalyst Injection	Catalyst is added and mixed at or in the gun head requiring Cypriot lines and a method of metering catalyst and material flow. This is the most common system used in larger shops.
Atomization	Internal	Air and resin meet inside the gun head and come out a single orifice. This system is not recommended for gel coats as it has a tendency to cause porosity and produce a rougher film. Internal mix air nozzles are typically used in high production applications where finish quality is not critical. The nozzles are subject to wear, although replacement is relatively inexpensive. Some materials tend to clog nozzles.
	External	Air and resin meet outside the gun head or nozzle. This is the most common type of spray gun. The resin is atomized in three stages: First Stage Atomization - fluid leaving the nozzle orifice is immediately surrounded by an envelope of pressurized air emitted from an annular ring. Second Stage Atomization - the fluid stream next intersects two streams of air from converging holes indexed to 90° to keep the stream from spreading. Third Stage Atomization - the "wings" of the gun have air orifices that inject a final stream of air designed to produce a fan pattern.
	Airless Atomization	Resin is pressurized to 1200 to 2000 psi via a high ratio pump. The stream atomizes as it passes through the sprayer orifice. This system is used for large and high volume operations, as it is cleaner and more efficient than air atomized systems.
	Air Assist Airless	Material is pressurized to 500 to 1000 psi and further atomized with low pressure air at the gun orifice to refine the spray pattern.

Impregnator

Impregnators are high output machines designed for wetting and placing woven roving and other materials that can retain their integrity when wetted. These machines can also process reinforcements that combine mat and woven roving as well as Kevlar.®

Laminates are layed into the mold under the impregnator by using pneumatic drive systems to move the machine with overhead bridge-crane or gantries. Figure 5-11 shows a configuration for a semi-gantry impregnator, which is used when the span between overhead structural members may be too great.

Roll goods to 60 inches can be wetted and layed up in one continuous movement of the machine. The process involves two nip rollers that control a pool of catalyzed material on either side of the reinforcement. An additional set of rubber rollers is used to feed the reinforcement through the nip rollers and prevent the reinforcement from being pulled through by its own weight as it drops to the mold. Figure 5-12 is a schematic representation of the impregnator material path.

Impregnators are used for large scale operations, such as mine countermeasure vessels, 100 foot yachts and barge volume production of barge covers. In addition to the benefits achieved through reduction of labor, quality control is improved by reducing the variation of laminate resin content. High fiber volumes and low void content are also claimed by equipment manufacturers. [5-5]

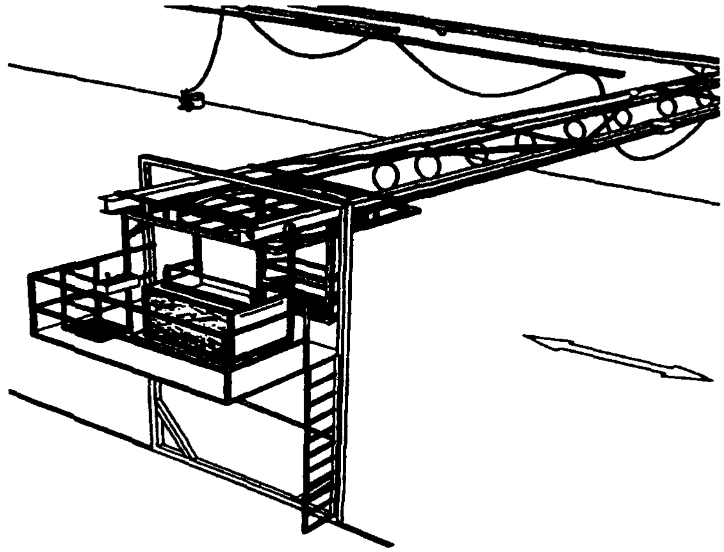


Figure 5-11 Configuration of Semi-Gantry Impregnator [Venus-Gusmer]

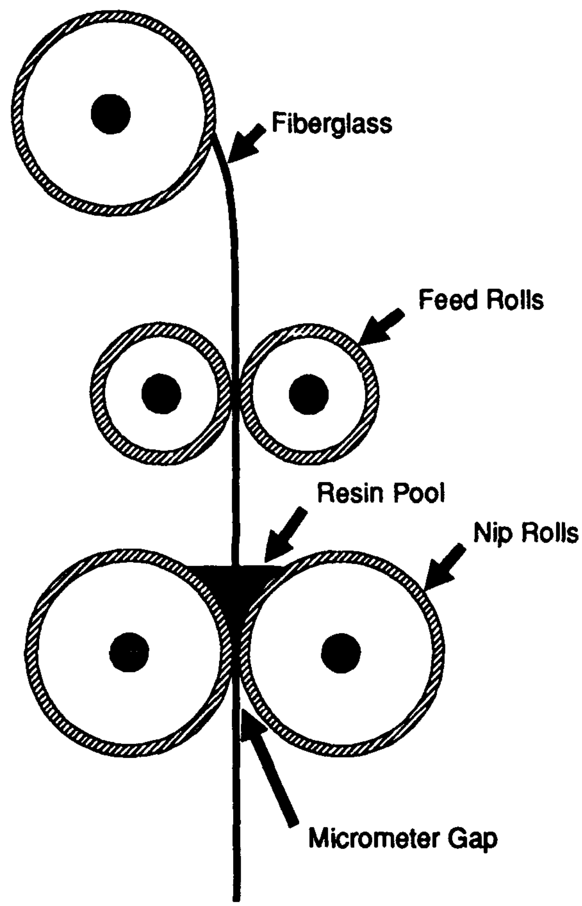


Figure 5-12 Impregnator Material Path [Raymer, *Large Scale Processing Machinery for Fabrication of Composite Hulls and Superstructures*]

Health Considerations

This document's treatment of the industrial hygiene topic should serve only as an overview. Builders are advised to familiarize themselves with all relevant federal, state and local regulations. An effective in-plant program considers the following items: [5-6]

- Exposure to styrene, solvents, catalysts, fiberglass dust, noise and heat
- The use of personal protective equipment to minimize skin, eye and respiratory contact to chemicals and dust
- The use of engineering controls such as ventilation, enclosures or process isolation
- The use of administrative controls, such as worker rotation, to minimize exposure
- Work practice control, including material handling and dispensing methods, and storage of chemicals
- A hazard communication program to convey chemical information and safe handling techniques to employees

Some health related terminology should be explained to better understand the mechanisms of worker exposure and government regulations. The relationship between the term "toxicity" and "hazard" should first be defined. All chemicals are toxic, if they are handled in an unsafe manner. Alternatively, "hazard" takes into account the toxicity of an agent and the exposure that a worker has to that agent. "Acute toxicity" of a product is its harmful effect after short-term exposure. "Chronic toxicity" is characterized by the adverse health effects which have been caused by exposure to a substance over a significant period of time or by long-term effects resulting from a single or few doses. [5-7]

Exposure to agents can occur several ways. Skin and eye contact can happen when handling composite materials. At risk are unprotected areas, such as hands, lower arms and face. "Irritation" is defined as a localized reaction characterized by the presence of redness and swelling, which may or may not result in cell death. "Corrosive" materials will cause tissue destruction without normal healing. During the manufacturing and curing of composites, the release of solvents and other volatiles from the resin system can be inhaled by workers. Fiber and resin grinding dust are also a way that foreign agents can be inhaled. Although not widely recognized, ingestion can also occur in the work place. Simple precautions, such as washing of hands prior to eating or smoking can reduce this risk.

Worker exposure to contaminants can be monitored by either placing a sophisticated pump and air collection device on the worker or using a passive collector that is placed on the worker's collar. Both techniques require that the interpretation of data be done by trained personnel. Exposure limits are based on standards developed by the American Conference of Governmental Industrial Hygienists (ACGIH) as follows:

Threshold Limit Value - Time Weighted Average (TLV-TWA) - the time-weighted average for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be exposed, day after day, without adverse effect.

Threshold Limit Value - Short Term Exposure Limit (TLV-STEL) - the concentration to which workers can be exposed continuously for a short period of time (15 minutes) without suffering from (1) irritation, (2) chronic or irreversible tissue damage, or (3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue or materially reduce work efficiency, and provided that the daily TLV-TWA is not exceeded.

Threshold Limit Value - Ceiling (TLV-C) - the concentration that should not be exceeded during any part of the working day.

The Occupational Safety and Health Administration (OSHA) issues legally binding Permissible Exposure Limits (PELs) for various compounds based on the above defined exposure limits. The limits are published in the Code of Federal Regulations 29 CFR 19100.1000 and are contained in OSHA's revised Air Contaminant Standard (OSHA, 1989). Table 5-2 lists the permissible limits for some agents found in a composites fabrication shop.

Table 5-2. Permissible Exposure Limits and Health Hazards of Some Composite Materials [SACMA, *Safe Handling of Advanced Composite Material Components: Health Information*]

Component	Primary Health Hazard	TLV-TWA	TLV-STEL
Styrene Monomer	Styrene vapors can cause eye and skin irritation. It can also cause systemic effects on the central nervous system.	50 ppm	100 ppm
Acetone	Overexposure to acetone by inhalation may cause irritation of mucous membranes, headache and nausea.	750 ppm	1000 ppm
Methyl ethyl keytone (MEK)	Eye, nose and throat irritation.	200 ppm	300 ppm
Polyurethane Resin	The isicyanates may strongly irritate the skin and the mucous membranes of the eyes and respiratory tract.	0.005 ppm	0.02 ppm
Carbon and Graphite Fibers	Handling of carbon and graphite fibers can cause mechanical abrasion and irritation.	10 mg/m^{3*}	—
Fiberglass	Mechanical irritation of the eyes, nose and throat.	10 $mg/m^{3\dagger}$	—
Aramid Fibers	Minimal potential for irritation to skin.	5 $fibrils/cm^{3\ddagger}$	—

* Value for total dust - natural graphite is to be controlled to 2.5 mg/m^3

† Value for fibrous glass dust - Although no standards exist for fibrous glass, a TWA of 15 mg/m^3 (total dust) and 5 mg/m^3 (respirable fraction) has been established for "particles not otherwise regulated"

‡ Acceptable exposure limit established by DuPont based on internal studies

The boat building industry has expressed concern that the PEL's for styrene would be extremely costly to achieve when large parts, such as hulls, are evaluated. In a letter to the Fiberglass Fabrication Association, OSHA stated:

> "The industry does not have the burden of proving the technical infeasibility of engineering controls in an enforcement case....The burden of proof would be on OSHA to prove that the level could be attained with engineering and work practice controls in an enforcement action if OSHA believed that was the case." [5-8]

OSHA also stated that operations comparable to boat building may comply with the PEL's through the use of respiratory protection when they:

> "(1) employ the manual or spray-up process, (2) the manufactured items utilize the same equipment and technology as that found in boat building, and (3) the same consideration of large part size, configuration interfering with air-flow control techniques, and resin usage apply."

The use of proper ventilation is the primary technique for reducing airborne contaminants. There are three types of ventilation used in polyester fabrication shops:

General (Dilution) Ventilation. The principal of dilution ventilation is to dilute contaminated air with a volume of fresh air. Figure 5-13 shows good and bad examples of general ventilation systems. These types of systems can be costly as the total volume of room air should be changed approximately every 2 to 12 minutes.

Local Ventilation. A local exhaust system may consist of a capture hood or exhaust bank designed to evacuate air from a specific area. Spray booths are an example of local ventilation devices used in shops where small parts are fabricated.

Directed-Flow Ventilation. These systems direct air flow patterns over a part in relatively small volumes. The air flow is then captured by an exhaust bank located near the floor, which establishes a general top-to-bottom flow. [5-6]

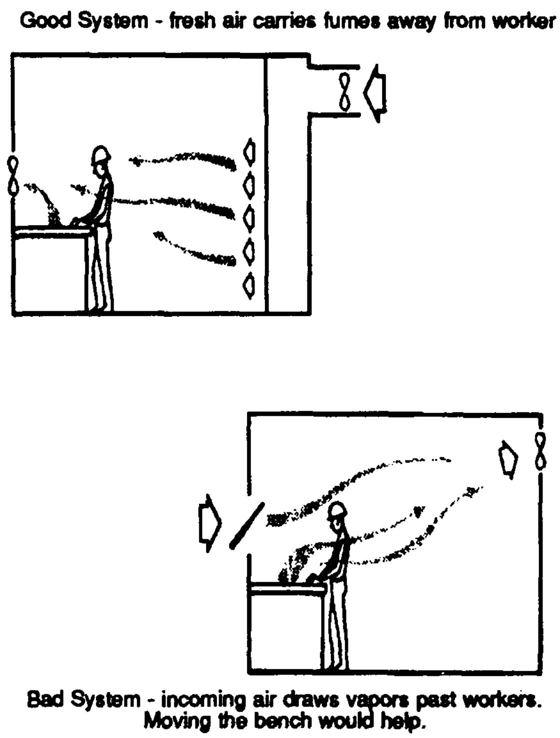


Figure 5-13 General Ventilation Techniques to Dilute Airborne Contaminants through Air Turnover [FRP Supply, *Health, Safety and Environmental Manual*]

One yard in Denmark, Danyard Aalborg A/S, has invested a significant amount of capital to reach that country's standards for styrene emission during the fabrication of fiberglass multipurpose navy vessels. Total allowable PELs in Denmark are 25 ppm, which translates to about 12 ppm for styrene when other contaminants are considered. The air-handling system that they've installed for a 50,000 square foot shop moves over 5 million cubic feet per hour, with roughly two thirds dedicated to styrene removal and one third for heating. [5-9]

Many U.S. manufacturers are switching to replacement products for acetone to clean equipment as an effort to reduce volatiles in the workplace. Low-styrene emission laminating resins have been touted by their manufacturers as a solution to the styrene exposure problem. An example of such a product is produced by USS Chemicals and is claimed to have a 20% reduction in styrene monomer content. [5-10] To document company claims, worker exposure in Florida and California boat building plants were monitored for an 8-hour shift. In the Florida plant, average worker exposure was 120 ppm for the conventional resin and 54 ppm for the low-styrene emission resin. The California plant showed a reduction of 31% between resin systems. Table 5-3 is a breakdown of exposure levels by job description.

Table 5-3. Personnel Exposure to Styrene in Boat Manufacturing [Modern Plastics, *Low-Styrene Emission Laminating Resins Prove It in the Workplace*]

Worker Occupation	Styrene Exposure, TLV-TWA	
	Standard Resin	Low-Styrene Emission Resin
Florida Plant		
Hull gun runner	113.2	64.0
Gun runner 1	158.2	37.7
Gun runner 2	108.0	69.6
Gun runner 3	80.3	43.9
Roller 1	140.1	38.4
Roller 2	85.1	43.6
Roller 3	131.2	56.9
California Plant		
Foreman (chopper)	30	7
Chopper 2	106	77
Chopper 3	41	47
Roller 1	75	37
Roller 2	61	40
Roller 3	56	42
Area sampler 1	18	12
Area sampler 2	19	4
Area sampler 3	9	13
Area sampler 4	30	16

Future Trends

Open Mold Resin Transfer Molding (RTM)

Seemann Composites of Gulfport, Mississippi has developed a vacuum assisted RTM process that utilizes a single open-mold. Resin is injected under a vacuum film, thus eliminating the need for a second mold. Figure 5-14 shows the various elements of the process. The process is patented, primarily because of the uniqueness of the resin distribution medium. Parts up to 1000 pounds have been manufactured by the process. Materials tested include polyester, vinyl ester phenolic and epoxy resins and E-glass, carbon fiber and Kevlar® reinforcement.

Because reinforcement material is layed up dry and resin infusion is controlled, fiber volumes to 75% with wovens and 80% with unidirectionals have been achieved. Correspondingly, tensile strengths of 87 ksi and flexural strengths of 123 ksi have been documented with E-glass in vinyl ester resin. Additional advantages of the process include enhanced quality control and reduced volatile emissions. [5-11]

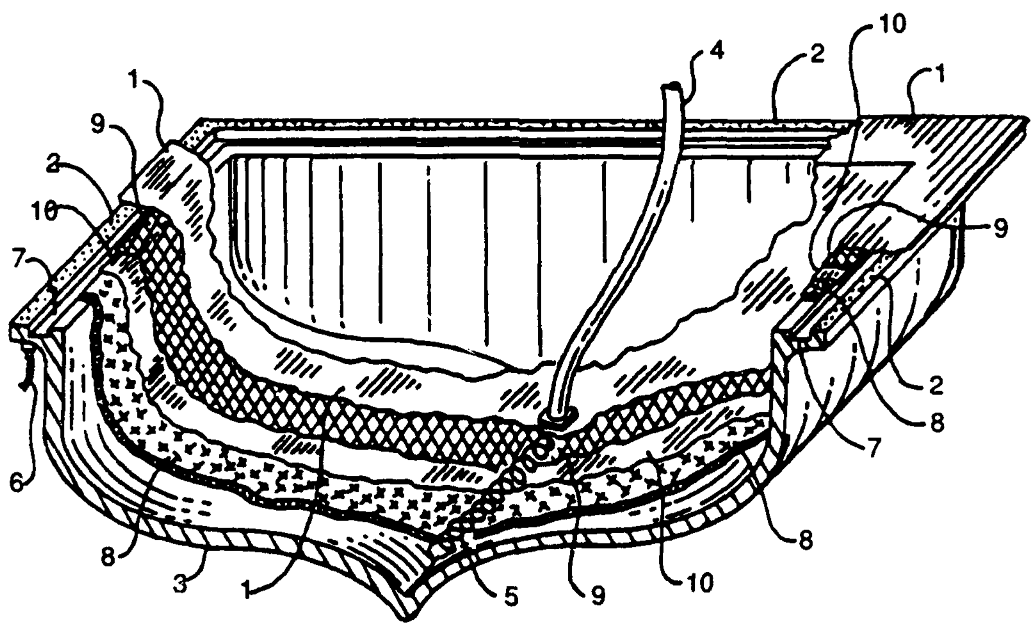


Figure 5-14 Seemann Composites Resin Infusion Molding Process (SCRIMP©) Showing: **1.** *Fluid Impervious Outer Sheet*, **2.** Sealing Tape, **3.** Rigid Mold, **4.** Resin Inlet, **5.** Helical Spring Extension, **6.** Vacuum Outlet, **7.** Continuous Peripheral Trough, **8.** Dry Lay-Up of Reinforcement Material, **9.** Distribution Medium, **10.** Peel Ply [Seemann Composites, US Patent # 4,902,215]

Thermoplastic-Thermoset Hybrid Process

A company called Advance USA is currently constructing a 15 foot racing sailboat called the JY 15 using a combination of vacuum forming, injection foam and resin transfer molding. Designed by Johnstone Yachts, Inc. the boat is a very high-performance planing boat.

The hull is essentially a three-element composite, consisting of a laminated thermoplastic sheet on the outside, a polyurethane foam core and an inner skin of RTM produced, reinforced polyester. The 0.156 inch outer sheet is vacuum formed and consists of pigmented Rovel® (a weatherable rubber-styrene copolymer made by Dow Chemical and used for hot tubs, among other things) covered with a scratch resistant acrylic film and backed by an impact grade of Dow's Magnum ABS. The foam core is a two part urethane that finishes out to be about three pounds per cubic foot. The inner skin is either glass cloth or mat combined with polyester resin using an RTM process.

The hull and deck are built separately and bonded together with epoxy as shown in Figure 5-15. Although investment in the aluminum-filled, epoxy molds is significant, the builder claims that a lighter and stronger boat can be built by this process in two-thirds the time required for spray-up construction. Additionally, the hull has the advantage of a thermoplastic exterior that is proven to be more impact resistant than FRP. Closed-mold processes also produce less volatile emmisions. [5-12]

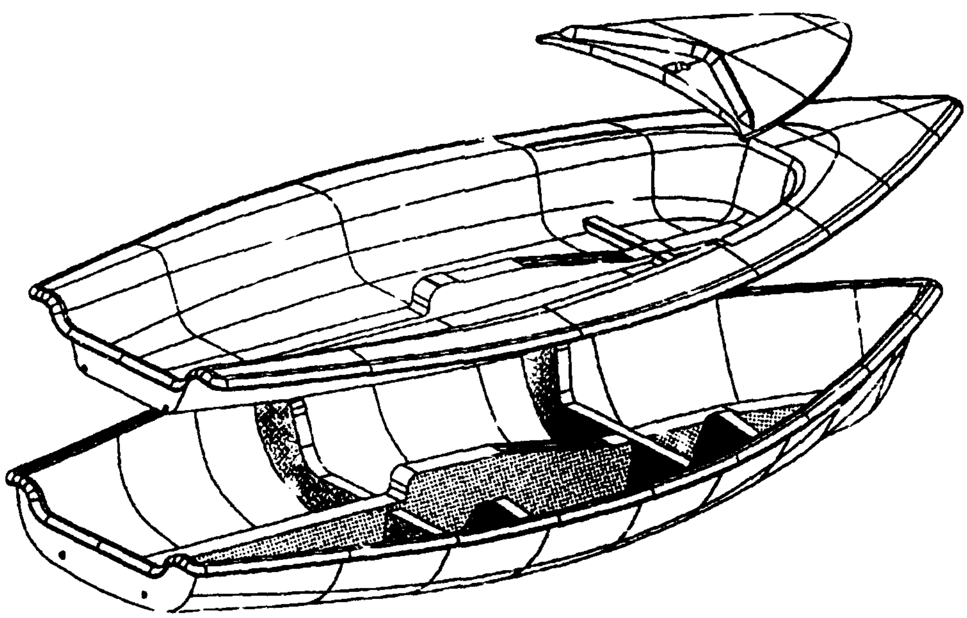


Figure 5-15 Schematic of JY-15 Showing Hull and Deck Parts prior to Joining with Epoxy [Yachting, *Yachting's 1990 Honor Roll*]

Post Curing

The physical properties of polymer laminates is very dependent upon the degree of cross-linking of the matrices during polymerization. Post curing can greatly influence the degree of cross-linking and thus the glass-transition temperature of thermoset resin systems. Some builders of custom racing yachts are post curing hulls, especially in Europe where epoxies are used to a greater extent. An epoxy such as Gougeon's GLR 125 can almost double its tensile strength and more than double ultimate elongation when cured at 250°F for three hours. [5-13]

Owens-Corning performed a series of tests on several resin systems to determine the influence of cure cycle on material properties. Resin castings of isophthalic polyester, vinyl ester and epoxy were tested, with the results shown in Table 5-4.

Table 5-4. Effect of Cure Conditions on Mechanical Properties [Owens-Corning, *Postcuring Changes Polymer Properties*]

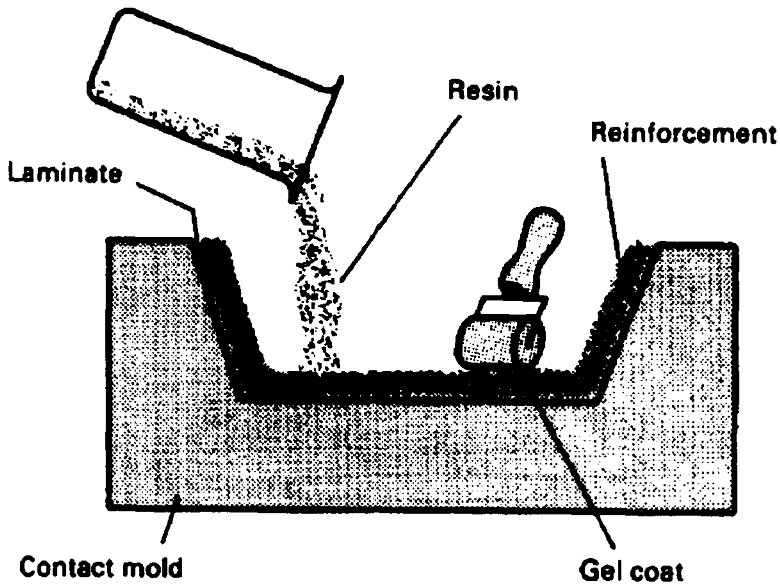
Resin System	Cure Cycle	Tensile Properties			Flexural Properties	
		Young's Modulus (x 10^6)	Ultimate Strength (psi)	Ultimate Deformation (%)	Young's Modulus (x 10^6)	Ultimate Strength (psi)
Owens-Corning E-737 Polyester/6%Cobalt/DMA/ MEKP(100:2:1:2)	A	3.61	8000	7.0	2.0	7000
	B	4.80	13500	3.4	5.0	18900
	C	4.80	13400	3.4	5.0	18900
Dow 411-415 Vinyl Ester (100:0.4)	A	2.71	3000	9.0	2.8	6500
	B	2.80	3400	6.8	4.0	15600
	C	4.20	9500	4.2	4.8	17000
Dow DER-331 Epoxy/MDA (100:26.2)	D	3.72	12700	7.0	4.0	15600
	E	3.72	12700	6.5	4.1	15600
	F	4.39	13300	6.0	4.4	16200

Cure Cycles

A	24 hours @ 72°F
B	24 hours @ 72°F plus 1 hour @ 225°F
C	24 hours @ 72°F plus 2 hours @ 225°F
D	2 hours @ 250°F
E	2 hours @ 250°F plus 1.5 hours @ 350°F
F	2 hours @ 250°F plus 2.5 hours @ 350°F

HAND LAY-UP

A contact mold method suitable for making boats, tanks, housings and building panels for prototypes and other large parts requiring high strength. Production volume is low to medium.



Process Description

A pigmented gel coat is first applied to the mold by spray gun for a high-quality surface. When the gel coat has become tacky, fiberglass reinforcement (usually mat or cloth) is manually placed on the mold. The base resin is applied by pouring, brushing or spraying. Squeegees or rollers are used to densify the laminate, thoroughly wetting the reinforcement with the resin, and removing entrapped air. Layers of fiberglass mat or woven roving and resin are added for thickness.

Catalysts and accelerators are added to the resin system to allow the resin to cure without external heat. The amounts of catalyst and accelerator are dictated by the working time necessary and overall thickness of the finished part.

The laminate may be cored or stiffened with PVC foam, balsa and honeycomb materials to reduce weight and increase panel stiffness.

Resin Systems

General-purpose, room-temperature curing polyesters which will not drain or sag on vertical surfaces. Epoxies and vinyl esters are also used.

Molds

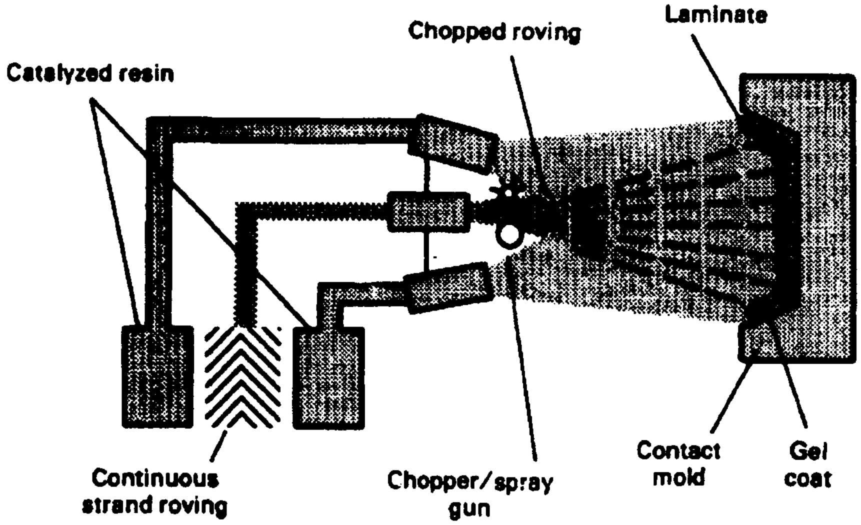
Simple, single-cavity, one-piece, either male or female, of any size. Vacuum bag or autoclave methods may be used to speed cure, increase fiber content and improve surface finish.

Major Advantages

Simplest method offering low-cost tooling, simple processing and a wide range of part sizes. Design changes are readily made. There is a minimum investment in equipment. With good operator skill, good production rates and consistent quality are obtainable.

SPRAY-UP

A low-to-medium volume, open mold method similar to hand lay-up in its suitability for making boats, tanks, tub/shower units and other simple, medium to large size shapes such as truck hoods, recreational vehicle panels and commercial refrigeration display cases. Greater shape complexity is possible with spray-up than with hand lay-up.



Process Description

Fiberglass continuous strand roving is fed through a combination chopper and spray gun. This device simultaneously deposits chopped roving and catalyzed resin onto the mold. The laminate thus deposited is densified with rollers or squeegees to remove air and thoroughly work the resin into the reinforcing strands. Additional layers of chopped roving and resin may be added as required for thickness. Cure is usually at room temperature or may be accelerated by moderate application of heat.

As with hand lay-up, a superior surface finish may be achieved by first spraying gel coat onto the mold prior to spray-up of the substrate. Woven roving is occasionally added to the laminate for specific strength orientation. Also, core materials are easily incorporated.

Resin Systems

General-purpose, room-temperature curing polyesters, low-heat-curing polyesters.

Molds

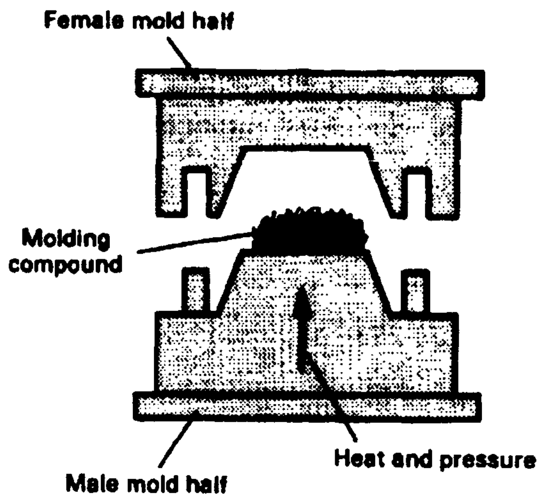
Simple, single-cavity, usually one-piece, either male or female, as with hand lay-up molds. Occasionally molds may be assembled in several pieces, then disassembled when removing the part. This technique is useful when part complexity is great.

Major Advantages

Simple, low-cost tooling, simple processing; portable equipment permits on-site fabrication; virtually no part size limitations. The process may be automated.

COMPRESSION MOLDING

A high-volume, high-pressure method suitable for molding complex, high-strength fiberglass-reinforced plastic parts. Fairly large parts can be molded with excellent surface finish. Thermosetting resins are normally used.



Process Description

Matched molds are mounted in a hydraulic or mechanical molding press. A weighed charge of sheet or bulk molding compound, or a "preform" or fiberglass mat with resin added at the press, is placed in the open mold. In the case of preform or mat molding, the resin may be added either before or after the reinforcement is positioned in the mold, depending on part configuration. The two halves of the mold are closed, and heat (225 to 320°F) and pressure (150 to 2000 psi) are applied. Depending on thickness, size, and shape of the part, curing cycles range from less than a minute to about five minutes. The mold is opened and the finished part is removed. Typical parts include: automobile front ends, appliance housings and structural components, furniture, electrical components, business machine housings and parts.

Resin Systems

Polyesters (combined with fiberglass reinforcement as bulk or sheet molding compound, preform or mat), general purpose flexible or semirigid, chemical resistant, flame retardant, high heat distortion; also phenolics, melamines, silicones, dallyl phtalate, some epoxies.

Molds

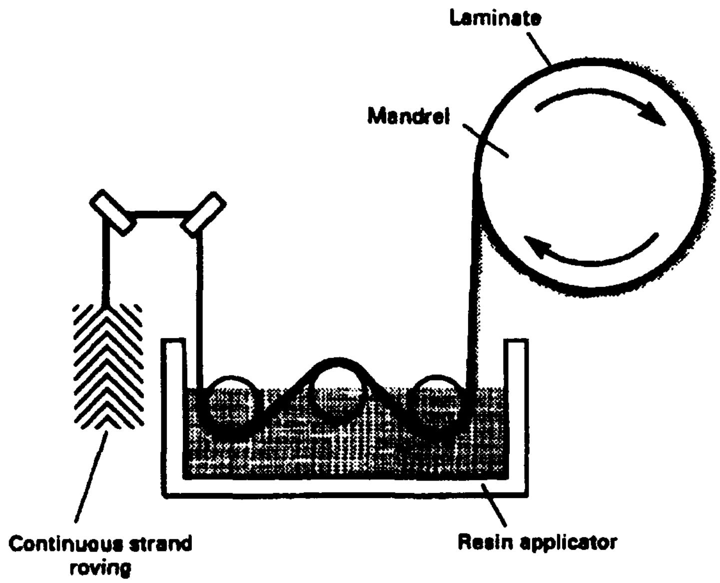
Single- or multiple-cavity hardened and chrome plated molds, usually cored for steam or hot oil heating; sometimes electric heat is used. Side cores, provisions for inserts, and other refinements are often employed. Mold materials include cast of forged steel, cast iron and cast aluminum.

Major Advantages

Highest volume and highest part uniformity of any thermoset molding method. The process can be automated. Great part design flexibility, good mechanical and chemical properties obtainable. Inserts and attachments can be molded in. Superior color and finish are obtainable, contributing to lower part finishing cost. Subsequent trimming and machining operations are minimized.

FILAMENT WINDING

A process resulting in a high degree of fiber orientation and high fiber loading to provide extremely high tensile strengths in the manufacture of hollow, generally cylindrical products such as chemical and fuel storage tanks and pipe, pressure vessels and rocket motor cases.



Process Description

Continuous strand reinforcement is utilized to achieve maximum laminate strength. Reinforcement is fed through a resin bath and wound onto a suitable mandrel (pre-impregnated roving may also be used). Special winding machines lay down continuous strands in a predetermined pattern to provide maximum strength in the directions required. When sufficient layers have been applied, the wound mandrel is cured at room temperature or in an oven. The molding is then stripped from the mandrel. Equipment is available to perform filament winding on a continuous basis.

Resin Systems

Polyesters and epoxies.

Molds

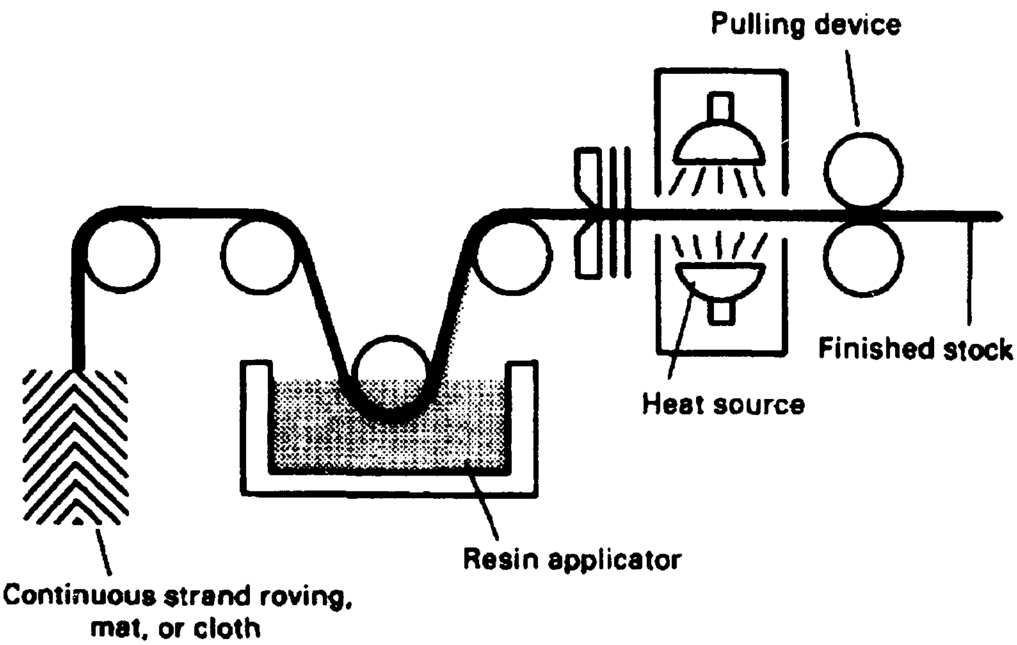
Mandrels of suitable size and shape, made of steel or aluminum form the inner surface of the hollow part. Some mandrels are collapsible to facilitate part removal.

Major Advantages

The process affords the highest strength-to-weight ratio of any fiberglass reinforced plastic manufacturing practice and provides the highest degree of control over uniformity and fiber orientation. Filament wound structures can be accurately machined. The process may be automated when high volume makes this economically feasible. The reinforcement used is low in cost. Integral vessel closures and fittings may be wound into the laminate.

PULTRUSION

A continuous process for the manufacture of products having a constant cross section, such as rod stock, structural shapes, beams, channels, pipe, tubing and fishing rods.



Process Description

Continuous strand fiberglass roving, mat or cloth is impregnated in a resin bath, then drawn through a steel die, which sets the shape of the stock and controls the fiber/resin ratio. A portion of the die is heated to initiate the cure. With the rod stock, cure is effected in an oven. A pulling device establishes production speed.

Resin Systems

General-purpose polyesters and epoxies.

Molds

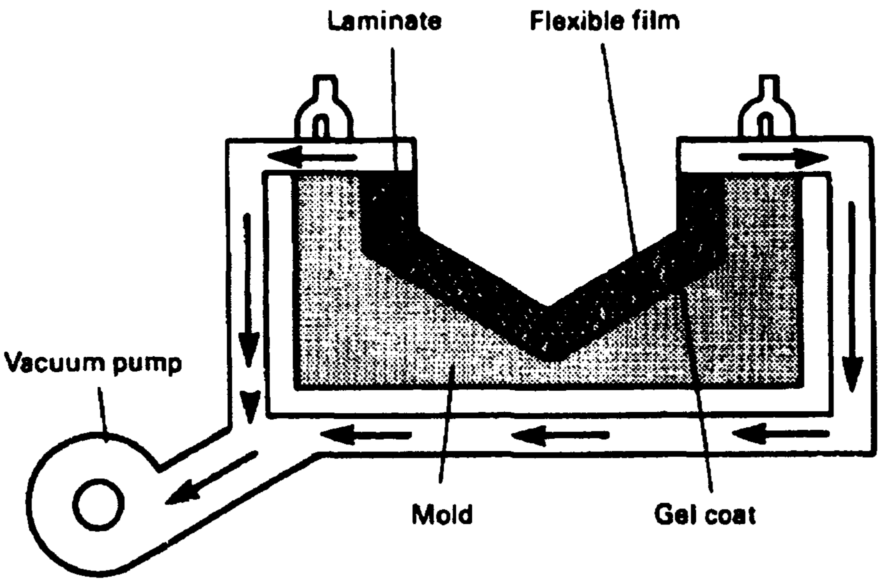
Hardened steel dies.

Major Advantages

The process is a continuous operation that can be readily automated. It is adaptable to shapes with small cross-sectional areas and uses low cost reinforcement. Very high strengths are possible due to the length of the stock being drawn. There is no practical limit to the length of stock produced by continuous pultrusion.

VACUUM BAG MOLDING

Mechanical properties of open-mold laminates can be improved with a vacuum-assist technique. Entrapped air and excess resin are removed to produce a product with a higher percentage of fiber reinforcement.



Process Description

A flexible film (PVA or cellophane) is placed over the completed lay-up, its joint sealed, and a vacuum drawn. A bleeder ply of fiberglass cloth, non-woven nylon, polyester cloth or other absorbent material is first placed over the laminate. Atmospheric pressure eliminates voids in the laminate, and forces excess resin and air from the mold. The addition of pressure further results in high fiber concentration and provides better adhesion between layers of sandwich construction. When laying non-contoured sheets of PVC foam or balsa into a female mold, vacuum bagging is the technique of choice to ensure proper secondary bonding of the core to the outer laminate.

Resin Systems

Polyesters, vinyl esters and epoxies.

Molds

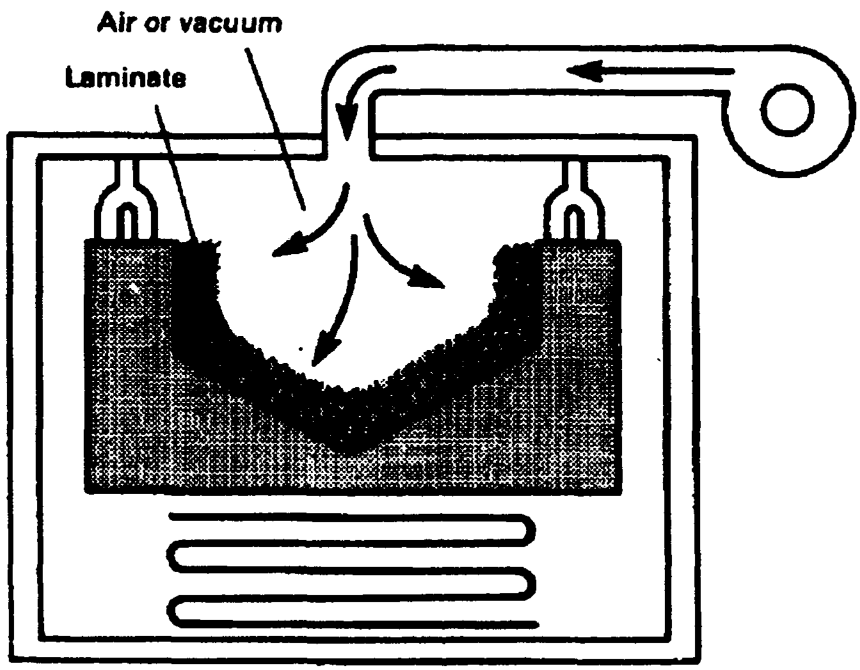
Molds are similar to those used for conventional open-mold processes.

Major Advantages

Vacuum bag processing can produce laminates with a uniform degree of consolidation, while at the same time removing entrapped air, thus reducing the finished void content. Structures fabricated with traditional hand lay-up techniques can become resin rich, especially in areas where puddles can collect. Vacuum bagging can eliminate the problem of resin rich laminates. Additionally, complete fiber wet-out can be accomplished if the process is done correctly. Improved core-bonding is also possible with vacuum bag processing.

AUTOCLAVE MOLDING

A pressurized autoclave is used for curing high-quality aircraft components at elevated temperatures under very controlled conditions. A greater laminate density and faster cure can be accomplished with the use of an autoclave.



Process Description

Most autoclaves are built to operate at 200°F, which will process the 250° to 350°F epoxies used in aerospace applications. The autoclaves are usually pressurized with nitrogen or carbon dioxide to reduce the fire hazard associated with using shop air. Most autoclaves operate at 100 psi under computer control systems linked to thermocouples embedded in the laminates.

Resin Systems

Mostly epoxies incorporated into prepreg systems.

Molds

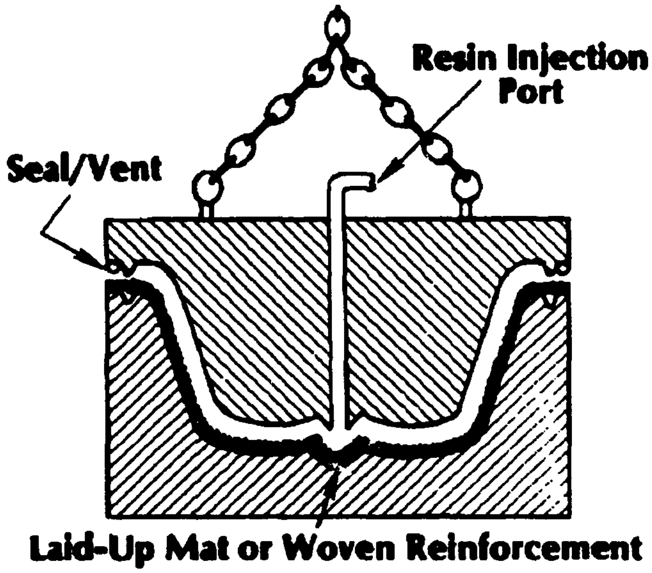
Laminated structures can be fabricated using a variety of open- or close-mold techniques.

Major Advantages

Very precise quality control over the curing cycle can be accomplished with an autoclave. This is especially important for high temperature cure aerospace resin systems that produce superior mechanical properties. The performance of these epoxy systems is very much dependent on the time and temperature variables of the cure cycle, which is closely controlled during autoclave cure.

RESIN TRANSFER MOLDING

Resin transfer molding is an intermediate-volume molding process for producing reinforced plastic parts, and a viable alternative to hand lay-up, spray-up and compression molding.



Process Description

Most successful production resin transfer molding (RTM) operations are now based on the use of resin/catalyst mixing machinery using positive displacement piston-type pumping equipment to ensure accurate control of resin/catalyst ratio. A constantly changing back pressure condition exists as resin is forced into a closed tool already occupied by reinforcement fiber.

The basic RTM molding process involves the connection of a meter, mix and dispense machine to the inlet of the mold. Closing of the mold will give the predetermined shape with the inlet injection port typically at the lowest point and the vent ports at the highest.

Resin Systems

Polyesters, vinyl esters, polyurethanes, epoxies and nylons.

Molds

RTM can utilize either "hard" or "soft" tooling, depending upon the expected duration of the run. Hard tooling is usually machined from aluminum while soft tooling is made up of a laminated structure, usually epoxy.

Major Advantages

The close-mold process produces parts with two finished surfaces. By laying up reinforcement material dry inside the mold, any combination of materials and orientation can be used, including 3-D reinforcements. Part thickness is also not a problem as exotherm can be controlled. Carbon/epoxy structures up to four inches thick have been fabricated using this technique.

Quality Assurance

Unlike a structure fabricated from metal plate, a composite hull achieves its form entirely at the time of fabrication. As a result, the overall integrity of an FRP marine structure is very dependent on a successful Quality Assurance Program (QAP) implemented by the builder. This is especially true when advanced, high-performance craft are constructed to scantlings that incorporate lower safety factors. In the past, the industry has benefited from the process control leeway afforded by structures considered to be "overbuilt" by today's standards. Increased material, labor and fuel costs have made a comprehensive QAP seem like an economically attractive way of producing more efficient marine structures.

The basic elements of a QAP include:

- Inspection and testing of raw materials including reinforcements, resins and cores
- In-process inspection of manufacturing and fabrication processes
- Destructive and non-destructive evaluation of completed composite structures

The last topic will be covered in the section on Testing of Marine Composites. Each builder must develop a QAP consistent with the product and facility. Figure 5-16 shows the interaction of various elements of a QAP. The flowing elements should be considered by management when evaluating alternative QAPs: [5-14]

- Program engineered to the structure
- Sufficient organization to control labor intensive nature of FRP construction
- Provide for training of production personnel
- Timely testing during production to monitor critical steps
- Continuous production process monitoring with recordkeeping
- Simple, easily implemented program consistent with the product
- Emphasis on material screening and in-process monitoring as laminates are produced on site
- The three sequences of a QAP, pre, during and post construction, should be allocated in a manner consistent with design and production philosophy
- Specifications and standards for composite materials must be tailored to the material used and the application
- The balance between cost, schedule and quality should consider the design and performance requirements of the product

Table 5-5 lists some questions that engineering personnel must evaluate when considering the design and implementation of a QAP. [5-14]

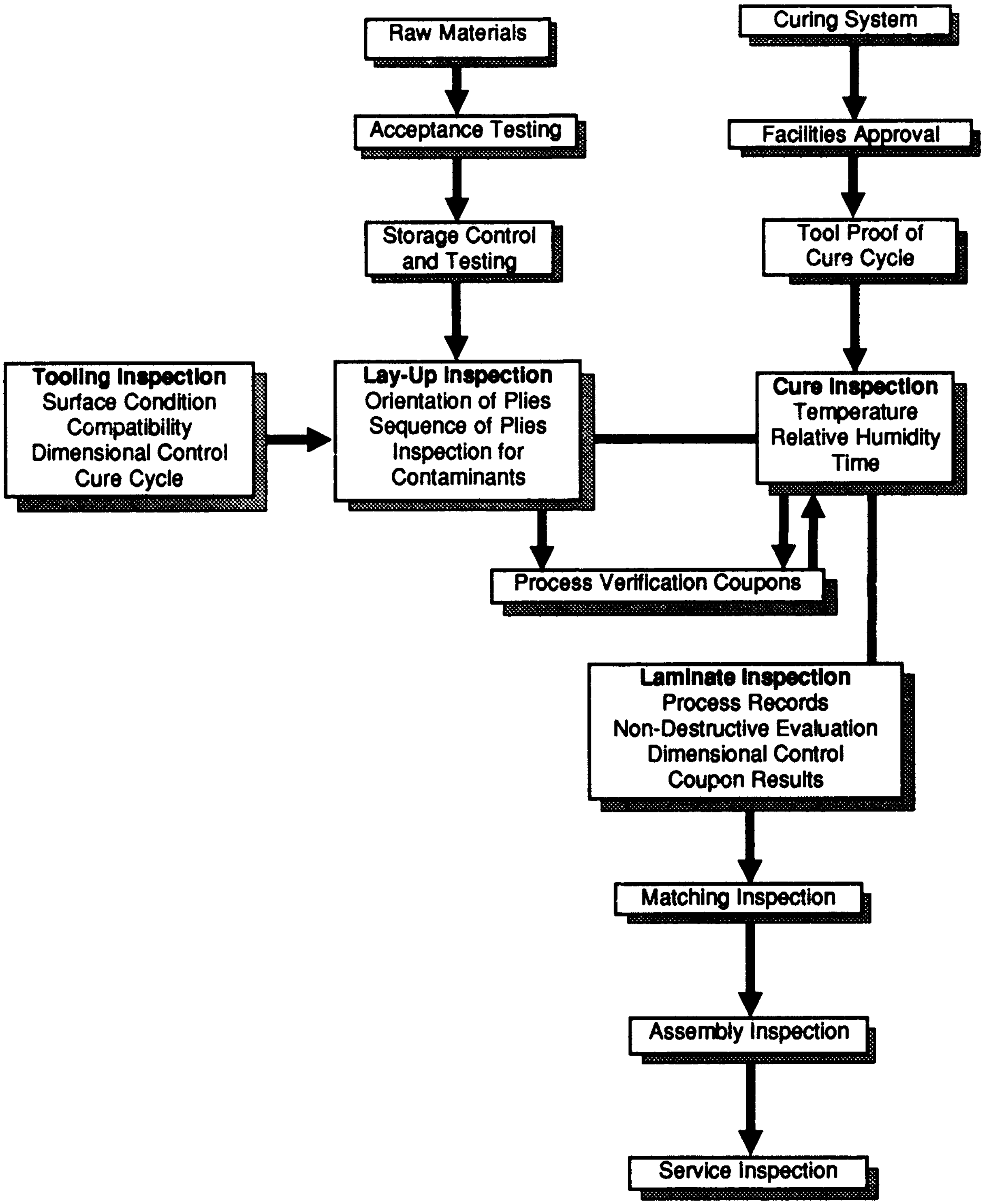


Figure 5-16 Inspection Requirements for Composite Materials [U.S. Air Force, *Advanced Composite Design*]

Table 5-5. Engineering Considerations Relevant to an FRP Quality Assurance Program [Thomas and Cable, *Quality Assessment of Glass Reinforced Plastic Ship Hulls in Naval Applications*]

Engineering Considerations	Variables
Design Characteristics	Longitudinal bending, panel deflection, cost, weight, damage tolerance
Material Design Parameters	Interlaminar shear strength, compressive strength, shear strength, tensile strength, impact strength, stiffness, material cost, material production cost, material structural weight, material maintenance requirements
Stress Critical Areas	Keel area, bow, shell below waterline, superstructure, load points
Important Defects	Delaminations, voids, inclusions, uncured resin, improper overall glass to resin ratio, local omission of layers of reinforcement, discoloration, crazing, blisters, print-through, resin starved or rich areas, wrinkles, reinforcement discontinuities, improper thickness, foreign object damage, construction and assembly defects
Defect Prevention	Proper supervision, improving the production method, material screening, training of personnel, incorporation of automation to eliminate the human interface in labor intensive production processes
Defect Detection	Evaluation of sample plugs from the structure, testing of built-in test tabs, testing of cutouts for hatches and ports, nondestructive testing of laminated structure
Defect Correction	Permanent repair, replacement, temporary repair
Defect Evaluation	Comparison with various standards based on: defect location, severity, overall impact on structural performance
Effort Allocation	Preconstruction, construction, post-construction

Materials

Quality assurance of raw materials can consist of qualification inspections or quality conformance inspections. Qualification inspections serve as a method for determining the suitability of particular materials for an application prior to production. Quality conformance inspections are the day-to-day checks of incoming raw material designed to insure that the material conforms with minimum standards. These standards will vary, depending on the type of material in question.

Reinforcement Material

Inspection of reinforcement materials consists of visual inspection of fabric rolls, tests on fabric specimens and tests on laminated samples. This section will concentrate on visual inspection as it represents the most cost effective way an average boat builder can insure raw material conformance. Exact inspection requirements will vary depending upon the type of material (E- and S-Glass, Kevlar®, carbon fiber, etc.) and construction (mat, gun-roving, woven roving, knit, unidirectional, prepreg, etc.). As a general guideline, the following inspection criteria should be used for rolled goods: [5-15]

- Uncleanliness (dirt, grease, stains, spots, etc.)

- Objectionable odor (any odor other than finishing compounds)
- Color not characteristic of the finish or not uniform
- Fabric brittle (fibers break when flexed) or fused
- Uneven weaving or knitting throughout clearly visible
- Width outside of specified tolerance

The builder will also want to make sure that rolls are the length specified and do not contain an excessive number of single pieces. As the material is being rolled out for cutting or use, the following defects should be noted and compared to established rejection criteria:

- Fiber ply misalignment
- Creases or wrinkles embedded
- Any knots
- Any hole, cut or tear
- Any spot, stain or streak clearly visible
- Any brittle or fused area
- Any smashed fibers or fiber bundles
- Any broken or missing ends or yarns
- Any thickness variation that is clearly visible
- Foreign matter adhering to the surface
- Uneven finish
- Damaged stitching or knitted threads

As part of a builder's overall QAP, lot or batch numbers of all reinforcements should be recorded and correlated with the specific application. The following information should accompany all incoming reinforcement material and be recorded:

- Manufacturer
- Material identification
- Vendor or supplier
- Lot or batch number
- Date of manufacture
- Fabric weight
- Fabric width
- Type or style of weave
- Chemical finish

The handling and storage of reinforcement material should conform with the manufacturer's recommendations. Material can easily be damaged by rough handling or exposure to water, organic solvents or other liquids. Ideally, reinforcement material should be stored under controlled temperature and relative humidity conditions, as some are slightly hydroscopic. Usually room temperature conditions with adequate protection from rain water is sufficient for fiberglass products. Advanced materials and especially prepregs will have specific handling instructions that must be followed. If the ends of reinforcement rolls have masking tape to prevent fraying, all the adhesive must be thoroughly removed prior to lamination.

Resin

Laminating resin does not reveal much upon visual inspection. Therefore, certain tests of the material in a catalyzed and uncatalyzed state must be performed. The following tests can be performed on uncatalyzed resin:

Specific Gravity - The specific gravity of resin is determined by precisely weighing a known volume of liquid.

Viscosity - The viscosity of uncatalyzed resin is determined by using a calibrated instrument such as a MacMichael or Brookfield viscometer, like the one shown in Figure 5-17.

Acid Number - The acid number of a polyester or vinyl ester resin is an indictor of the relative reactivity of the resin. It is defined as the number of milligrams of potassium hydroxide required to neutralize one gram of polyester. It is determined by titrating a suitable sample of material as a solution in neutral acetone with 0.1 normal potassium hydroxide using phenolphthalein as an indicator. Most builders will instead rely on the gel test of catalyzed resin to determine reactivity.

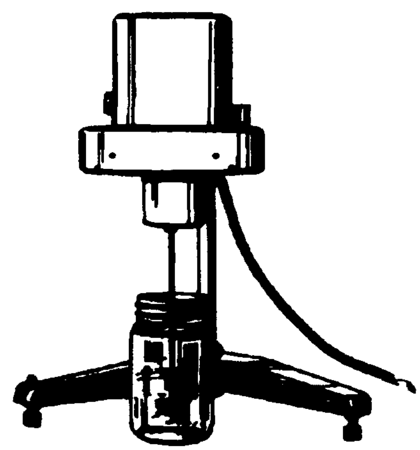


Figure 5-17 Brookfield Model LVF Viscometer and Spindles [Cook, *Polycor Polyester Gel Coats and Resins*]

The testing of catalyzed resin using the following tests will provide more information, as the tests reflect the specific catalysts and ambient temperature conditions of the builder's shop.

Gel Time - The gel time of a resin is an indicator of the resin's ability to polymerize and harden and the working time available to the manufacturer. The Society of the Plastics Industry and ASTM D-2471 specify alternative but similar methods for determining gel time. Both involve the placement of a fixed amount of catalyzed resin in a elevated temperature water bath. Gel time is measured as the time required for the resin to rise from 150°F to 190°F with temperature measurements made via an embedded thermocouple.

An alternative procedure that is coomonly used involves a cup gel timer. Catalyzed resin is placed in a cup and a motorized spindle is activated with a timer. As the resin cures, the spindle slows and eventually stalls the moter at a given torque. Gel time is then read off of the unit's timer device.

Peak Exotherm - The peak exotherm of a catalyzed resin system is an indicator of the heat generation potential of the resin during polymerization, which involves exothermic chemical reactions. It is desirable to minimize the peak exotherm to reduce the heat build-up in thick laminates. The peak exotherm is usually determined by fabricating a sample laminate and recording the temperature rise and time to peak. ASTM D-2471 provides a detailed procedure for accomplishing this.

Barcol Hardness - The Barcol hardness of a cured resin sample is measured with a calibrated Barcol impressor, as shown in Figure 5-18. This test will indicate the degree of hardness achieved during cure as well as the degree of curing during fabrication. Manufacturer's will typically specify a Barcol hardness value for a particular resin.

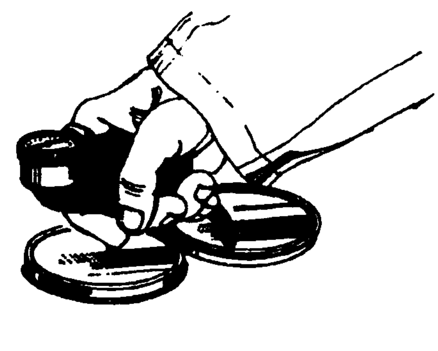


Figure 5-18 Barcol Impressor (Model 934 or 935 for readings over 75) [Cook, *Polycor Polyester Gel Coats and Resins*]

Specific Gravity - Measurement of specific gravity of cured, unfilled resin system involves the weighing of known volume of cured resin.

The following information should accompany all incoming shipments of resin and be recorded by the manufacturer for future reference:

- Product name or code number and chemical type
- Limiting values for mechanical and physical properties
- Storage and handling instructions
- Maximum usable storage life and storage conditions
- Recommended catalysts, mixing procedure; finishes to use in reinforcements; curing time and conditions
- Safety information

The storage and handling of resin is accomplished either with 55 gallon drums or via specially designed bulk storage tanks. Table 5-6 lists some precautions that should be observed for drum and bulk storage.

Table 5-6. Precautions for Storage and Handling of Resin [SNAME, *Guide for Quality Assured Fiberglass Reinforced Plastic Structures*]

Drum Storage	Bulk Storage
Date drum upon receipt and store using first-in first-out system to assure stock rotation	Use a strainer to prevent impurities from either the tank truck or to delivery lines
Do not store material more than three months (or per manufacturer's recommendation)	Install a vacuum pressure relief valve to allow air to flow during tank filling and resin usage
Keep drums out of direct sunlight, using covers if outdoors, to prevent water contamination	Use a manhole or conical tank bottom to permit periodic cleanout
Store drums in well ventilated area between 32°F and 77°F	Phenolic and epoxy tank liners prevent the attack of tank metal by stored resin
If drums are stored at a temperature substantially different from laminating area, resin temperature must be brought to the temperature of the laminating area, which usually requires a couple of days	A pump should provide for both the delivery through the lines and the circulation of resin to prevent sedimentation, which can also be controlled with a blade or propeller type stirring device
Keep drums sealed until just prior to use	Electrically ground tank to filling truck
Just prior to insertion of a spigot or pump, make sure that the top of the drum is clean to reduce the risk of contamination	Throttling valves are used to control resin flow rates and level indicators are useful for showing the amount of material on hand

Core Material

In general, core material should be visually examined upon receipt to determine size, uniformity, workmanship and correct identification. Core material can be tested to determine tensile, compressive and shear strength and moduli using appropriate ASTM methods. Density and water absorption, as a minimum, should be tested.

Manufacturers will supply storage requirements specific to their product. All core materials should be handled and stored in such a way as to eliminate the potential for contact with water and dirt. This is critical during fabrication as well as storage. Perspiration from workers is a major contamination problem that seriously effects the quality of surface bonds.

In-Process Quality Control

In order to consistently produce a quality laminated product, the fabricator must have some control over the laminating environment. Some guidelines proposed by ABS [5-16] include:

- Premises are to be fully enclosed, dry, clean, shaded from the sun, and adequately ventilated and lighted.
- Temperature is to be maintained adequately constant between 60°F and 90°F. The humidity is to be kept adequately constant to prevent condensation and is not to exceed 80%. Where spray-up is taking place, the humidity is not to be less than 40%.

- Scaffolding is to be provided where necessary so that all laminating work can be carried out without standing on cores or on laminated surfaces.

An in-process quality control program must be individually tailored to the project and personnel involved. Smaller jobs with highly trained laminators may proceed flawlessly with little oversight and controls. Big jobs that utilize more material and a large work force typical need more built-in controls to insure that a quality laminate is constructed. Selection of materials also plays a critical role in the amount of in-process inspection required. Figure 5-19 gives an indication of some techniques used by the boat building industry. The following topics should be addressed in a quality control program:

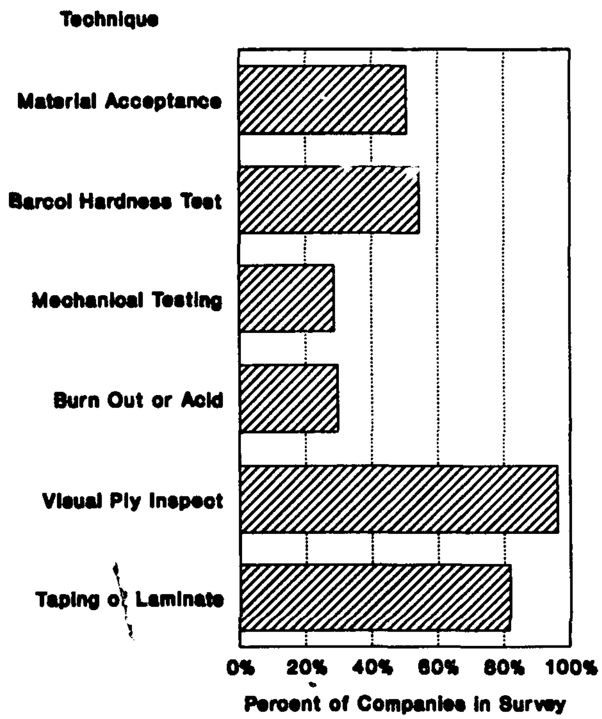


Figure 5-19 Marine Industry Quality Control Efforts [EGA Survey]

- Mold inspection prior to applying releasing agent and gel coat
- Gel coat thickness, uniformity of application and cure check prior to laminating
- Check resin formulation and mixing; check and record amounts of base resin, catalysts, hardeners, accelerators, additives and fillers
- Check that reinforcements are uniformly impregnated and well wet-out and that lay-up is in accordance with specifications
- Check and record fiber/resin
- Check that curing is occurring as specified with immediate remedial action if improper curing or blistering is noted
- Overall visual inspection of completed lay-up for defects listed in Table 5-7 that can be corrected before release from the mold
- Check and record Barcol hardness of cured part prior to release from mold

Finished laminates should be tested to guarantee minimum physical properties. This can be done on cut-outs, run-off tabs or on test panels fabricated simultaneously with the hull on a surface that is 45° to the horizontal. Burn-out or acid tests are used to determine the fiber/resin ratio. Thickness, which should not vary more than 15%, can also be checked from these specimens. With vessels in production, ABS requires the following testing schedule:

Table 5-6. Proposed Test Schedule for ABS Inspected Vessels [ABS, *Proposed Guide for Building and Classing High-Speed and Displacement Motor Yachts*]

Vessel Length (feet)	Frequency of Testing
Under 30	Every 12th vessel
30 to 40	Every 10th vessel
40 to 50	Every 8th vessel
50 to 60	Every 6th vessel
60 to 70	Every 4th vessel
70 to 80	Every other vessel
80 and over	Every vessel

Table 5-7. Defects Present in Laminated Structures [SNAME, *Guide for Quality Assured Fiberglass Reinforced Plastic Structures*]

Defect Description	Probable Cause
Air Bubble or Voids - May be small and non-connected or large and interconnected	Air entrapment in the resin mix, insufficient resin or poor wetting, styrene boil-off from excessive exotherm, insufficient working of the plies or porous molds
Delaminations - This is the separation of individual layers in a laminate and is probably the most structurally damaging type of defect	Contaminated reinforcement, insufficient pressure during wet-out, failure to clean surfaces during multistage lay-ups, forceful removal of a part from a mold, excessive drilling pressure, damage from sharp impacts, forcing a laminate into place during assembly or excessive exotherm and shrinkage in heavy sections
Crazing - Minute flaws or cracks in a resin	Excessive stresses in the laminate occurring during cure or by stressing the laminate
Warping or Excessive Shrinkage - Visible change in size or shape	Defective mold construction, change in mold shape during exotherm, temperature differentials or heat contractions causing uneven curing, removal from mold before sufficient cure, excess styrene, cure temperature too high, cure cycle too fast or extreme changes in part cross sectional area
Washing - Displacement of fibers by resin flow during wet-out and wiping in the lay-up	Resin formulation too viscous, loosely woven or defective reinforcements, wet-out procedure too rapid or excessive force used during squeegeeing
Resin Rich - Area of high resin content	Poor resin distribution or imperfections such as wrinkling of the reinforcement
Resin Starved - Area of low resin content	Poor resin distribution, insufficient resin, poor reinforcement finish or too high of a resin viscosity
Surface Defects - Flaws that do not go beyond outer ply	Porosity, roughness, pitting, alligatoring, orange peel, blistering, wrinkles, machining areas or protruding fibers
Tackiness or Undercure - Indicated by low Barcol reading or excessive styrene odor	Low concentration of catalyst or accelerators, failure to mix the resin properly, excessive amounts of styrene or use of deteriorated resins or catalysts

Mechanical Testing

Ideally, all testing should be conducted using standardized test methods. Standardized test procedures have been established by the American Society for Testing Materials (ASTM), the U.S. Military (MIL), various industrial associations, as well as foreign agencies and organizations. The individual tests have been established for specific purposes and applications. The tests may or may not be applicable to other applications, but must be evaluated on a case by case basis. The test methods for FRP materials have been developed primarily for the aerospace industry, thus they may or may not be applicable to the marine industry.

There are three major types of testing: 1) tests of the individual FRP components, 2) tests of the FRP laminates, 3) tests of the FRP structure. In general, the tests of individual FRP components tend to be application independent, however, some of the properties may not be useful in certain applications. Tests of the FRP laminates tend to be more application dependent, and tests of FRP structures are heavily application dependent. ASTM tests which are applicable to the marine industry are examined, and their limitations are discussed.

ASTM FRP Material Tests

Resins

ASTM D 570-81 Test Method for Water Absorption of Plastics

This test is commonly used to determine the water absorption characteristics of neat resins and FRP materials. The test results are often used to compare the water absorption rates of different resin systems.

ASTM D 638-84 Test Method for Tensile Properties of Plastics

This test can used to obtain the tensile modulus and strength of cured resins, but is most commonly used to obtain tensile properties of FRP laminates. The principal difficulty with tensile tests is casting pure resin samples of appropriate dimensions without introducing stress and stress cracks during the resin cure process.

ASTM D 695-85 Test Method for Compressive Properties of Rigid Plastics

This test can used to obtain the compressive modulus and strength of cured resins, but is most commonly used to obtain compressive properties of FRP laminates. One difficulty with this test is casting pure resin samples of appropriate dimensions without introducing stress and stress cracks during the resin cure process. Another difficulty is actually obtaining a compression failure for calculation of compressive strength. The samples are restrained from Euler buckling and shear failure by a test jig, which is bolted to the sample. If this jig is not positioned and tightened correctly, failure modes other than pure compression failure may occur. Also, if the jig is too tight it could effect the modulus values.

ASTM D 792-66 Test Methods for Specific Gravity and Density of Plastics by Displacement

This test can be used to determine the specific gravity or density of cured resin or FRP samples. It is not suitable for most sandwich laminates due to water absorption and/or trapping of air bubbles by the core materials.

ASTM D 1201-81 Specification for Thermoseting Polyester Molding Compounds
These specifications apply only to reinforced polyester compression molding compounds, but similar guidelines could be developed for polyester thermosetting resins and FRP laminates.

ASTM D 1652 Test Method for Epoxy Content of Epoxy Resins
This test is used to determine the purity of epoxy resins. It is often used as part of the material acceptance/rejection testing in a quality control program.

ASTM D 1763-81 Specification for Epoxy Resins
These specifications apply to epoxy resins, and can be used to establish material acceptance/rejection criteria for quality control programs.

ASTM D 2471-71 Test Method for Gel Time and Peak Exotherm Temperature of Reacting Thermosetting Resins
Variations of this test are commonly used to determine appropriate catalyst levels, working time and cure times by fiberglass fabricators. This test can also be used as part of the material acceptance/rejection testing for a quality control program.

Fibers and Fabric

ASTM D 1910-xx Test Methods for Construction Characteristics of Woven Fabrics
This test deals with inspection of the fabric with respect to thread count, width and weight of the fabric. This test should be included as part of the material acceptance/rejection testing of a quality control program.

ASTM D 2150-81 Specification for Woven Roving Glass Fabric for Polyester-Glass Laminates
This test establishes specifications for woven roving glass fabric and appropriate testing procedures for the material acceptance/rejection testing of a quality control program.

ASTM D 2343-67 Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics
This test is commonly used to determine fiber properties before the glass fiber is converted into fabric. This data should be supplied to the boat builder from the converter as part of fabric documentation. This test can be used to determine the stiffness and strength of unidirectional tapes.

ASTM D 2408-82 Test Method for Finish Content of Woven Glass Fabric, Cleaned and After-Finished with Amino-Silane Type Finishes for Plastic Laminates
This test evaluates the amount of amino-silane finish, or sizing, applied to lass fabric. Amino-silane finished fabric is used with epoxy and phenolic resin systems. The data is useful, since the sizing is applied to enhance the bonding between the glass fibers and the resin system.

ASTM D 2409-84 Test Method for Finish Content of Woven Glass Fabric, Cleaned and After -Finished with Vinyl-Silane Type Finishes for Plastic Laminates
This test evaluates the amount of vinyl-silane finish, or sizing, applied to glass fabric. Vinyl-silane finished fabric is used with polyester resin systems. The data is useful, since the sizing is applied to enhance the bonding between the glass fibers and the resin system.

ASTM D 2410-82 Test Method for Finish Content of Woven Glass Fabric, Cleaned and After-Finished with Chrome Complexes, for Plastic Laminates
This test evaluates the amount of chrome complex finish, or sizing, applied to glass fabric. Chrome complex finished fabric is used with polyester, epoxy and phenolic resin systems. The data is useful, since the sizing is applied to enhance the bonding between the glass fibers and the resin system.

ASTM D 2660-84 Test Method for Finish Content of Woven Glass Fabric, Cleaned and After-Finished with Acrylic-Silane Type Finishes, for Plastic Laminates
This test evaluates the amount of acrylic-silane finish, or sizing, applied to glass fabric. Acrylic-silane finished fabric is used with polyester resin systems. The data is useful, since the sizing is applied to enhance the bonding between the glass fibers and the resin system.

ASTM D 3317-81 Specification for High Modulus, Organic Yarn and Roving
This standard sets specifications for high modulus organic yarn and roving (i.e. carbon fiber). The specification can be used as a guide for acquisition specifications and for material acceptance/rejection testing.

ASTM D 3800-79 Test Method for Density of High Modulus Fibers
This test method is used to establish the density of fibers. This information is of use to converters (manufacturers of fabric) and direct users of tow, such as filament winding.

ASTM D 4018-81 Test Method for Tensile Properties of Continuous Filament Carbon and Graphite Yarns, Strands, Rovings and Tows
This test method is used to establish the tensile modulus and strength of carbon fiber tow. This information is of use to converters (manufacturers of fabric) and direct users of tow, such as filament winding.

Core Materials

ASTM C 271-61 Test Method for Density of Core Materials for Structural Sandwich Constructions
This test is commonly used to determine the density of core materials. The test is simple, however hand measurement of the samples can be inconsistent, which may lead to errors in density. Also, the test does not make provision for testing of sandwich specimen, thus the effects of the face/core adhesive on apparent core density are not included. (see ASTM D 1622-83)

ASTM C 272-53 Test Method for Water Absorption of Core Materials for Structural Sandwich Constructions
This test is used to determine the water absorption properties of core materials such as foam, honeycomb and balsa. The test is conducted on sandwich core materials without faces or other methods of sealing the surfaces. Also, the duration of the test is only 24 hours. These factors make this test inappropriate for direct use in the marine industry. However, the mechanical properties of the core materials are often a function of the water content. This test can be used to determine the water content levels of the core materials before mechanical testing to determine the variation of the mechanical properties as a function of water content.

ASTM C 273-61 Method of Shear Test in Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores

This test is commonly used to determine the shear properties of various core materials. The test has some serious flaws, but can yield useful information. The shear modulus is dependent on the stiffness of the mounting plates, therefore, the specifications for these plates must be closely followed. The test specimen shape is such that stress concentrations are produced at the edge of the specimen, which may lead to premature failure and artificially low strength. Materials with high strain to failure undergo a transition from dominant shear stress at low strains to dominant tensile stress at high strains, thus the shear strengths of these materials are highly suspect.

ASTM C 365-57 Test Method for Flatwise Compressive Strength of Sandwich Cores

This test is commonly used for quality assurance/material acceptance testing, since the specimen preparation is quite simple. Cylindrical or rectangular samples are used, however cylindrical samples appear to yield more consistent results. The material properties are dependent on the load or strain rate, thus the load rate or strain rate must be controlled within the guidelines of the test procedures.

ASTM C 366-57 Methods for Measurement of Thickness of Sandwich Cores

This test can be used to measure the thickness and variation in thickness of various core materials. The test is simple, but requires special apparatus, which is not commonly available in the marine industry.

ASTM C 394-62 Test Method for Shear Fatigue of Sandwich Core Materials

This test was designed to measure shear fatigue of sandwich core materials. The test apparatus is similar to ASTM C 273-61, thus ASTM C 394-62 is subject to some of the same problems. The dominant problem is the stress concentrations which occur at the edge of the test sample. Most fatigue failures begin at these locations and propagate into the core material fairly rapidly, thus this test is not representative of core fatigue phenomena in sandwich constructions.

ASTM D 1621-73 Test Method for Compressive Properties of Rigid Cellular Plastics

This test is commonly used to determine the compressive properties of foam core materials. Procedure A, utilizing cross-head motion for the strain calculation, yields significantly different modulus values and strain to failure values than procedure B, which utilizes direct strain measurement. Also, samples may be either square or cylindrical. There can be substantially different modulus, strength and strain to failure values between the two sample shapes. There appears to be general agreement between experts in the field of foam core testing that procedure B with cylindrical samples is the preferred test. Care must be taken when cutting the samples to avoid damaging the surface of the foam, since this can alter test results dramatically. Foam material properties are strongly dependent on strain rate, thus strain rate or loading rate must carefully controlled within the guidelines of the test method.

ASTM D 1622-83 Test Method for Apparent Density of Rigid Cellular Plastics

This test is commonly used to determine the density of foam core materials. The test is simple, however hand measurement of the foam samples can be inconsistent, which may lead to errors in density. The test does make provision for determining the apparent density of sandwich constructions, thus the effects of the face material and the face/core adhesive material on density can be determined.

ASTM D 1623-78 Test Method for Tensile and Adhesion Properties of Rigid Cellular Plastics
This test is commonly used to determine tensile properties of foam core materials and face/core tensile adhesion strength of foam sandwich constructions. There are three specimen types, two for tensile properties and one for face/core tensile adhesion strength.

Type A specimens are tapered cylinders, which are mounted in matching tapered collars. The fabrication of these specimen is more involved than the other specimen, thus is more subject to error. The tapered collars introduce compression stresses into the ends of the specimen, which can lead to premature failure, however, this type of failure can be determined through location of the failure in the region of the collar. Tensile modulus and strain to failure can be determined using extensometer data, but cross-head motion is not suitable for calculating these parameters.

Type B specimen are square or cylindrical in shape, and are bonded to face plates. Cylindrical specimen appear to yield more consistent results. Strength calculations can be affected by the failure mode (adhesive failure or tensile foam failure), therefore extra samples must be tested to insure sufficient data for strength calculations.The failure mode is easily determined, however, the tensile strength can be calculated using only samples with tensile foam failures. Modulus and strain to failure can be calculated from extensometer data.

Type C specimens are similar to Type B specimens, except that the specimen is a sandwich laminate, and is used only for strength calculations. An additional failure mode (face/core adhesion failure) is possible, thus care must be taken to identify the failure mode accurately. Also, if the face/core adhesion strength is greater than *the face/test fixture adhesion or the foam* core tensile strength, it can not be determined using this test. The properties of foam are dependent on strain rate, thus strain rate or load rate must be carefully controlled within the guidelines of the test method.

Solid FRP Laminates

ASTM D 638-84 Test Method for Tensile Properties of Plastics
This test can used to obtain the tensile modulus and strength of cured resins, but is most commonly used to obtain tensile properties of FRP laminates. The principal difficulty with this test is that the sample is cut to a dog bone shape, as shown in Figure 6-1. This causes stress concentrations in the area of the taper, with failure often occurring in this area instead of the test section, making determination of tensile strength impossible (see ASTM D 3039). This test is appropriate for (0°, 90°) and randomly oriented reinforcing fabrics, and the laminates must be symmetric. Off-axis fibers (directions other than 0° or 90°) introduce stress concentrations into the laminate, which lowers the ultimate strength. Flexural stresses occur in unsymmetrical laminates subjected to uniaxial in-plane loads, which can cause premature failure of the test samples.

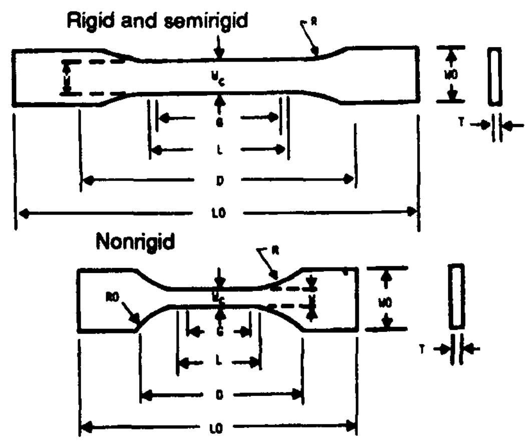


Figure 6-1 Dogbone Tensile Test Specimens [ASTM D638]

ASTM D 671-71 Test Method for Flexural Fatigue of Plastics by Constant-Amplitude-of-Force

This test is commonly used to determine the flexural fatigue properties of FRP laminates. The testing is conducted at 30 Hz, which is representative of the natural frequency of many boat structures. This frequency is high enough to heat up the sample,thus this will have an effect on the data. The test samples are machined with a tapered "neck." There is a tendency for stress concentrations and premature failures in the taper due to the cut fibers, thus the failures must be examined and recorded.

ASTM D 695-85 Test Method for Compressive Properties of Rigid Plastics

This test can used to obtain the compressive modulus and strength of cured resins, but is most commonly used to obtain compressive properties of FRP laminates. The principal difficulty with this test is actually obtaining a compression failure for calculation of compressive strength. The samples are restrained from Euler buckling and shear failure by a test jig which is bolted to the sample. If this jig is not positioned and tightened correctly, failure modes other than pure compression failure may occur. Also, if the jig is too tight, it could effect the modulus values. This test is appropriate for (0,90) and randomly oriented reinforcing fabrics, and the laminates must be symmetric. Off-axis fibers (directions other than 0 or 90 degrees) introduce stress concentrations into the laminate which lowers the ultimate strength. Flexural stresses occur in unsymmetrical laminates subjected to uniaxial in-plane loads, which can cause premature failure of the test samples.

ASTM D 732-85 Test Method for Shear Strength of Plastics by Punch Tool

This test is used to determine out-of-plane shear strength, thus it is representative of "punch through" or impacts with sharp edged objects. There are so many factors which contribute to the out-of-plane shear strength that test results are most commonly used to directly compare the shear resistance of two or more laminates.

ASTM D 790-84 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

This test is one of the most commonly used tests in the marine industry. The dominate loads on boats are often localized loads which introduce bending stresses into the laminate, thus flexural stiffness and strength are important properties for marine laminates. The test is also a good quality control test, since the laminate is subjected to all three major stresses: tensile, compressive, and shear. The test is not used to determine material properties, but is often used to compare candidate laminates.

ASTM D 2344-84 Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method

This test is similar to ASTM D 790, except that the span is very short, thus the shear stresses are dominant. The test is used to determine the interlaminar shear strength developed by the resin, thus it is most commonly used as a quality control test for evaluating the resin.

ASTM D 2583-81 Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor

This is probably the most common test in the marine industry. Barcol hardness can be used to determine the state of cure of the resin at intermediate steps in the fabrication process. It can also be used to monitor the rate of cure of the resin. It is simple and inexpensive, thus it provides an excellent quality control test.

<u>ASTM D 2584-68 Test Method for Ignition Loss of Cured Reinforced Resins</u>

Fiber-resin ratio is one of the most important quality control tests. This data is also necessary for interpretation of physical and mechanical test data. This test is the most common method of obtaining the fiber-resin ratio for GRP laminates.

<u>ASTM D 2587-68 Test Method for Acetone Extraction and Ignition of Glass Fiber Strands, Yarns, and Roving for Reinforced Plastics</u>

This test is an alternate method for obtaining fiber-resin ratios for GRP laminates (see ASTM D 2584).

<u>ASTM D 3039-76 Test Method for Tensile Properties of Fiber-Resin Composites</u>

This is the preferred test for determining tensile modulus and strength of FRP laminates. The test samples utilize adhesively bonded tabs shown in Figure 6-2, instead of a dog bone taper, to obtain a high stress test section. Failures can still occur outside of the test section, but these failures are usually tab debonding, thus it is easy to determine if failure data should be included in the ultimate tensile strength calculation. This test is appropriate for (0°, 90°) and randomly oriented reinforcing fabrics, and the laminates must be symmetric. Off-axis fibers (directions other than 0° or 90°) introduce stress concentrations into the laminate which lowers the ultimate strength. Flexural stresses occur in unsymmetrical laminates subjected to uniaxial in-plane loads which can cause premature failure of the test samples.

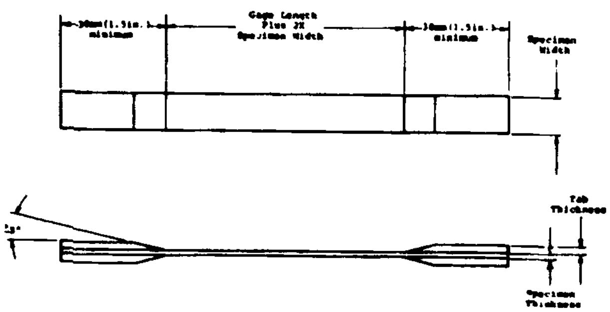


Figure 6-2 Tensile Test Specimen with Tabs [ASTM D 3039]

<u>ASTM D 3171-76 Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion</u>

This test is an alternate method for obtaining fiber-resin ratios for GRP laminates (see ASTM D 2584), but is the primary method for obtaining fiber-resin ratios for carbon fiber or graphite fiber reinforced laminates.

<u>ASTM D 3410-75 Test Method for Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites</u>

This test yields more consistent results than ASTM D 695, but the test jig, shown in Figure 6-3, is very complicated and the tolerances on sample size are very tight, thus it is not as commonly used as ASTM D 695. This test is appropriate for (0°, 90°) and randomly oriented reinforcing fabrics, and the laminates must be symmetric. Off-axis fibers (directions other than 0° or 90°) introduce stress concentrations into the laminate, which lowers the ultimate strength. Flexural stresses occur in unsymmetrical laminates subjected to uniaxial in-plane loads, which can cause premature failure of the test samples.

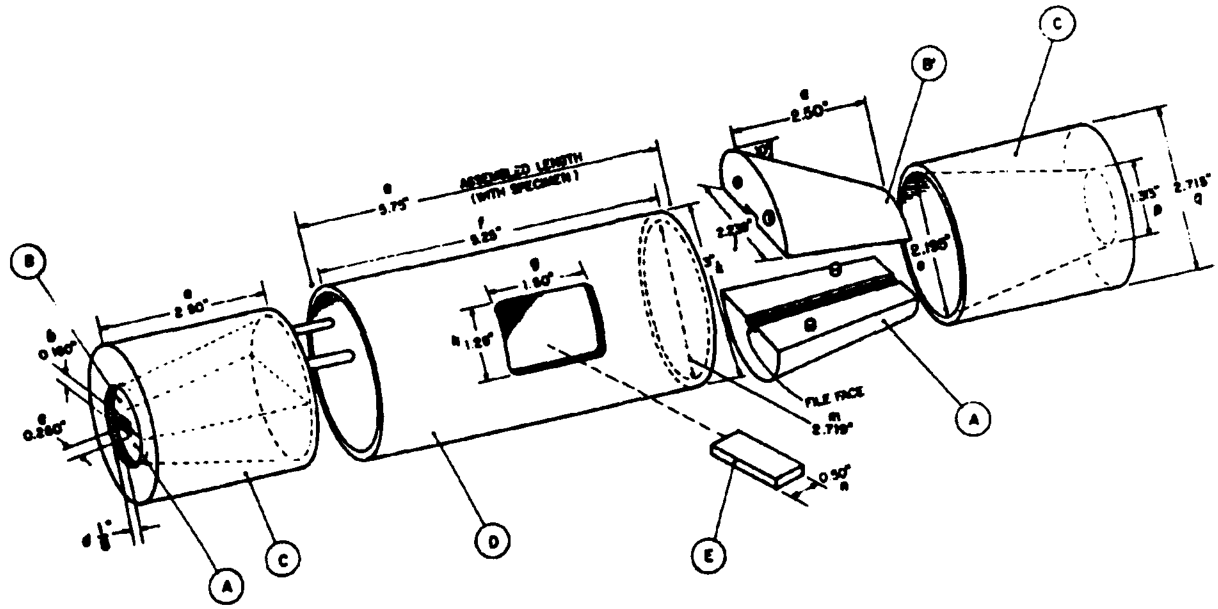


Figure 6-3 Restraining Fixture for Testing Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites [ASTM D 3410]

<u>ASTM D 3479-76 Test Methods for Tension-Tension Fatigue of Oriented Fiber, Resin Matrix Composites</u>

This test is designed to provide fatigue data for designers so that laminates can be designed to a predetermined life span. The test is tension-tension, thus it is an in-plane fatigue test without reversing loads. This limits the usefulness of the data, because most parts of the boat structure are subjected to tension-compression loading or flexural loading. Samples must not be cycled too quickly (<30 Hz) to avoid heating the sample, which could effect the data.

<u>ASTM D 3518-76 Practice for In-Plane Shear Stress-Strain Response of Unidirectional Reinforced Plastics</u>

This test utilizes a double bias laminate (±45°) with the ASTM D 3039 tensile test to determine in-plane shear stiffness and strength. The test results are of questionable use to a marine designer, since the test involves uniaxial loading of a sample in which all of the fibers are discontinuous at the edge of the sample, while a marine hull panel has continuous fibers and multi-axial loading. Thus the test is a uniaxial attempt to simulate a biaxial or multi-axial phenomena.

FRP Sandwich Laminates

<u>ASTM C 297-61 Method for Tension Test of Flat Sandwich Constructions in Flatwise Plane</u>

This test is commonly used to determine the tensile adhesion strength of the face/core bond. The test utilizes square samples bonded to a test fixture. The failure mechanism must be determined in order to calculate the face/core adhesion strength, since the sample adhesive bond to the test fixture or the core material itself can fail at lower strengths than the face/skin bond.

ASTM 364-61 Test Method for Edgewise Compressive Strength of Flat Sandwich Constructions

This test is commonly used to determine the in-plane strength of sandwich constructions. There are several different failure mechanisms which can limit the in-plane strength of sandwich constructions: general column buckling (Euler Buckling), wrinkling, dimpling, and crimping. There are established equations for the critical stress for each type of failure mode, but these equations assume a high quality laminate. Therefore, this test can be used to determine the quality of the laminate, as well as to check the results of the predicted failures. Thus it is important to know the failure mode, as well as the mechanical properties of the face and core materials used in the predictive equations, to make use of the results of this test.

ASTM C 393-62 Method of Flexure Test of Flat Sandwich Constructions

This test is commonly used to determine the flexural properties of a sandwich construction. The main advantage of sandwich construction is to enhance flexural stiffness and strength, and since all the important factors, such as face stiffness and strength, face/core bond, and shear stiffness and strength contribute to the overall flexural stiffness and strength, this test is an excellent quality control/quality assurance test. The test can also be used as an alternative to ASTM C 273-61 for calculating the shear properties of the core material. The procedures for obtaining the shear properties of the core material are quite involved, but appear to yield excellent results. Investigations into the possibility of using this test method for fatigue testing of core materials shows great potential, but a standard test needs to be established.

ASTM C 480-62 Test Method for Flexure Creep of Sandwich Constructions

This test is used to determine deflection as a function of time for sandwich constructions subjected to long duration static loading (creep). This test is one of the few which addresses testing at different temperatures, an important feature for marine laminates. The mathematics associated with the test are very limited, however, it is difficult to extend test data through predictions, which is important when examining creep phenomena.

ASTM FRP Structure Tests

ASTM D 2563-70 Recommended Practice for Classifying Visual Defects in Glass-Reinforced Plastic Laminate Parts

This test sets standards for visual inspection and classification of defects in GRP laminates. Most boat builders utilize visual inspection as the primary structural quality control test, but the results are not transferable due to lack of standardization. Use of this standard practice guideline would allow this information to be used quantitatively.

SACMA FRP Material Tests

The Suppliers of Advanced Composite Materials Association (SACMA) has developed a set of recommended test methods for oriented fiber resin composites. These tests are similar to ASTM standard tests, and are either improvements on the corresponding ASTM standard tests or are new tests to obtain data not covered by ASTM standard tests. The tests are intended for use with prepreg materials, thus some modifications may be necessary to accommodate common marine laminates. Also, the tolerances on fiber orientations (1°) and specimen size (approximately 0.005 inch) are not realistic for marine laminates.

SRM 1-88 SACMA Recommended Test Method for Compressive Properties of Oriented Fiber-Resin Composites

This test corresponds to ASTM D 695, Test for Compressive Properties of Plastic Materials. The major difference between the two tests is that the SACMA test calls for tabs to be bonded to the ends of the specimen to minimize the possibility of premature failure of the sample at the ends where the load is introduced. Thus one of the major problems with using the ASTM D 695 test for FRP materials is eliminated. SRM 1-88 and ASTM D 695 both rely on a metal jig to prevent buckling of the sample. The sample must be installed in the jig very carefully to avoid biasing the results,thus leaving the repeatability and reliability of the test open to question. This also makes determination of the compressive modulus very difficult and time consuming, since it can only be done by use of strain gages. SRM 1-88 should yield better compressive data for marine laminates than ASTM D 695.

SRM 2-88 SACMA Recommended Test Method for Compression After Impact Properties of Oriented Fiber-Resin Composites

This test has no corresponding ASTM test. The method involves determination of the compression after impact properties of fiber-resin composites reinforced by oriented high modulus fibers. The method specifies impact and compression testing procedures for specimen 4 x 6 inches in size, with a thickness of 0.18 to 0.22 inches. The sample size limits the applicability to marine laminates, since thick laminates (greater than 0.22 inches) can not be tested. Also, the method does not allow testing of sandwich laminates. Another potential problem is that the impact level is determined from the energy of the impact, however, research has shown that low velocity and high velocity impacts at the same energy levels cause different types and amounts of damage. The loading is uniaxial, while most marine laminates are subjected to multi-axial loads. Use for marine applications appears to be extremely limited.

SRM 3-88 SACMA Recommended Test Method for Open-Hole Compression Properties of Oriented Fiber-Resin Composites

This test has no corresponding ASTM test. The method involves determination of the compression properties of fiber-resin composites reinforced by oriented high modulus fibers containing a circular hole. The recommended specimen size is 1.5 inches wide by 12 inches long with a 0.25 inch hole, but other sizes can be tested as long as the 6:1 specimen width to hole diameter ratio is maintained. The test fixture is shown in Figure 6-4. The test method does not allow testing of sandwich laminates, and specifies a quasi-isotropic laminate (+45°, 0°, -45°, 90°)$_s$, but should be useful for solid FRP marine laminates.

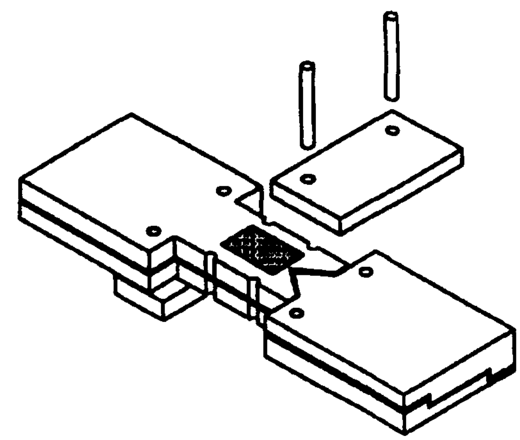


Figure 6-4 Test Fixture for Compression Testing of Composites with Holes [SACMA 3-

SRM 4-88 SACMA Recommended Test Method for Tensile Properties of Oriented Fiber Composites

This test corresponds to ASTM D 3039, Test for Tensile Properties of Oriented Fiber Composites. The major difference between ASTM D 3039 and SRM 4-88 is specification of the specimen tabs. SRM 4-88 specifies tabs with a more gradual taper (15°) than ASTM D 3039, thus it should yield more consistent strength data. The major difficulty with this test, as with ASTM D 3039, is that the test is a uniaxial test, and while it works well for unidirectional and (0,90) laminates, it does not work well for multi-axial laminates containing bias fibers.

SRM 5-88 SACMA Recommended Test Method for Open-Hole Tensile Properties of Oriented Fiber-Resin Composites

This test has no corresponding ASTM test. The method involves determination of the tensile properties of fiber-resin composites reinforced by oriented high modulus fibers containing a circular hole. The recommended specimen size is 1.5 inches wide by 12 inches long with a 0.25 inch hole. The test method does not allow testing of sandwich laminates, and specifies a quasi-isotropic laminate (+45°, 0°, -45°, 90°)s, but should be useful for solid FRP marine laminates.

SRM 7-88 SACMA Recommended Test Method for In-plane Shear Stress-Strain Properties of Oriented Fiber-Resin Composites

This test corresponds to ASTM D 3518, Test for In-plane Shear Stress-Strain Response of Unidirectional Reinforced Plastics. The method involves determination of the in-plane shear stress-strain properties of fiber-resin composites reinforced by oriented continuous high modulus fibers. The method is based on the uniaxial tensile stress-strain response of a ±45° laminate, which is symmetrically laminated about a mid-plane. There does not appear to be any significant enhancement over ASTM D 3518.

SRM 8-88 SACMA Recommended Test Method for Apparent Interlaminar Shear Strength of Oriented Fiber-Resin Composites.

This test corresponds to ASTM D 2344, Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Shear Method. SRM 8-88 does not appear to contain any significant enhancement over ASTM D 2344, however the discussion on failure modes, shown in Figure 6-5, is very useful.

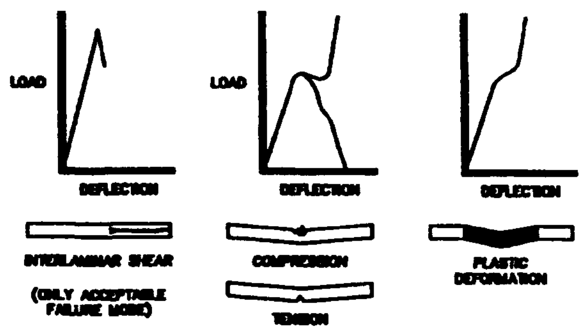


Figure 6-5 Typical Load-Deflection Curves and Failure Modes [SACMA 8-88]

SRM 10-88 SACMA Recommended Method for Calculation of Fiber Volume of Composite Test Laminates

There is no ASTM test corresponding to SRM 10-88. This method sets procedures for calculation of fiber volume content as a percentage of reinforcing fiber volume versus the total laminate volume. This is a simple procedure, but it will not be accurate for most marine laminates as there is no allowance for air trapped in the laminate. The errors depend on the amount of trapped air (more air, larger errors), the ratio of the fiber density to the resin density (lower ratios, larger errors), and the fiber content (lower fiber content, larger errors). This calculation method is not likely to be useful for marine laminates.

Sandwich Panel Testing

Background

Finite element models can be used to calculate panel deflections for various laminates under worst case loads [6-1, 6-2], but the accuracy of these predictions is highly dependent on test data for the laminates. *Traditional test methods [6-3] involve testing narrow strips, using ASTM standards outlined above.* Use of these tests assumes that hull panels can be accurately modeled as a beam, thus ignoring the membrane effect, which is particularly important in sandwich panels [6-4]. The traditional tests also cause much higher stresses in the core, thus leading to premature failure [6-5].

A student project at the Florida Institute of Technology investigated three point bending failure stress levels for sandwich panels of various laminates and span to width ratios. The results were fairly consistent for biaxial (0°, 90°) laminates, but considerable variation in deflection and failure stress for double bias (±45°) laminates was observed as the aspect ratio was changed. Thus while the traditional tests yield consistent results for biaxial laminates, the test properties may be significantly lower than actual properties, and test results for double bias and triaxial laminates are generally inaccurate.

Riley and Isley [6-6] addressed these problems by using a new test procedure. They pressure loaded sandwich panels, which were clamped to a rigid frame. Different panel aspect ratios were investigated for both biaxial and double bias sandwich laminates. The results showed that the double bias laminates were favored for aspect ratios less than two, while biaxial laminates performed better with aspect ratios greater than three. Finite element models of these tests indicated similar results, however, the magnitude of the deflections and the pressure at failure was quite different. This was probably due to the method of fastening the edge of the panel. The method of clamping of the edges probably caused local stress concentrations and could not be modeled by either pinned- or fixed-end conditions.

Pressure Table Design

The basic concept of pressure loading test panels is sound, however, the edges or boundary conditions need to be treated more realistically. In an actual hull, a continuous outer skin is supported by longitudinal and transverse framing, which defines the hull panels. The appropriate panel boundary condition is one which reflects the continuous nature of the outer skin, while providing for the added stiffness and strength of the frames. One possible solution to this problem is to include the frame with the panel, and restrain the panel from the frame, rather than the panel edges. Also, extending the panel beyond the frame can approximate the continuous nature of the outer skin.

A test apparatus, consisting of a table, a water bladder for pressurizing the panel, a frame to constrain the sides of the water bladder, and framing to restrain the test panel, was developed and is shown in Figure 6-6. The test panel is loaded on the "outside," while it is restrained by means of the integral frame system. The pressurization system can be operated either manually or under computer control, for pressure loading to failure or for pressure cycling to study fatigue.

Test Results

Sandwich laminates using four different reinforcements and three aspect ratios were constructed for testing. All panels used non-woven E-glass, vinyl ester resin and cross-linked PVC foam cores over fir frames and stringers. The panels were loaded slowly (approximately 1 psi per minute) until failure.

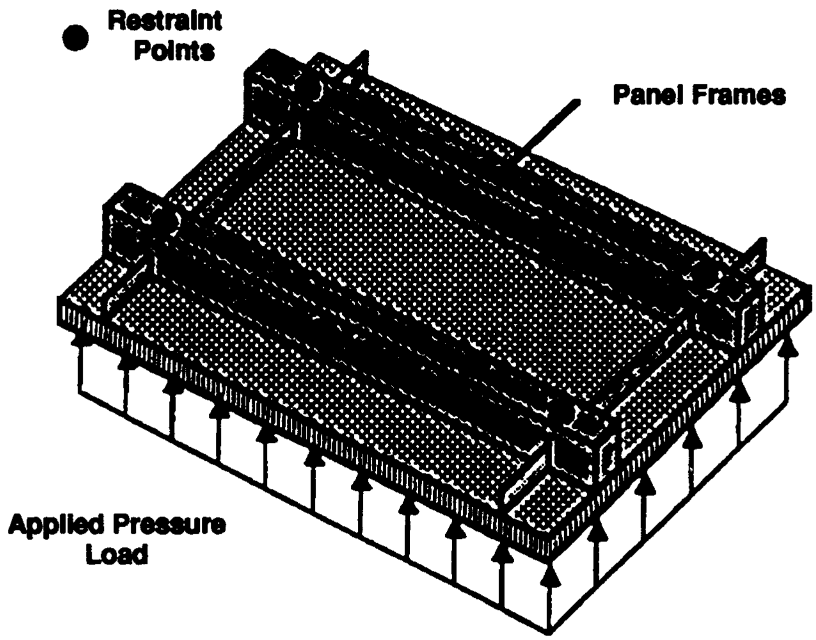


Figure 6-6 Schematic Diagram of Panel Testing Pressure Table [Reichard]

MSC/NASTRAN, a finite element structural analysis program, was used to model the panel tests. The models were run using two different boundary conditions, pinned edges and fixed edges. The predicted deflections for fixed- and pinned-edge conditions along with measured results are shown in Figure 6-7.

The pinned-edge predictions most closely model the test results. Other conclusions that can be made as a result of early pressure table testing include:

- Quasi-isotropic laminates are favored for square panels.
- Triaxial laminates are favored for panels of aspect ratios greater than two.
- Deflection increase with aspect ratio until asymptotic values are obtained. Asymptotic values of deflection are reached at aspect ratios between 2.0 and 3.5.

Material Testing Conclusions

In the previous text there is a review of ASTM and SACMA test procedures for determining physical and mechanical properties of various laminates.

In order to properly design a boat or a ship, the designer must have accurate mechanical properties. The properties important to the designer are the tensile strength and modulus, the compressive strength and modulus, the shear strength and modulus, the interply shear strength, and the flexural strength and modulus.

The ASTM and SACMA tests are all uniaxial tests. There are some parts of a boat's structure that are loaded uniaxially, however, much of the structure, the hull, parts of the deck and bulkheads, etc., receive multiaxial loads. One factor which is very important to determine in

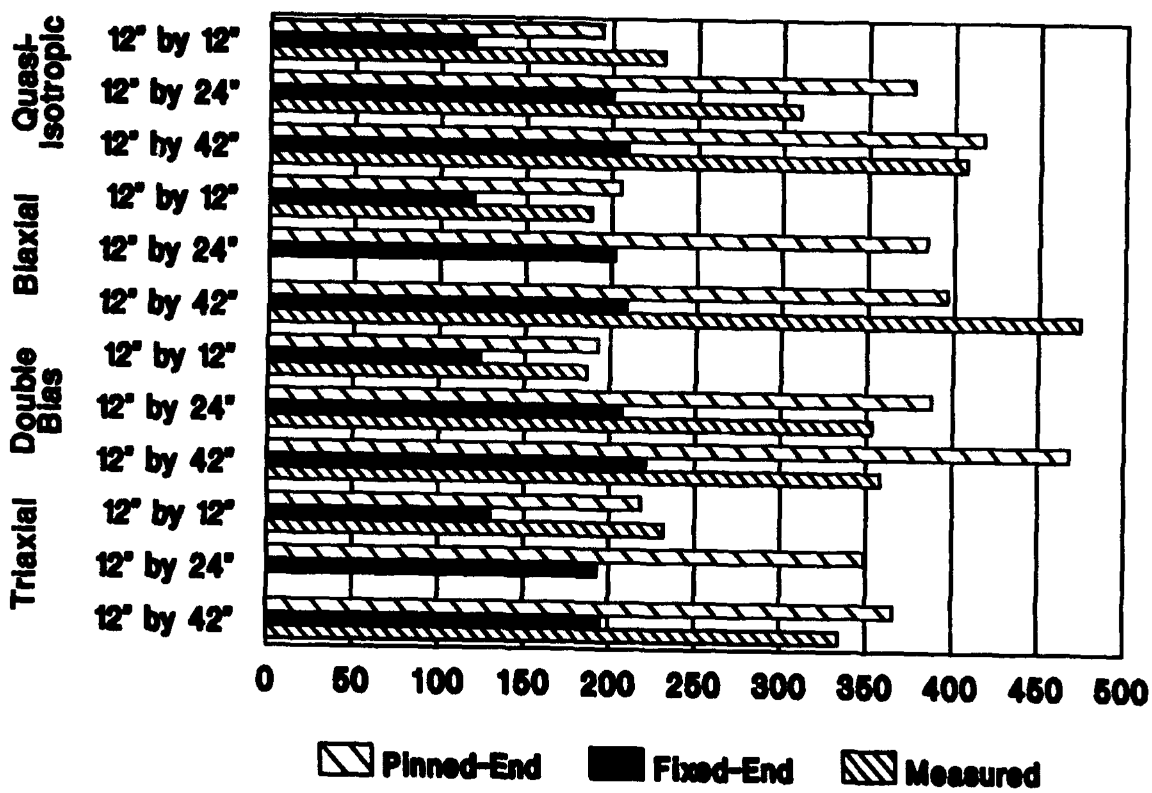


Figure 6-7 Theoretical and Measured Deflections (mils) of PVC Foam Core Panels Subjected to a 10 psi Load [Reichard]

composite materials is the interaction between loads in more than one axis. Poisson's ratio is not something which is easily determined. The effects of stress in the x and y directions combined are difficult to determine for composites, although they are relatively easy to determine for isotropic materials. Therefore, one thing that really needs to be done before a designer can design with confidence and using reasonable factors of safety is to determine the interaction between multiaxial stresses for given laminates. This is not possible using these standard tests, since they are all uniaxial in nature.

It's going to be very important for the marine industry to develop a set of tests which yield the right type of data for the marine designer. Once this has been accomplished and an industry wide set of accepted tests has been developed, then a comprehensive testing program, testing all the materials that are commonly used in the marine industry, would be very beneficial to the designers to try to yield some common data. Meanwhile, until these tests are developed, and this development could take a number of years, there is still a need for some common testing. In particular, the tests recommended to be performed on laminates are the ASTM D3039 tensile test or the appropriate SACMA variation of that, SRM 4-88. The ASTM compressive tests, all of them, leave something to be desired for marine laminates. However, the SACMA compression test looks like it might yield some useful uniaxial compressive load data for marine laminates, and therefore, at this time would probably be the recommended test for compression data. Flexural data should be determined using ASTM D790. This is a fairly good test. As far as shear is concerned, there is really no good test for determining the inplane shear properties. The ASTM test (D3518) is basically a 3039 tensile test performed on a fabric that has been laid up at a bias so that all the fibers are at ±45°. This has a number of problems, since the fibers are not continuous, and the results are heavily dependent on the resin, much more so than would be in a continuous laminate. So this test isn't particularly good. Currently, there is not a test that would yield the right type of data for the inplane shear properties. For the interply shear, about the only test that's available is the short beam shear test (ASTM D2344). The data yielded there is more useful in a quality control situation. It may be, however, that some of the other tests might yield some useful information. There's a shear test where slots are cut half way through the laminate on opposite sides of the laminate (ASTM D3846). This one might yield some useful information, but because they're cutting into the laminate and there's some variability involved in that it's difficult to come up with consistent data.

In summary, what is recommended as a comprehensive laminate test program is the ASTM D3039 tensile test, the SACMA compressive test, ASTM D790 flexural test and a panel test using the method developed at FIT. It's not clear whether or not this will become an industry standard, but at this point it's the best test that's available for looking at the out of plane loading and multiaxial loading.

Accelerated Testing

There are two mechanisms to accelerate tests for water absorption over normal speeds. One is to elevate the temperature of the water, the other is to increase the pressure of the water. Neither of these methods work particularly well. Increasing the temperature is unrealistic and affects the resin, softening it and making it more susceptible to hydrolysis or water attack, therefore, more water will be absorbed than would normally occur with a regular laminate. Resins which may be highly resistant to absorption may become very susceptible to it from raising the temperature. Increasing the pressure of the water will cause water absorption in laminates that would not normally absorb water because of the high pressure. The main issue here, however, is not so much absolute data but relative data, and it may be that increasing the pressure could give fairly good relative data between the different resins, since a resin that is more porous, with the higher pressure, would tend to take on even more water than a laminate, which is not quite so porous.

The second type of accelerated testing that's often done pertains to blistering. The comments here are very similar to those above for the accelerated water absorption tests, except that higher pressure is not an issue, since increasing the pressure tends to minimize the effects of the osmotic pressure, which causes the blistering. By using higher pressure to try to accelerate water absorption, which one might think would accelerate blistering, the formation of blisters is actually reduced or eliminated . It appears that the only viable method for accelerated blister testing is to elevate the temperature of the water, which is a common method throughout the industry. There are some problems with doing this, but it might yield reasonable relative results. One of the things that has been a problem in the past is the use of different temperatures. It's relatively easy to hold the water at boiling temperatures, but boiling is 212°F, which is well above the heat distortion temperature of all the polyester resins. Therefore, you will see a significant breakdown of the resin and blistering is much more likely to occur in the laminate. Recently, the industry seems to have settled on 65°C (149°F) for this testing, and the results seem to be more reasonable at 65°C.

Fire Testing

Composite materials based on organic matrices are flammable elements that should be evaluated to determine the potential risk associated with their use. In a fire, general purpose resins will burn off, leaving only the reinforcement, which has no inherent structural strength. Vessels inspected by the U.S. Coast Guard must be fabricated using fire retardant resins. These resins usually have additives such as chlorine, bromine or antimony. Physical properties of the resins are usually reduced when these compounds are added to the formulation. There is also some concern about the toxicity of the gases emitted when these resins are burned.

The fire resistance of individual composite components can be improved if they are coated with intumescent paints or foaming agents that will char and protect the component during minor fires. This consideration is generally only relevant to military projects where composites may be integrated into larger steel structures. The commercial designer is primarily concerned with the following general restrictions (see appropriate Code of Federal Regulation for detail):

- Subchapter T - Small Passenger Vessels: Use of fire retardant resins
- Subchapter I - Cargo Vessels: Use of incombustible materials - construction is to be of steel or other equivalent material
- Subchapter H - Passenger Vessels: SOLAS requires non-combustable structural materials or materials insulated with approved non-combustable materials so that the average temperature will not rise above a designated temperature

More detail will be given on SOLAS requirements later in this section. The industry is currently in the process of standardizing tests that can quantify the performance of various composite material systems in a fire. The U.S. Navy has taken the lead in an effort to certify materials for use on submarines. Table 6-7 at the end of the section presents some composite material test data compiled for the Navy. The relevant properties and associated test methods are outlined in the following topics. No single test method is adequate to evaluate the fire hazard of a particular composite material system. The behavior of a given material system in a fire is dependent not only on the properties of the fuel, but also on the fire environment to which the material system may be exposed. The proposed standardized test methods [6-7] for flammability and toxicity characteristics cover the spectrum from small scale to large scale tests.

Small Scale Tests

Small scale tests are quick repeatable ways to determine the flammability characteristics of organic materials. Usually, a lot of information can be obtained, using relatively small test specimens.

Oxygen-Temperature Limiting Index (LOI) Test - ASTM D 2863 (Modified)

The Oxygen Temperature Index Profile method determines the minimum oxygen concentration needed to sustain combustion in a material at temperatures from ambient to 570°F. During a fire, the temperature of the materials in a compartment will increase due to radiative and conductive heating. As the temperature of a material increases, the oxygen level required for ignition decreases. This test assesses the relative resistance of the material to ignition over a range of temperatures. The test apparatus is shown in Figure 6-8.

Approximately (40) ¼" to ½" x ⅛" x 6" samples are needed for the test. Test apparatus consists of an Oxygen/Nitrogen mixing system and analysis equipment. The test is good for comparing similar resin systems, but may be misleading when vastly different materials are compared.

N.B.S. Smoke Chamber - ASTM E662

This test is used to determine the visual obscuration due to fire. The sample is heated by a small furnace in a large chamber and a photocell arrangement is used to determine the visual obscuration due to smoke from the sample.

The test is performed in flaming and non-flaming modes, requiring a total of (6) 3" x 3" x ⅛" samples. Specific Optical Density, which is a dimensionless number, is recorded. The presence of toxic gases, such as CO, CO_2, HCN and HCl can also be recorded at this time. Table 6-1 shows some typical values recorded using this test.

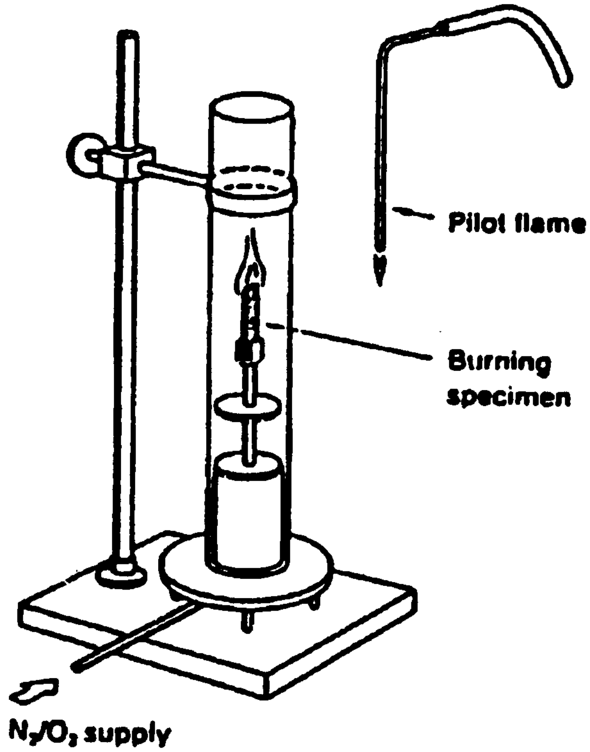


Figure 6-8 Sketch of the Functional Parts of the Limiting Oxygen Index Apparatus [Rollhauser, *Fire Tests of Joiner Bulkhead Panels*]

Table 6-1. Results of Smoke Chamber Tests (E-662) for Several Materials [Rollhauser, *Fire Tests of Joiner Bulkhead Panels*]

Material	Exposure	Optical Density 20 minutes	Optical Density 5 minutes
Phenolic Composite	Flaming	7	
	Nonflaming	1	
Polyester Composite	Flaming	660	321
	Nonflaming	448	22
Plywood	Flaming	45	
Nylon Carpet	Flaming	270	
Red Oak Flooring	Flaming	300	

Cone Calorimeter - ASTM P 190

This is an oxygen consumption calorimeter that measures the heat output of a burning sample by determining the amount of oxygen consumed during the burn and calculating the amount of energy involved in the process. The shape of the heating coil resembles a truncated cone. The test apparatus may be configured either vertically or horizontally, as shown in Figure 6-9. The device is used to determine the heat flux needed to ignite a sample, the mass loss of the sample, the sample's heat loss generation and smoke and toxic gas generation. This is a new test procedure that uses relatively small (4" x 4") test specimens, usually requiring (24) for a full series of tests.

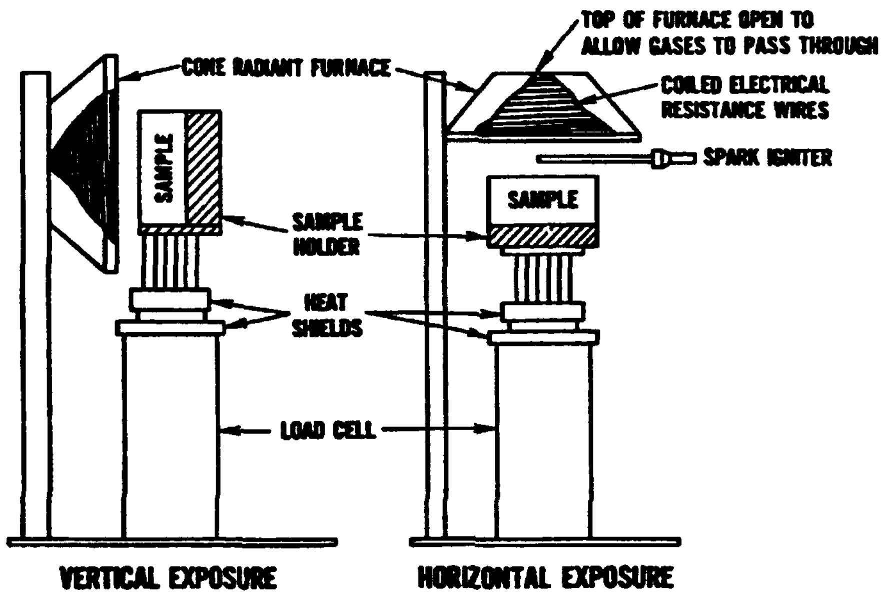


Figure 6-9 Sketch of the Functional Parts of a Cone Calorimeter [Rollhauser, *Fire Tests of Joiner Bulkhead Panels]*

Radiant Panel - ASTM E 162

This test procedure is intended to quantify the surface flammability of a material as a function of flame spread and heat contribution. The ability of a panel to stop the spread of fire and limit heat generated by the material is measured. A 6" x 18" specimen is exposed to heat from a 12" x 18" radiant heater. The specimen is held at a 45° angle, as shown in Figure 6-10.

The test parameters measured include the time required for a flame front to travel down the sample's surface, and the temperature rise in the stack. The Flame Spread Index is calculated from these factors. The Flame Spread Index for Red Oak is 100 and 0 for asbestos.

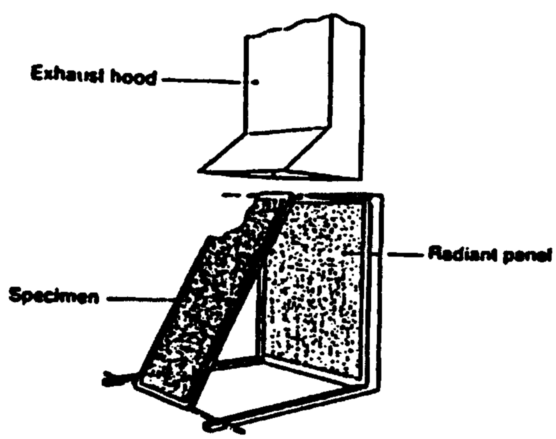


Figure 6-10 Sketch of the Functional Parts of the NBS Radiant Panel Test Configuration [Rollhauser, *Fire Tests of Joiner Bulkhead Panels]*

Intermediate Scale Tests

Intermediate scale tests help span the gap between the uncertainties associated with small scale tests and the cost of full scale testing. Three tests used by the U.S. Navy are described in the following.

DTRC Burn Through Test

This test determines the time required to burn through materials subjected to 2000°F under a controlled laboratory fire condition. This is a temperature that may result from fluid hydrocarbon fueled fires and can simulate the ability of a material to contain such a fire to a compartment. Figure 6-11 shows the arrangement of specimen and flame source for this test. (2) 24" x 24" samples are needed for this test. Burn through times for selected material is presented in Table 6-2.

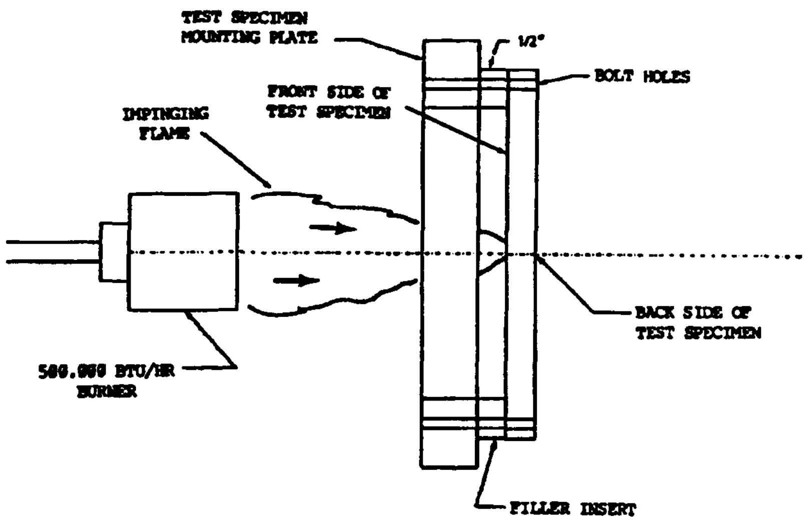
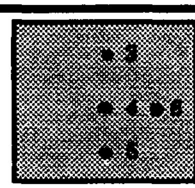


Figure 6-11 Sketch of the DTRC Burn Through Sample and Holder [Rollhauser, *Fire Tests of Joiner Bulkhead Panels]*

Table 6-2. DTRC Burnthrough Times for Selected Materials [Rollhauser, *Fire Tests of Joiner Bulkhead Panels*]

Sample	Burn Through Time	Maximum Temperatures, °F, at Locations on Panel, as Indicated at Right			
	Min:Sec	T3	T4	T5	T6
Plywood 1	5:00	300	425	150	125
	4:45	1150	1000	200	1100
Plywood 2	2:40	900	1000	200	200
	2:45	350	100	100	100
Polyester Composite	26:00	—	—	—	—
	30:00	—	—	—	—
Phenolic Composite	>60:00	—	—	—	—
Aluminum, ¼"	2:35	450	2000	600	100
	2:05	525	2000	600	200

U.S. Navy Quarter Scale Room Fire Test

This test determines the flashover potential of materials in a room when subjected to fire exposure. The test reduces the cost and time associated with full scale testing. A 10' x 10' x 8' room with a 30" x 80" doorway is modeled. (1) 36" x 36" and (3) 36" x 30" samples are required.

One Meter Furnace Test - ASTM E 119 (Modified)

This test subjects one side of a specimen to a small Class A fire. The samples are about 40 square feet, which yields more realistic results than small scale tests, but at a greater cost. This test is not widely used outside of the Navy.

Large Scale Tests

These tests are designed to be the most realistic simulation of a shipboard fire scenario. Tests are generally not standardized, instead designed to compare several material systems for a specific application.

Corner Tests

Corner tests are used to observe flame spread, structural response and fire extinguishment of the tested materials. The test was developed to test joiner systems. The geometry of the inside corner creates what might be a worst case scenario where the draft from each wall converges. 7' high by 4' wide panels are joined with whatever connecting system is part of the joinery. Approximately two gallons of hexane fuel is used as the source fire burning in a 1' x 1' pan.

Room Tests

This type of test is obviously the most costly and time consuming procedure. Approximately 98 square feet of material is required to construct an 8' x 6' room. Parameters measured include: temperature evolution, smoke emission, structural response, flame spread and heat penetration through walls. Instrumentation includes: thermocouples and temperatures recorders, thermal imaging video cameras and regular video cameras.

Summary of Proposed MIL-STD-2202 (SH) Requirements

Although MIL-STD-X108 (SH), "Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems used in Hull, Machinery, and Structural Applications inside Naval Submarines" is still in draft form, it is instructive to look at the requirements proposed by this standard. The foreword states:

> "The purpose of this standard is to establish the fire and toxicity test methods, requirements and the qualification procedure for composite material systems to allow their use in hull, machinery, and structural applications inside naval submarines. This standard is needed to evaluate composite material systems not previously used for these applications."

Table 6-3 summarizes the requirements outlined in the new military standard.

Table 6-3. Proposed General Requirements of MIL-STD-2202 (SH), *Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems Used in Hull, Machinery and Structural Applications Inside Naval Submarines*

Fire Test/Characteristic		Requirement		Test Method
Oxygen-Temperature Index (%)	The minimum concentration of oxygen in a flowing oxygen nitrogen mixture capable of supporting flaming combustion of a material.		Minimum	ASTM D 2863 (modified)
		% oxygen @ 25°C	35	
		% oxygen @ 75°C	30	
		% oxygen @ 300°C	21	
Flame Spread Index	A number or classification indicating a comparative measure derived from observations made during the progress of the boundary of a zone of flame under defined test conditions.		Maximum	ASTM E 162
			20	
Ignitability (seconds)	The ease of ignition, as measured by the time to ignite in seconds, at a specified heat flux with a pilot flame.		Minimum	ASTM P 190
		100 kW/m^2 irradiance	60	
		75 kW/m^2 irradiance	90	
		50 kW/m^2 irradiance	150	
		25 kW/m^2 irradiance	300	
Heat Release Rate (kW/m2)	Heat produced by a material, expressed per unit of exposed area, per unit of time.		Maximum	ASTM P 190
		100 kW/m^2 irradiance		
		Peak	150	
		Average 300 secs	120	
		75 kW/m^2 irradiance		
		Peak	100	
		Average 300 secs	100	
		50 kW/m^2 irradiance		
		Peak	65	
		Average 300 secs	50	
		25 kW/m^2 irradiance		
		Peak	50	
		Average 300 secs	50	

Fire Test/Characteristic		Requirement		Test Method
Smoke Obscuration	Reduction of light transmission by smoke as measured by light attenuation.		**Maximum**	ASTM E 662
		D_s during 300 secs	100	
		D_{max} occurrence	≥ 240 secs	
Combustion Gas Generation	Rate of production of combustion gases (e.g. CO, CO_2, HCl, HCN, NO_x, SO_x, halogen, acid gases and total hydrocarbons.	25 kW/m^2 irradiance:	**Maximum**	ASTM P 190
		CO	200 ppm	
		CO_2	4% (vol)	
		HCN	30 ppm	
		HCL	100 ppm	
Burn Through Fire Test	Test method to determine the time for a flame to burn through a composite material system under controlled fire exposure conditions.	No burn through in 30 minutes		DTRC Burn Through Fire Test
Quarter Scale Fire Test	Test method to determine the flashover potential of materials in a room when subjected to a fire exposure.	No flashover in 10 minutes		Navy Procedure
Large Scale Open Environment Test	Method to test materials at full size of their intended application under controlled fire exposure to determine fire tolerance of ease of extinguishment.	Pass		Navy Procedure
Large Scale Pressurable Fire Test	Method to test materials using an enclosed compartment in a simulated environment under a controlled fire exposure.	Pass		Navy Procedure
N-Gas Model Smoke Toxicity Screening Test	Test method to determine the potential toxic effects of combustion products (smoke and fire gases) using laboratory rats.	Pass		Navy Procedure

Review of SOLAS Requirements for Structural Materials in Fires

SOLAS is the standard that all passenger ships built or converted after 1984 must meet. Chapter II-2 Fire Protection, Fire Detection and Fire Extinction defines minimum fire standards for the industry. SOLAS divides ships into three class divisions and requires different levels of fire protection, detection and extinction. Each class division is measured against a standard fire test. This test is one in which specimens of the relevant bulkheads or decks are exposed in a fire test furnace to temperatures corresponding approximately to the Standard Time-Temperature Curve of ASTM E119, which is shown in Figure 6-11 along with other standards. The standard time-temperature curve for this purpose is developed by a smooth curve drawn through the following temperature points measured above the initial furnace temperature:

- at the end of the first 5 minutes 556°C (1032°F)
- at the end of the first 10 minutes 659°C (1218°F)
- at the end of the first 15 minutes 718°C (1324°F)
- at the end of the first 30 minutes 821°C (1509°F)
- at the end of the first 60 minutes 925°C (1697°F)

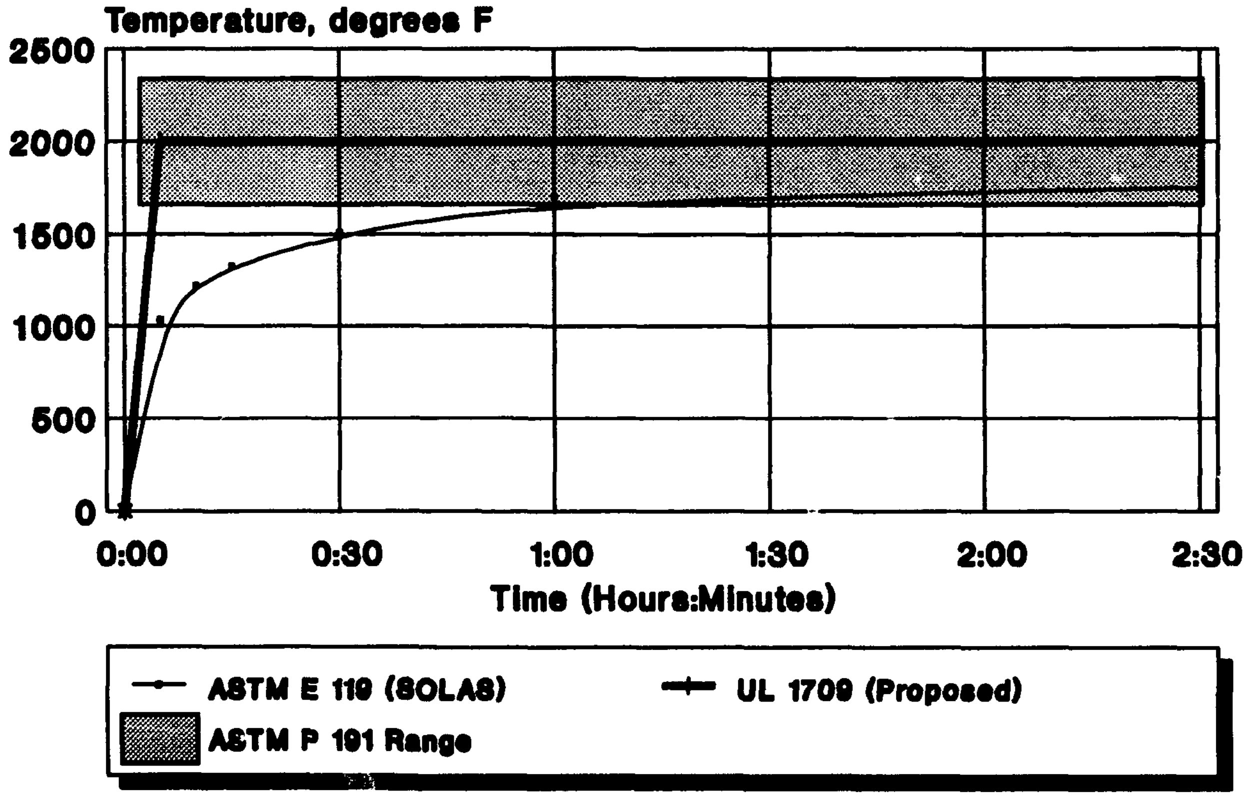


Figure 6-11 Comparison of Three Fire Tests [Rollhauser, *Integrated Technology Deckhouse*]

Non-combustible materials are identified for use in construction and insulation in all three class divisions. Non-combustible material is a material which neither burns nor gives off flammable vapors in sufficient quantity for self-ignition when heated to approximately 750°C (1382°F), this being determined to the satisfaction of the administration by an established test procedure. Any other material is a combustible material.

The actual class divisions are A, B, and C. "A" class divisions are those divisions formed by bulkheads and decks which:

a. shall be constructed of steel or other equivalent material;

b. shall be suitably stiffened;

c. shall be so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test;

d. shall be insulated with approved non-conbustible materials such that the average temperature of the unexposed side will not rise more than 139°C (282°F) above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180°C (356°F) above the original temperature, within the time listed below:

- Class "A-60" 60 minutes
- Class "A-30" 30 minutes
- Class "A-15" 15 minutes
- Class "A-0" 0 minutes

"B" class divisions are those divisions formed by bulkheads, decks, ceilings or linings which comply with the following:

a. shall be constructed as to be capable of preventing the passage of smoke and flame to the end of the first half hour standard fire tests;

b. shall have an insulation value such that the average temperature of the unexposed side will not rise more than 130°C (282°F) above the original temperature, nor will the temperature at any point, including any joint, rise more than 225°C (437°F) above the original temperature, within the time listed below:

- Class "B-15" 15 minutes
- Class "B-0" 0 minutes

c. they shall be constructed of approved non-combustible materials and all materials entering into the construction and erection of "B" class divisions shall be non-combustible, with the exception that combustible veneers may be permitted provided they meet other requirements of the chapter.

Table 6- 4. Heat Release Rates and Ignition Fire Test Data for Composite Materials [Hughes Associates, *Heat Release Rates and Ignition Fire Test Data for Representative Building and Composite Materials*]

Material/Reference		Applied Heat Flux (kW/m²)	Peak HRR (kW/m²)	Average Heat Release Rate - HRR (kW/m²) 1 min	2 min	5 min	Ignition Time
Epoxy/fiberglass	A	25,50,75					32,8,5
Epoxy/fiberglass	B	25,50,75					30,8,6
Epoxy/fiberglass 7mm	C	25,50,75	158,271,304				
Epoxy/fiberglass 7mm	D	25,50,75	168,238,279				
Epoxy/fiberglass 7mm	E	26,39,61	100,150,171				
Epoxy/fiberglass 7mm	F	25,37	117,125				
Epoxy/fiberglass 7mm	G	25,50,75	50,154,117				
Epoxy/fiberglass 7mm	H	25,50,75	42,71,71				
Epoxy/fiberglass 7mm	I	35	92				
Phenolic/fiberglass	A	25,50,75					28,8,4
Phenolic/fiberglass	B	25,50,75					NI,8,6
Phenolic/FRP 7mm	C	25,50,75	4,140,204				
Phenolic/FRP 7mm	D	25,50,75	4,121,171				
Phenolic/FRP 7mm	E	26,39,61	154,146,229				
Phenolic/FRP 7mm	F	25,37	4,125				
Phenolic/FRP 7mm	G	25,50,75	4,63,71				
Phenolic/FRP 7mm	H	25,50,75	4,50,63				
Phenolic/FRP 7mm	I	35	58				
Polyester/fiberglass	J	20	138				
FRP	J	20,34,49	40,66,80				
GRP	J	33.5	81				
Epoxy/Kevlar® 7mm	A	25,50,75					33,9,4
Epoxy/Kevlar® 7mm	B	25,50,75					36,7,6
Epoxy/Kevlar® 7mm	C	25,50,75	108,138,200				
Epoxy/Kevlar® 7mm	D	25,50,75	100,125,175				
Epoxy/Kevlar® 7mm	E	26,39,61	113,150,229				
Epoxy/Kevlar® 7mm	F	20,25,27	142,75,133				
Epoxy/Kevlar® 7mm	G	25,50,75	20,83,83				
Epoxy/Kevlar® 7mm	H	25,50,75	20,54,71				
Epoxy/Kevlar® 7mm	I	35	71				
Phenolic/Kevlar® 7mm	A	25,50,75					NI,12,6

Material/Reference		Applied Heat Flux (kW/m²)	Peak HRR (kW/m²)	Average Heat Release Rate - HRR (kW/m²) 1 min	2 min	5 min	Ignition Time
Phenolic/Kevlar® 7mm	B	25,50,75					NI,9,6
Phenolic/Kevlar® 7mm	C	25,50,75	0,242,333				
Phenolic/Kevlar® 7mm	D	25,50,75	0,200,250				
Phenolic/Kevlar® 7mm	E	26,39,64	100,217,300				
Phenolic/Kevlar® 7mm	F	30,37	147,125				
Phenolic/Kevlar® 7mm	G	25,50,75	13,92,117				
Phenolic/Kevlar® 7mm	H	25,50,75	13,75,92				
Phenolic/Kevlar® 7mm	I	35	83				
Phenolic/Graphite 7mm	C	25,50,75	4,183,233				
Phenolic/Graphite 7mm	D	25,50,75	0,196,200				
Phenolic/Graphite 7mm	E	39,61	138,200				
Phenolic/Graphite 7mm	F	20,30,37	63,100,142				
Phenolic/Graphite 7mm	G	25,50,75	13,75,108				
Phenolic/Graphite 7mm	H	25,50,75	13,63,88				
Phenolic/Graphite 7mm	I	35	71				
Phenolic/Graphite 7mm	A	25,50,75					NI,12,6
Phenolic/Graphite 7mm	B	25,50,75					NI,10,6
Epoxy	K	35,50,75		150,185,210	155,170,190	75,85,100	116,76,40
Epoxy/Nextel-Prepreg	K	35,50,75		215,235,255	195,205,240	95,105,140	107,62,31
Bismaleimide (BMI)	K	35,50,75		105,120,140	130,145,170	105,110,125	211,126,54
BMI/Nextel-Prepreg	K	35,50,75		100,120,165	125,135,280	120,125,130	174,102,57
BMI/Nextel-Dry	K	35,50,75		145,140,150	150,150,165	110,120,125	196,115,52
Koppers 6692T	L	25,50,75					263,60,21
Koppers 6692T/FRP	L	25,35,35	59,NR,101	50,55,70	40,65,55	25,65,40	
Koppers 6692T/FRP	L	50,50,75	85,NR,100	60,60,80	50,45,80	40,35,60	
Koppers Iso/FRP	L	50		215	180	150	55
Koppers Iso/Bi Ply	L	50		210	75	145	50
Koppers Iso/FRP	L	50		235	190	160	45
Koppers Iso/mat/WR	L	50		135	115	100	35
Koppers Iso/S2WR	L	50		130	110	0	45
Dow Derakane 3mm	L	35,50,75					
Dow Derakane 25mm	L	35,50,75					
Dow Vinylester/FRP	L	35,50,50		295,225,190	255,195,170	180,145,160	
Dow Vinylester/FRP	L	75,75,75		240,217,240	225,205,225	185,165,185	
Lab Epoxy 3mm	LL	35,50,75					116,76,40

Material/Reference		Applied Heat Flux (kW/m²)	Peak HRR (kW/m²)	Average Heat Release Rate - HRR (kW/m²) 1 min	2 min	5 min	Ignition Time
Lab Epoxy/Graphite	L	35,50,75		150,185,210	155,170,190	75,85,100	
Lab BMI 3mm	L	35,50,75					211,126,54
Lab BMI/Graphite	L	35,50,75		105,120,140	130,145,170	105,110,125	
Glass/Vinylester	M	25,75,100	377,498,557	290,240,330		180,220,—	281,22,11
Graphite/Epoxy	M	25,75,100	0,197,241	0,160,160		0,90,—	NI,53,28
Graphite/BMI	M	25,75,100	0,172,168	0,110,130		0,130,130	NI,66,37
Graphite/Phenolic	M	25,75,100	0,159,—	0,80,—		0,80,—	NI,79,—

Designation	Furnace	Reference
A	Cone - H	Babrauskas, V. and Parker, W.J., "Ignitability Measurements with the Cone Calorimeter," Fire and Materials, Vol. 11, 1987, pp. 31-43.
B	Cone - V	
C	Cone - V	Babrauskas, V., "Comparative Rates of Heat Release from Five Different Types of Test Apparatuses," Journal of Fire Sciences, Vol. 4, March/April 1986, pp. 148-159.
D	Cone - H	
E	FMRC - H	
F	Flame Height - V	
G	OSU/02 - V	
H	OSU - V (a)	
I	OSU - V (b)	
J	OSU - V	Smith, E.E., "Transit Vehicle Material Specification Using Release Rate Tests for Flammability and Smoke,"Report No. IH-5-76-1, American Public Transit Association, Washington, DC, Oct. 1976.
K	Cone	Brown, J . E ., "Combustion Characteristics of Fiber Reinforced Resin Panels," Report No. FR3970, U.S.Department of Commerce, N.B.S., April 1987.
L	Cone	Brown, J . E ., Braun, E. and Twilley, W.H., "Cone Calorimeter Evaluation of the Flammability of Composite Materials," US Department of the Navy, NAVSEA 05R25,Washington, DC, Feb. 1988.
M	Cone	Sorathia, U., "Survey of Resin Matrices for Integrated Deckhouse Technology," DTRC SME-88-52, David Taylor Research Center, August 1988.

H = horizontal

V = vertical

NI = not ignited

(a) = initial test procedure

(b) = revised test procedure

Nondestructive Testing

Unlike metallic structures, composites may have a variety of different defects that are either due to fabrication inconsistencies or from in-service damage. A variety of specialized nondestructive testing (NDT) techniques have evolved that can characterize defects present in composite structures. The U.S. Coast Guard Research Center in New London, CT is currently investigating a range of NDT techniques as applied to typical marine laminates for detection of the following defects:

- Resin rich/poor areas
- Excessive moisture
- Voids
- Delamination
- Impact Damage
- Shear Failure

A total of (40) panels are being fabricated for the effort. The report should be available to the public through the National Technical Information Service in the Spring of 1991. This section will briefly describe some of NDT techniques in use today.

Radiography Techniques

Radiography includes a number of different techniques such as X-rays, gamma rays, neutrons, radiation backscatter and flouroscopy. Each method uses a radiation beam that passes through the material, whereby varying amounts of radiation are absorbed by different sections of the laminate and discontinuities within the laminate.

Radiography is primarily used to determine fiber alignment, bond integrity and defects in sandwich structures. [6-8] X-ray radiography is unable to detect fiber breaks in graphite or aramid fiber. Very low-energy sources of about 15 to 25 kV must be used with graphite composites, otherwise the material would appear completely transparent. Often image enhancing penetrants are used to obtain good information about interior damage. [6-9]

Ultrasonic Inspection

Ultrasonic techniques are the most common form of NDT used with composites. In ultrasonic inspection, a beam of ultrasonic energy is directed into the laminate, and the energy is either transmitted or reflected. The laminate is usually immersed in water to direct sound waves. Ultrasonic transducers are placed on each side of the laminate that convert electric energy into mechanical vibrations, which are then transmitted through the laminate. Table 6-5 shows the applications of various types of ultrasonic techniques.

Table 6-5. Ultrasonic Inspection Techniques [M.M. Schwartz, *International Product News*]

Ultrasonic Technique	Application
Pulse Echo	Fiberglass-fiberglass bonds; delamination in fiberglass laminates up to ¾" thick; and facing to core unbonds
Pulse Echo Reflector Plate	Delamination in thin fiberglass or boron laminates
Through Transmission	Inspect sandwich constructions and thick fiberglass laminates
Resonant Frequency	Detect unbonds in fiberglass-metal bonds and fiberglass-fiberglass bonds where the exposed layer is not too thick

Acoustic Emission

The acoustic emission from composites under load is a research tool under development for assessing damage. Researchers have postulated that acoustic emission signals can be categorized by energy levels indicating fiber breakage, matrix cracking and delamination. The technique is most widely accepted in the filament wound pressure vessel industry.

Thermography

Thermographic analysis of composite materials uses thermal gradients in either a passive or active mode, to delineate defects or damage. In the passive method, an external heat source is applied to the laminate. Heat may be conducted either into or away from the laminate by an external heat source of either higher or lower temperature. In the active method, mechanical or electrical energy is applied. Video-thermographic cameras are the most efficient way of recording thermographic phenomena. Vibrothermography uses mechanical vibrational energy that is applied to the laminate, which is transformed into heat at damage sites.

This page intentionally left blank

Rules and Regulations

The U.S. Coast Guard is statutorily charged with administering maritime safety on behalf of the people of the United States. In carrying out this function, the Coast Guard monitors safety aspects of commercial vessels from design stages throughout the vessel's useful life. Often design standards such as those developed by the American Bureau of Shipping are used. Codes are referenced directly by the U.S. Code of Federal Regulations (CFR) [7-1]. Other countries, such as England, France, Germany, Norway, Italy and Japan have their own standards that are analogous to those developed by ABS. Treatment of FRP materials is handled differently by each country. This section will only describe the U.S. agencies.

U.S. Coast Guard

The Coast Guard operates on both a local and national level to accomplish their mission. On the local level, 42 Marine Safety Offices (MSOs) are located throughout the country. These offices are responsible for inspecting vessels during construction, inspecting existing vessels, licensing personnel and investigating accidents. The Office of Marine Safety, Security and Environment Protection is located in Washington, DC. This office primarily disseminates policy, directs marine safety training, oversees port security and responds to the environmental need of the country. The Marine Safety Center, also located in Washington, is the office where vessel plans are reviewed. The Coast Guard's technical staff reviews machinery, electrical arrangement, structural and stability plans, calculations and instructions for new construction and conversions for approximately 18,000 vessels a year.

The Coast Guard has authorized ABS for plan review of certain types of vessels. These do not include Subchapter T vessels and novel craft. The following section will attempt to describe the various classifications of vessels, as defined in the CFR. Table 7-1 summarizes some of these designations. Structural requirements for each class of vessel will also be highlighted.

Subchapter C - Uninspected Vessels

The CFR regulations that cover uninspected vessels are primarily concerned with safety, rather than structural items. The areas covered include:

- Life preservers and other lifesaving equipment
- Emergency position indicating radio beacons (fishing vessels)
- Fire extinguishing equipment
- Backfire flame control
- Ventilation
- Cooking, heating and lighting systems
- Garbage retention.

Organizations that are cited for reference:

American Boat and Yacht Council
P.O. Box 747
Millersville, MD 21108-0747

National Fire Protection Association (NFPA)
60 Batterymarch Park
Quincy, MA 02260

Table 7-1. Summary of CFR Vessel Classifications [46 CFR, Part 2.01 - 7(a)]

<table>
<tr><th colspan="2" rowspan="2">Size or Other Limitations</th><th>Subchapter H - Passenger</th><th>Subchapter T - Small Passenger</th><th>Subchapter I Cargo and Miscellaneous</th><th>Subchapter C Uninspected</th></tr>
<tr><th>46 CFR, Parts 70-80</th><th>46 CFR, Part 175</th><th>46 CFR, Parts 90-106</th><th>46 CFR, Parts 24-26</th></tr>
<tr><td rowspan="3">Motor</td><td rowspan="2">Vessels over 15 gross tons except seagoing motor vessels of 300 gross tons and over.</td><td>Vessels over 100 gross tons</td><td>Vessels under 100 gross tons</td><td rowspan="3">All vessels carrying freight for hire except those covered by H or T vessels</td><td rowspan="3">All vessels except those covered by H, T or I vessels</td></tr>
<tr><td colspan="2">All vessels carrying more than 12 passengers on an international voyage, except yachts.

All vessels not over 65 feet in length which carry more than 6 passengers.

All other vessels of over 65 feet in length carrying passengers for hire.</td></tr>
<tr><td>Seagoing motor vessels of 300 gross tons and over.</td><td colspan="2">All vessels carrying more than 12 passengers on an international voyage, except yachts.

All other vessels carrying passengers except yachts.</td></tr>
<tr><td rowspan="3">Sail</td><td rowspan="2">Vessels not over 700 gross tons.</td><td>Vessels over 100 gross tons</td><td>Vessels under 100 gross tons</td><td rowspan="2">None</td><td rowspan="2">None</td></tr>
<tr><td colspan="2">All vessels carrying more than 6 passengers.</td></tr>
<tr><td>Vessels over 700 gross tons.</td><td colspan="2">All vessels carrying passengers for hire.</td><td>None</td><td>None</td></tr>
</table>

Subchapter H - Passenger Vessels

Part 72 of CFR 46 is titled Construction and Arrangement. Subpart §72.01-15 Structural Standards states:

> In general, compliance with the standards established by ABS will be considered satisfactory evidence of structural efficiency of the vessel. However, in special cases, a detailed analysis of the entire structure or some integral part may be made by the Coast Guard to determine the structural requirements.

Looking at Subpart 72.05 - Structural Fire Protection, under §72.05-10 Type, location and construction of fire control bulkheads and decks, it is noted:

> The hull, structural bulkheads, decks, and deckhouses shall be constructed of steel or other equivalent metal construction of appropriate scantlings.

The section goes on to define different types of bulkheads, based fire performance.

Subchapter I - Cargo and Miscellaneous Vessels

The requirements for "I" vessels is slightly different than for "H". Under Subpart 92.07 - Structural Fire Protection, §92.07-10 Construction states:

> The hull, superstructure, structural bulkheads, decks and deckhouses shall be constructed of steel. Alternately, the Commandant may permit the use of other suitable materials in special cases, having in mind the risk of fire.

Subchapter T - Small Passenger Vessels

Subpart 177.10 - Hull Structure is reproduced here in its entirety:

§177.10-1 Structural standards

> (a) In general, compliance with the standards established by a recognized classification society (Lloyds' "Rules for the Construction and Classification of Composite and Steel Yachts" and Lloyds' "Rules for the Construction and Classification of Wood Yachts" are acceptable for this purpose.) will be considered satisfactory evidence of the structural adequacy of a vessel. When scantlings differ from such standards and it can be demonstrated that craft approximating the same size, power and displacement have been built to such scantlings and have been in satisfactory service insofar as structural adequacy is concerned for a period of at least 5 years, such scantlings may be approved. A detailed structural analysis may be required for specialized types or integral parts thereof.
>
> (b) Special consideration will be given to:
>
> (1) The structural requirements of vessels not contemplated by the standards of a recognized classification society; or
>
> (2) The use of materials not specifically included in these standards.

§177.10-5 Fire Protection

> (a) The general construction of the vessel shall be such as to minimize fire hazards insofar as reasonable and practicable. Vessels contracted for on or after July 1, 1961, which carry more than 150 passengers shall meet the requirements of Subpart 72.05 of Subchapter H (Passenger Vessels) of the chapter. The

application of these requirements to specific vessels shall be as determined by the Officer in Charge, Marine Inspection.

(a-1) Except for a vessel complying with the requirements contained in paragraph (a-2) of this section, each hull, structural bulkhead, deck, or deckhouse made of fibrous glass reinforced plastic on each vessel that carries 150 passengers or less must be constructed with fire retardant resins, laminates of which have been demonstrated to meet military specification MIL-R-21607 after 1-year exposure to weather. Military specification MIL-R-21607 may be obtained from the Commanding Officer, Naval Supply Depot, 5801 Tabor Avenue, Philadelphia, PA 19120.

(a-2) Each hull, structural bulkhead, deck, or deckhouse, made of fibrous reinforced plastic on a vessel that carries 150 passengers or less, that was certificated on July 11, 1973, and remains certificated may continue in service. Any repairs must be as follows:

(1) Minor repairs and alterations must be made to the same standard as the original construction or a higher standard; and

(2) Major alterations and conversions must comply with the requirements of this subpart.

(b) Internal combustion engine exhausts, boiler and galley uptakes, and similar sources of ignition shall be kept clear of and suitably insulated from any woodwork or other combustible matter.

(c) Lamp, paint, and oil lockers and similar compartments shall be constructed of metal or lined with metal.

American Bureau of Shipping

The American Bureau of Shipping (ABS) is a nonprofit organization that develops rules for the classification of ship structures and equipment. Although ABS is primarily associated with large, steel ships, their involvement with small craft dates back to the 1920's, when a set of rules for wood sailing ship construction was published. The recent volume of work done for FRP yachts is summarized in Table 7-2. The publications and services offered by ABS are detailed below. [7-2]

Rules for Building and Classing Reinforced Plastic Vessels 1978

These give hull structure, machinery and engineering system requirements for commercial displacement craft up to 200 feet in length, and special requirements for limited service craft such as yachts and ferries etc. They contain comprehensive sections on materials and manufacture and are essentially for E-glass chopped strand mat and woven roving laminates with a means of approving other laminates given.

These general Rules have served and continue to service industry and ABS very well - they are adopted as Australian Government Regulations and are used by the USCG. They are applied currently by ABS to all commercial displacement craft in unrestricted ocean service, and to limited service craft such as sailing yachts over 100 feet in length, ferries, passenger vessels, and fishing vessels.

Table 7-2. Statistics on ABS Services for FRP Yachts During the Past Decade [Curry, American Bureau of Shipping]

ABS Service	Sailing Yachts	Motor Yachts
Completed or contracted for class or hull certification as of 1989	336	94
Plan approval service only as of 1989	160	9
Currently in class	121	164
Plan approval service from 1980 to 1989	390	35

Guide for Building and Classing Offshore Racing Yachts, 1986

These were developed by ABS at the request of the Offshore Racing Council (ORC) 1978-1980 out of their concern for ever lighter advanced composite boats and the lack of suitable standards. At that time, several boats and lives had been lost. ABS staff referred to the design and construction practice for offshore racing yachts, reflected in designers' and builders' practice and to limited full scale measured load data and refined the results by analysis of many existing proven boats, and analysis of damaged boat structures. Advice and guidance on the scope, detail and needs of the standards were given by the Chairman and two members of the International Technical Committee of the ORC, respectively Olin Stephens, Gary Mull and Hans Steffensen.

As the Guide was to provide for all possible hull materials, including advanced composites, it was essential that it be given in a direct engineering format of design loads and design stresses, based on ply, laminate and core material mechanical properties. Such a format permits the designer to readily see the influence of design loads, material mechanical properties and structural arrangement on the requirements, thereby giving as much freedom as possible to achieve optimum use of materials.

The Guide gives hull structural design and construction standards for offshore racing yachts and for cruising yachts. Boats that are to receive the ABS classification ✠A1 Yachting Service, are required to have engineering systems such as bilge system, fuel oil system, electrical system, fire protection in accordance with the ABYC recommendations. For sailing yachts over 100 feet in length the Guide and the ABYC standards are augmented by parts of the Rules for Building and Classing Reinforced Plastic Vessels.

All Rules and Guides are in a continuous state of development to reflect experience, advances in technology, new materials, changes in building procedures and occasionally to curtail exploitation of loopholes. This is nowhere more true than in the use of advanced composites for offshore racing yachts - already the development of additional in-house guidance to augment the Guide, suggests a third edition in the near future. It should be noted that the Coast Guard does not yet recognize the Guide as an acceptable standard for a vessel to meet the requirements of Subchapter T.

Proposed Guide for Building and Classing High Speed Craft (Commercial, Patrol and Utility Craft)

Since 1980, ABS has had specific in-house guidance for the hull structure of planing and semi-planing craft in commercial and government service.

This Guide, for vessels up to 200 ft. in length, covers glass fiber reinforced plastic, advanced composite, aluminum and steel hulls. Requirements are given in a direct engineering format expressed in terms of design pressures, design stresses, and material mechanical properties. Design planing slamming pressures for the bottom structure have been developed for the work of Heller and Jasper [7-3] Savitsky and Brown, [7-4] Allen and Jones [7-5], and Spencer [7-6]. Those for the side structure are based on a combination of hydrostatic and speed induced hydrodynamic pressures. In establishing the bottom design pressures and dynamic components of side structure, distinction is made for example between passenger-carrying craft, general commercial craft, and mission type craft such as patrol boats. Design pressures for decks superstructures, houses and bulkheads are from ABS and industry practice.

Design stresses, have been obtained from the ABS in-house guidance and from applying the various design pressures to many existing, proven vessels processed over the years by ABS. In providing requirements for advanced composites, criteria are given for strength in both 0° and 90° axes of structural panels.

Anticipating the desirability of extending the length of boats using standard or advanced composites, the Guide contains hull-girder strength requirements for vessels in both the displacement and planing modes. The former comes from current ABS Rules. The latter from Heller and Jasper bending moments together with hull-girder bending stresses obtained by applying these moments to many existing, proven planing craft designs. As might be expected, design stresses for the planing mode bending moments are relatively low, reflecting design for fatigue strength. Particularly for fiber reinforced plastic boats, criteria were established for hull-girder stiffness, by which, one of the potential limitations of fiber reinforced plastic, low tensile and compressive modulii, can be avoided by proper design.

Again, primarily for fiber reinforced plastic construction, there are extensive sections on materials and manufacturing.

Requirements for structural detail considering local structural stability and local shear strength are also included. For the first time in any set of ABS standards, the Guide contains proposed criteria for portlights and windows - for which, because of the empirical nature of development, we are seeking a comprehensive review and comment participation by industry. Distribution of the Guide for industry review is imminent.

Although the Guide contains specific, detailed standards for planing craft hull structures, it is not confined to these form hulls and operational modes. Brief, general requirements for surface effect, air cushion and hydrofoil craft are also included and will be developed into more specific detailed criteria over the next few years.

Proposed Guide for High Speed and Displacement Motor Yachts

As with high speed commercial and government service craft, ABS has had in-house guidance for many years for planing motor yachts. This has also been developed over the last few years into the Guide for High Speed and Displacement Motor Yachts.

The standards for high speed motor yachts parallel those for high speed commercial and government service craft and the preceding description of the Guide for the high speed commercial, patrol, and utility craft is equally applicable with the qualification that the design pressures for motor yachts reflect the less rigorous demands of this service.

Probably, 80% to 90%, of the motor yachts today are, by definition of this Guide, high speed. However to provide complete standards, the Guide also includes requirements for displacement motor yachts. Design loads and design stresses for these standards are essentially developed from ABS Rules for Reinforced Plastic Vessels, modified appropriately for advanced composite, aluminum and steel hulls and fine-tuned by review of a substantial number of existing proven, displacement hull motor yacht designs.

In addition to hull structural standards, this Guide includes requirements for propulsion systems and essential engineering systems. The hull part of this Guide is now complete and distribution for industry review is imminent.

Classification

This entails plan approval of the hull structural plans, including the building process descriptions, essential engineering systems for both sail and power craft, and for power craft, plan approval of the main propulsion system.

Following plan approval, the ABS surveyor inspects the boat during construction to verify compliance with these approved plans, and with the appropriate ABS Rules or Guide. The Surveyor also witnesses material tests, installation and testing of the propulsion system (for motor craft) and engineering systems (for sail and motor craft). The symbol ✠ in front of AMS is required for commercial craft but is optional for recreational and certain government service craft. The symbol ✠ indicates that the main propulsion engine, reduction gear, shafting, propellers and generators (over 100 kw) have been inspected by the ABS surveyor during their construction, and certificates for their construction have been issued by ABS. On completion of the boat and compliance with all of the conditions of classification the boat is issued with a Classification Certificate and bronze plaque. The boat is also included in the ABS Record of Classed Vessels.

In service, vessels are required to have ABS annual and special periodic surveys, as well as surveys after damage, to retain classification.

Table 7-3 shows basic ABS classification symbols and various ABS classification notations. Figure 7-1 shows a flow chart outlining the classification process.

Table 7-3. ABS Classification Symbols [ABS]

Symbol	Definition
✠A1	Hull plan approval; hull construction and hull material testing under ABS survey
A1	Hull plan approval; special ABS survey of completed hull
✠ AMS	Propulsion and essential engineering systems approval; propulsion system units manufactured under ABS survey, propulsion and engineering systems installed and tested under ABS survey
AMS	Propulsion and essential engineering systems approval; propulsion and engineering systems installed and tested under ABS survey
Ⓔ	Equipment of anchors, cables and windlasses approved in accordance with ABS Rules or Guide; material and equipment tested and installed under ABS survey

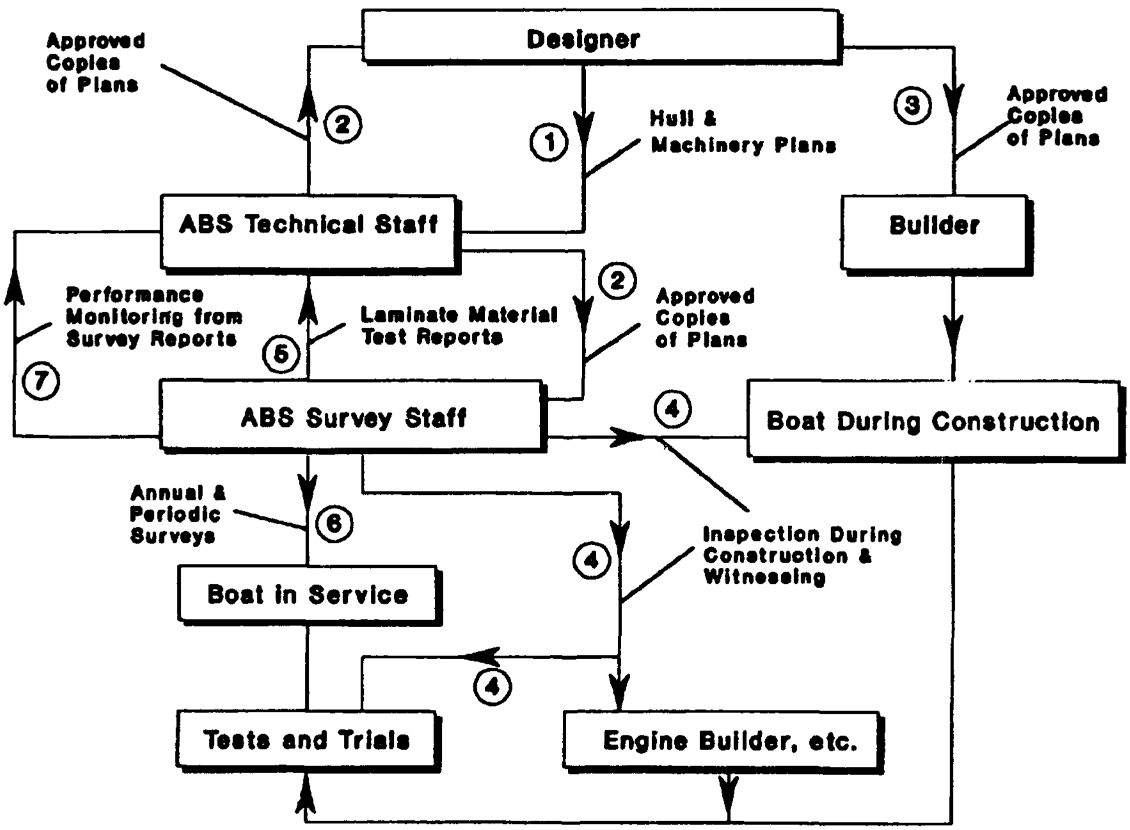


Figure 7-1 Flow Chart for ABS Classification Process [Curry, American Bureau of Shipping]

Hull Certification

Hull certification comprises plan approval of the hull structural plans, including the building process description and inspection of the hull during construction to verify compliance with these approved plans, and with the appropriate Rules or Guide. The Surveyor also witnesses required hull material tests.

On completion of the boat and compliance with all of the requirements for hull certification, the boat is issued with a Hull Construction Certificate and bronze plaque.

Hull certification is confined to the hull construction and there are no ABS surveys of the vessel in service. Figure 7-2 shows the hull certification procedure.

Plan Approval

Plan approval entails approval of hull structural plans and if desired, plan approval of the propulsion system (for motor vessels) and engineering systems (for sail and motor vessels). There is no inspection by an ABS Surveyor during construction.

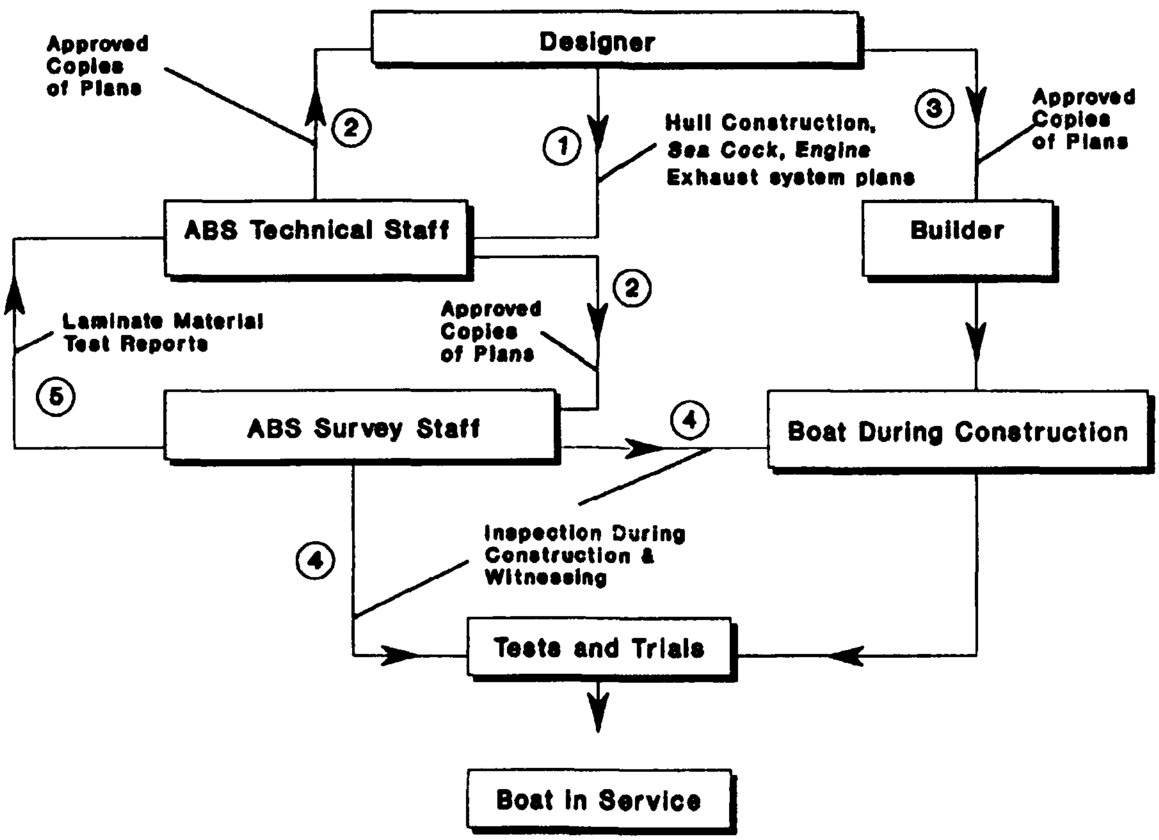


Figure 7-2 Flow Chart for ABS Hull Certification Process [Curry, American Bureau of Shipping]

Conversion Factors

LENGTH		
Multiply:	**By:**	**To Obtain:**
Centimeters	0.0328	Feet
Centimeters	0.3937	Inches
Feet	30.4801	Centimeters
Feet	0.30480	Meters
Inches	2.54	Centimeters
Meters	3.28083	Feet
Meters	39.37	Inches
Meters	1.09361	Yards
Mils	0.001	Inches
Mils	25.40	Microns

MASS		
Multiply:	**By:**	**To Obtain:**
Grams	0.03527	Ounces*
Grams	2.205×10^{-3}	Pounds*
Kilograms	35.27	Ounces*
Kilograms	2.205	Pounds*
Kilograms	1.102×10^{-3}	Tons*
Kilograms	9.839×10^{-4}	Long Tons*
Long Tons*	1016	Kilograms
Long Tons*	2240	Pounds*
Metric Tons	2204.6	Pounds*
Ounces*	28.35	Grams
Pounds*	453.6	Grams
Pounds*	0.4536	Kilograms
Pounds*	0.0005	Tons*
Pounds*	4.464×10^{-4}	Long Tons*
Pounds*	4.536×10^{-4}	Metric Tons
Tons*	907.2	Kilograms
Tons*	2000	Pounds*

* These quantities are not mass units, but are often used as such. The conversion factors are based on $g = 32.174$ ft/sec^2.

AREA		
Multiply:	**By:**	**To Obtain:**
Square centimeters	1.0764×10^{-3}	Square feet
Square centimeters	0.15499	Square inches
Square centimeters^2 (moment of area)	0.02403	Square inches^2 (moment of area)
Square feet	0.09290	Square meters
Square feet	929.034	Square centimeters
Square feet^2 (moment of area)	20736	Square inches^2 (moment of area)
Square meters	10.76387	Square feet
Square meters	1550	Square inches
Square meters	1.196	Square yards
Square yards	1296	Square inches
Square yards	0.8361	Square meters

VOLUME		
Multiply:	**By:**	**To Obtain:**
Cubic centimeters	3.5314×10^{-5}	Cubic feet
Cubic centimeters	2.6417×10^{-4}	Gallons
Cubic centimeters	0.03381	Ounces
Cubic [illegible]t	28317.016	Cubic centimeters
Cubic feet	1728	Cubic inches
Cubic feet	7.48052	Gallons
Cubic feet	28.31625	Liters
Cubic inches	16.38716	Cubic centimeters
Cubic inches	0.55441	Ounces
Cubic meters	35.314	Cubic feet
Cubic meters	61023	Cubic inches
Cubic meters	1.308	Cubic yards
Cubic meters	264.17	Gallons
Cubic meters	999.973	Liters
Cubic yards	27	Cubic feet
Cubic yards	0.76456	Cubic meters

DENSITY		
Multiply:	**By:**	**To Obtain:**
Grams per centimeters^3	0.03613	Pounds per inches^3
Grams per centimeters^3	62.428	Pounds per feet^3
Kilograms per meters^3	3.613×10^{-5}	Pounds per inches^3
Kilograms per meters^3	0.06243	Pounds per feet3
Pounds per inches^3	2.768 x 104	Kilograms per meters^3
Pounds per inches^3	1728	Pounds per feet3
Pounds per feet^3	16.02	Kilograms per meters3
Pounds per feet^3	5.787×10^{-4}	Pounds per inches^3

FORCE		
Multiply:	**By:**	**To Obtain:**
Kilograms-force	9.807	Newtons
Kilograms-force	2.205	Pounds
Newtons	0.10197	Kilograms-force
Newtons	0.22481	Pounds
Pounds	4.448	Newtons
Pounds	0.4536	Kilograms-force

PRESSURE		
Multiply:	**By:**	**To Obtain:**
Feet of saltwater (head)	3064.32	Pascals
Feet of saltwater (head)	64	Pounds per feet^2
Feet of saltwater (head)	0.44444	Pounds per inches^2
Inches of water	249.082	Pascals
Inches of water	5.202	Pounds per feet^2
Inches of water	0.03613	Pounds per inches^2
Pascals	0.02089	Pounds per feet^2
Pascals	1.4504×10^{-4}	Pounds per inches^2
Pounds per feet^2	47.88	Pascals
Pounds per feet^2	6.944 x 10-3	Pounds per inches^2
Pounds per inches^2	6895	Pascals
Pounds per inches^2	144	Pounds per feet^2
Pascals = Newtons per meters^2		

Weights and Conversion Factors [*Principles of Naval Architecture*]

Quantity	Water		Oil			Gasoline
	Salt	Fresh	Fuel	Diesel	Lube	
Cubic feet per long ton	35	36	38	41.5	43	50
Gallons per long ton	—	269.28	284.24	310.42	321.64	374.00
Barrels per long ton	—	—	6.768	7.391	7.658	8.905
Pounds per gallon	—	—	7.881	7.216	6.964	5.989
Pounds per cubic feet	64	62.222	58.947	53.976	52.093	44.800
Pounds per barrel	—	—	331	303	292.5	251.5

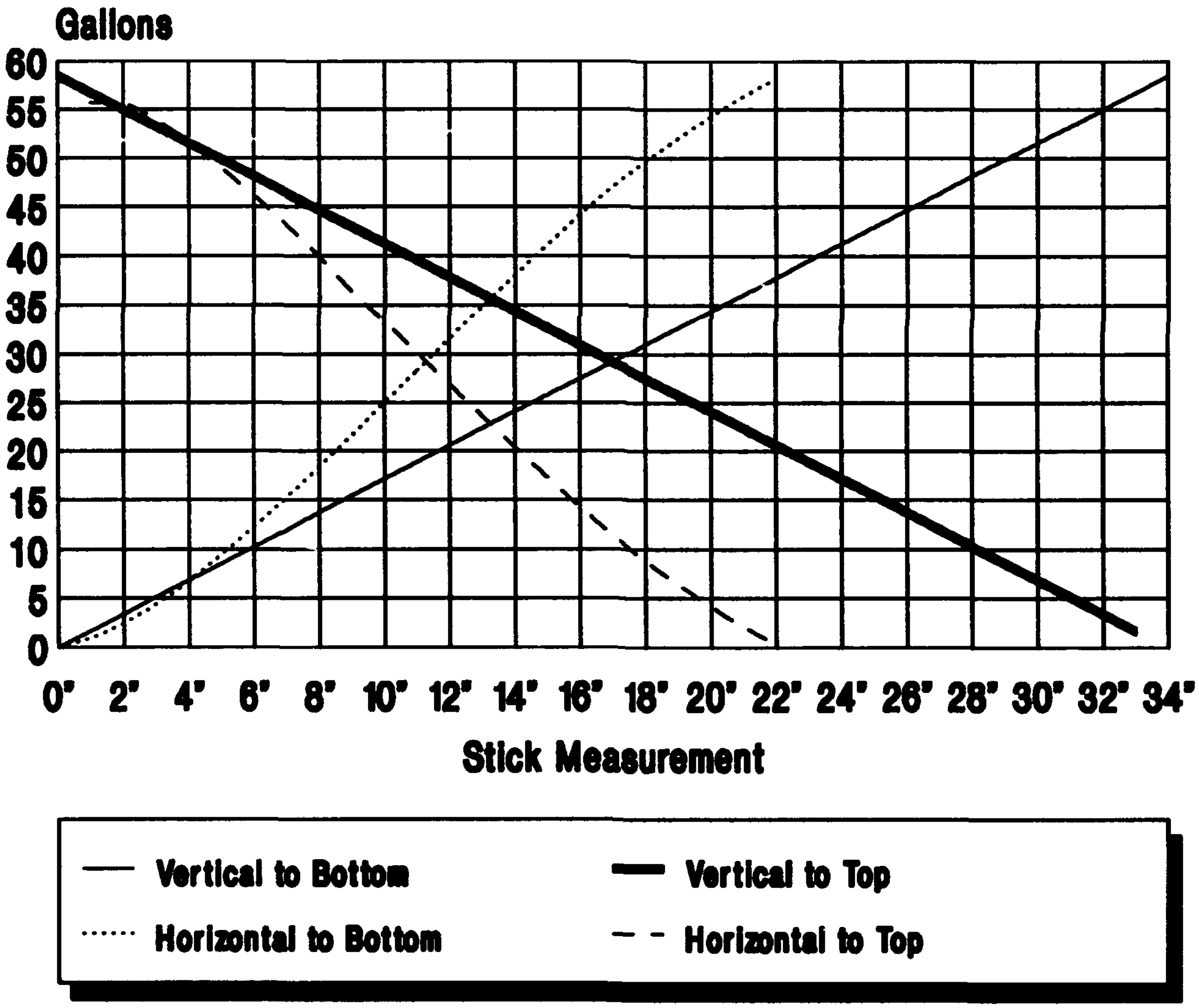


Figure 7-3 Volume Remaining in 55 Gallon Drums Based on Ruler Measurements from the Top and Bottom for Drums in Vertical and Horizontal Positions [Cook, *Polycor Polyester Gel Coats and Resins*]

Polyester Resin Conversion Factors
[Cook, *Polycor Polyester Gel Coats and Resins*]

Multiply:	By:	To Obtain:
Fluid ounces MEK Peroxide*	32.2	Grams MEK Peroxide*
Grams MEK Peroxide*	.0309	Fluid ounces MEK Peroxide*
Cubic centimeters MEK Peroxide*	1.11	Grams MEK Peroxide*
Grams MEK Peroxide*	0.90	Cubic centimeters MEK Peroxide*
Fluid ounces cobalt**	30.15	Grams cobalt**
Grams cobalt**	0.033	Fluid ounces cobalt**
Grams cobalt**	0.98	Cubic centimeters cobalt**
Gallon polyester resin†	9.2	Pounds
Gallon polyester resin†	13.89	Fluid ounces
Gallon polyester resin†	411	Cubic centimeters

* 9% Active Oxygen
** 6% Solution
† Unpigmented

Material Coverage Assuming No Loss
[Cook, *Polycor Polyester Gel Coats and Resins*]

Wet Film Thickness		Ft^2 per Gallon	Gallons per 1000 Ft^2
Inches	Mils		
.001	1	1600.0	0.63
.003	3	534.0	1.90
.005	5	320.0	3.10
.010	10	160.0	6.30
.015	15	107.0	9.40
.018	18	89.0	11.20
.020	20	80.0	12.50
.025	25	64.0	15.60
.030	30	53.0	19.00
.031	31	51.0	19.50
.060	60	27.0	38.00
.062	62	26.0	39.00

Non-woven E-Glass Reinforcement Designation Comparison

	Advanced Textiles, Inc.		Brunswick Technologies, Inc.		Hexcel Knytex		Fiber Orientation
	Product	oz/yd²	Product	oz/yd²	Product	oz/yd²	
Biaxial	NEMP 090	9.5			DB 090	9.3	±45°
	NEMP 120	12.4			DB 120	12.0	±45°
	NEWF 120	12.1	C 1200	12.0			0°, 90°
	NEMP 170	17.6	X 1800	18.0	DB 170	18.0	±45°
	NEWF 180	17.7	C 1800	18.0			0°, 90°
	NEMP 240	24.2	X 2400	24.0	DB 240	25.2	±45°
Triaxial	NEWMP 230	22.8			CDB 200	22.7	0°, ±45°
	NEFMP 230	22.8			DDB 222	22.5	90°, ±45°
	NEWMP 340	33.1	TV 3400	34.0	CDB 340	33.9	0°, ±45°
	NEFMP 340	33.1			DDB 340	34.7	90°, ±45°
Knits with Mat	NEMPC 1208	19.2			DBM 1208	19.7	±45°, ¾ oz. mat
	NEWFC 1208		CM 1208	18.8			0°, 90°, ¾ oz. mat
	NEMPC 1708	24.4	XM 1808	24.8	DBM 1708	25.7	±45°, ¾ oz. mat
	NEMPC 1715	31.1	XM 1815	31.5	DBM 1715	31.2	±45°, 1½ oz. mat
	NEWFC 1808	24.4	CM 1808	24.8	CDM 1808	26.6	0°, 90°, ¾ oz. mat
	NEWFC 1810	26.6	CM 1810	27.0	CDM 1810	28.8	0°, 90°, 1 oz. mat
	NEWFC 1815	31.2	CM 1815	31.5	CDM 1815	33.4	0°, 90°, 1 ½ oz. mat
	NEMPC 2408	31.0	XM 2408	30.8	DBM 2408	32.8	±45°, ¾ oz. mat
	NEMPC 2415	37.8	XM 2415	37.5	DBM 2415	38.3	±45°, 1½ oz. mat
	NEWFC 2308	29.0	CM 2408	30.8	CDM 2408	33.6	0°, 90°, ¾ oz. mat
	NEWFC 2310	32.2	CM 2410	33.0	CDM 2410	35.9	0°, 90°. 1 oz. mat
	NEWFC 2315	36.7	CM 2415	37.5	CDM 2415	40.4	0°, 90°, 1½ oz. mat
	NEWMPC 2308	29.5			CDBM 2008	30.4	0°, ±45°, ¾ oz. mat
	NEWMPC 3408	40.2	TVM 3408	40.8	CDBM 3408	42.1	0°, ±45°, ¾ oz. mat

GLOSSARY

A

ablation The degradation, decomposition and erosion of material caused by high temperature, pressure, time, percent oxidizing species and velocity of gas flow. A controlled loss of material to protect the underlying structure.

ablative plastic A material that absorbs heat (with a low material loss and char rate) through a decomposition process (pyrolysis) that takes place at or near the surface exposed to the heat.

absorption The penetration into the mass of one substance by another. The capillary or cellular attraction of adherend surfaces to draw off the liquid adhesive film into the substrate.

accelerated test A test procedure in which conditions are increased in magnitude to reduce the time required to obtain a result. To reproduce in a short time the deteriorating effect obtained under normal service conditions.

accelerator A material that, when mixed with a catalyst or resin, will speed up the chemical reaction between the catalyst and the resin (either polymerizing of resins or vulcanization of rubbers). Also called promoter.

acceptance test A test, or series of tests, conducted by the procuring agency upon receipt of an individual lot of materials to determine whether the lot conforms to the purchase order or contract or to determine the degree of uniformity of the material supplied by the vendor, or both.

acetone In an FRP context, acetone is primarily useful as a cleaning solvent for removal of uncured resin from applicator equipment and clothing. This is a very flammable liquid.

acoustic emission A measure of integrity of a material, as determined by sound emission when a material is stressed. Ideally, emissions can be correlated with defects and/or incipient failure.

activator An additive used to promote and reduce the curing time of resins. See also accelerator.

additive Any substance added to another substance, usually to improve properties, such as plasticizers, initiators, light stabilizers and flame retardants.

adherend A body that is held to another body, usually by an adhesive. A detail or part prepared for bonding.

advanced composites Strong, tough materials created by combining one or more stiff, high-strength reinforcing fiber with compatible resin system. Advanced composites can be substituted for metals in many structural applications with physical properties comparable or better than aluminum.

air-inhibited resin A resin by which surface cures will be inhibited or stopped in the presence of air.

aging The effect on materials of exposure to an environment for an interval of time. The process of exposing materials to an environment for a interval of time.

air-bubble void Air entrapment within and between the plies of reinforcement or within a bondline or encapsulated area; localized, noninterconnected, spherical in shape.

allowables Property values used for design with a 95 percent confidence interval: the "A" allowable is the minimum value for 99 percent of the population; and the "B" allowable, 90 percent.

alternating stress A stress varying between two maximum values which are equal but with opposite signs, according to a law determined in terms of the time.

alternating stress amplitude A test parameter of a dynamic fatigue test: one-half the algebraic difference between the maximum and minimum stress in one cycle.

ambient conditions Prevailing environmental conditions such as the surrounding temperature, pressure and relative humidity.

anisotropic Not isotropic. Exhibiting different properties when tested along axes in different directions.

antioxidant A substance that, when added in small quantities to the resin during mixing, prevents its oxidative degradation and contributes to the maintenance of its properties.

aramid A type of highly oriented organic material derived from polyamide (nylon) but incorporating aromatic ring structure. Used primarily as a high-strength high-modulus fiber. Kevlar® and Nomex® are examples of aramids.

areal weight The weight of fiber per unit area (width x length) of tape or fabric.

artificial weathering The exposure of plastics to cyclic, laboratory conditions, consisting of high and low temperatures, high and low relative humidities, and ultraviolet radiant energy, with or without direct water spray and moving air (wind), in an attempt to produce changes in their properties similar to those observed in long-term continuous exposure outdoors. The laboratory exposure conditions are usually intensified beyond those encountered in actual outdoor exposure, in an attempt to achieve an accelerated effect.

aspect ratio The ratio of length to diameter of a fiber or the ratio of length to width in a structural panel.

autoclave A closed vessel for conducting and completing a chemical reaction or other operation, such as cooling, under pressure and heat.

B

bagging Applying an impermeable layer of film over an uncured part and sealing the edges so that a vacuum can be drawn.

balanced construction Equal parts of warp and fill in fiber fabric. Construction in which reactions to tension and compression loads result in extension or compression deformations only and in which flexural loads produce pure bending of equal magnitude in axial and lateral directions.

balanced laminate A composite in which all laminae at angles other than 0° and 90° occur only in ± pairs (not necessarily adjacent) and are symmetrical around the centerline.

Barcol hardness A hardness value obtained by measuring the resistance to penetration of a sharp steel point under a spring load. The instrument, called a Barcol impressor, gives a direct reading on a scale of 0 to 100. The hardness value is often used as a measure of the degree of cure of a plastic.

barrier film The layer of film used to permit removal of air and volatiles from a composite lay-up during cure while minimizing resin loss.

bedding compound White lead or one of a number of commercially available resin compounds used to form a flexible, waterproof base to set fittings.

bias fabric Warp and fill fibers at an angle to the length of the fabric.

biaxial load A loading condition in which a laminate is stressed in two different directions in its plane.

bidirectional laminate A reinforced plastic laminate with the fibers oriented in two directions in its plane. A cross laminate.

binder The resin or cementing constituent (of a plastic compound) that holds the other components together. The agent applied to fiber mat or preforms to bond the fibers before laminating or molding.

bleeder cloth A woven or nonwoven layer of material used in the manufacture of composite parts to allow the escape of excess gas and resin during cure. The bleeder cloth is removed after the curing process and is not part of the final composite.

blister An elevation on the surface of an adherend containing air or water vapor, somewhat resembling in shape a blister on the human skin. Its boundaries may be indefinitely outlined, and it may have burst and become flattened.

bond The adhesion at the interface between two surfaces. To attach materials together by means of adhesives.

bond strength The amount of adhesion between bonded surfaces. The stress required to separate a layer of material from the base to which it is bonded, as measured by load/bond area. See also peel strength.

bonding angles An additional FRP laminate, or an extension of the laminate used to make up *the joined member, which extends onto the* existing laminate to attach additional items such as framing, bulkheads and shelves to the shell or to each other.

boundary conditions Load and environmental conditions that exist at the boundaries. Conditions must be specified to perform stress analysis.

buckling A mode of failure generally characterized by an unstable lateral material deflection due to compressive action on the structural element involved.

bulk molding compound (BMC) Thermosetting resin mixed with strand reinforcement, fillers, etc. into a viscous compound for compression or injection molding.

butt joint A type of edge joint in which the edge faces of the two adherends are at right angles to the other faces of the adherends.

C

carbon The element that provides the backbone for all organic polymers. Graphite is a more ordered form of carbon. Diamond is the densest crystalline form of carbon.

carbon fiber Fiber produced by the pyrolysis of organic precursor fibers, such as rayon, polyacrylonitrile (PAN), and pitch, in an inert environment. The term is often used interchangeably with the term graphite; however carbon fibers and graphite fibers differ. The basic differences lie in the temperature at which the fibers are made and heat treated, and in the amount of elemental carbon produced. Carbon fibers typically are carbonized in the region of 2400°F and assay at 93 to 95% carbon, while graphite fibers are graphitized between 3450° and 4500°F and assay to more than 99% elemental carbon.

carpet plot A design chart showing the uniaxial stiffness or strength as a function of arbitrary ratios of 0, 90, and ± 45 degree plies.

catalyst A substance that changes the rate of a chemical reaction without itself undergoing permanent change in composition or becoming a part of the molecular structure of the product. A substance that markedly speeds up the cure of a compound when added in minor quantity.

cell In honeycomb core, a cell is a single honeycomb unit, usually in a hexagonal shape.

cell size The diameter of an inscribed circle within the cell of a honeycomb core.

Charpy impact test A test for shock loading in which a centrally notched sample bar is held at both ends and broken by striking the back face in the same plane as the notch.

chain plates The metallic plates, embedded in or attached to the hull or bulkhead, used to evenly distribute loads from shrouds and stays to the hull of sailing vessels.

chopped strand Continuous strand yarn or roving cut up into uniform lengths, usually from 1/32 inch long. Lengths up to 1/8 inch are called milled fibers.

closed cell foam Cellular plastic in which individual cells are completely sealed off from adjacent cells.

cocuring The act of curing a composite laminate and simultaneously bonding it to some other prepared surface. See also secondary bonding.

coin test Using a coin to test a laminate in different spots, listening for a change in sound, which would indicate the presence of a defect. A surprisingly accurate test in the hands of experienced personnel.

compaction The application of a temporary vacuum bag and vacuum to remove trapped air and compact the lay-up.

compliance Measurement of softness as opposed to stiffness of a material. It is a reciprocal of the Young's modulus, or an inverse of the stiffness matrix.

composite material A combination of two or more materials (reinforcing elements, fillers and composite matrix binder), differing in form or composition on a macroscale. The constituents retain their identities; that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

compression molding A mold that is open when the material is introduced and that shapes the material by the presence of closing and heat.

compressive strength The ability of a material to resist a force that tends to crush or buckle. The maximum compressive load sustained by a specimen divided by the original cross-sectional area of the specimen.

compressive stress The normal stress caused by forces directed toward the plane on which they act.

contact molding A process for molding reinforced plastics in which reinforcement and resin are placed on a mold. Cure is either at room temperature using a catalyst-promoter system or by heating in an oven, without additional pressure.

constituent materials Individual materials that make up the composite material; e.g., graphite and epoxy are the constituent materials of a graphite/epoxy composite material.

copolymer A long chain molecule formed by the reaction of two or more dissimilar monomers.

core The central member of a sandwich construction to which the faces of the sandwich are attached. A channel in a mold for circulation of heat-transfer media. Male part of a mold which shapes the inside of the mold.

corrosion resistance The ability of a material to withstand contact with ambient natural factors or those of a particular artificially created atmosphere, without degradation or change in properties. For metals, this could be pitting or rusting; for organic materials, it could be crazing.

count For fabric, number of warp and filling yarns per inch in woven cloth. For yarn, size based on relation of length and weight.

coupling agent Any chemical agent designed to react with both the reinforcement and matrix phases of a composite material to form or promote a stronger bond at the interface.

crazing Region of ultrafine cracks, which may extend in a network on or under the surface of a resin or plastic material. May appear as a white band.

creep The change in dimension of a material under load over a period of time, not including the initial instantaneous elastic deformation. (Creep at room temperature is called cold flow.) The time dependent part of strain resulting from an applied stress.

cross-linking Applied to polymer molecules, the setting-up of chemical links between the molecular chains. When extensive, as in most thermosetting resins, cross-linking makes one infusible supermolecule of all the chains.

C-scan The back-and-forth scanning of a specimen with ultrasonics. A nondestructive testing technique for finding voids, delaminations, defects in fiber distribution, and so forth.

cure To irreversibly change the properties of a thermosetting resin by chemical reaction, i.e. condensation, ring closure or addition. Curing may be accomplished by addition of curing (crosslinking) agents, with or without heat.

curing agent A catalytic or reactive agent that, when added to a resin, causes polymerization. Also called a hardener.

D

damage tolerance A design measure of crack growth rate. Cracks in damage tolerant designed structures are not permitted to grow to critical size during expected service life.

delamination Separation of the layers of material in a laminate, either local or covering a wide area. Can occur in the cure or subsequent life.

debond Area of separation within or between plies in a laminate, or within a bonded joint, caused by contamination, improper adhesion during processing or damaging interlaminar stresses.

denier A yarn and filament numbering system in which the yarn number is numerically equal to the weight in grams of 9000 meters. Used for continuous filaments where the lower the denier, the finer the yarn.

dimensional stability Ability of a plastic part to retain the precise shape to which it was molded, cast or otherwise fabricated.

dimples Small sunken dots in the gel coat surface, generally caused by a foreign particle in the laminate.

draft angle The angle of a taper on a mandrel or mold that facilitates removal of the finished part.

drape The ability of a fabric or a prepreg to conform to a contoured surface.

dry laminate A laminate containing insufficient resin for complete bonding of the reinforcement. See also resin-starved area.

ductility The amount of plastic strain that a material can withstand before fracture. Also, the ability of a material to deform plastically before fracturing.

E

E-glass A family of glasses with a calcium aluminoborosilicate composition and a maximum alkali content of 2.0%. A general-purpose fiber that is most often used in reinforced plastics, and is suitable for electrical laminates because of its high resistivity. Also called electric glass.

elastic deformation The part of the total strain in a stressed body that disappears upon removal of the stress.

elasticity That property of materials by virtue of which they tend to recover their original size and shape after removal of a force causing deformation.

elastic limit The greatest stress a material is capable of sustaining without permanent strain remaining after the complete release of the stress. A material is said to have passed its elastic limit when the load is sufficient to initiate plastic, or nonrecoverable, deformation.

elastomer A material that substantially recovers its original shape and size at room temperature after removal of a deforming force.

elongation Deformation caused by stretching. The fractional increase in length of a material stressed in tension. (When expressed as percentage of the original gage length, it is called percentage elongation.)

encapsulation The enclosure of an item in plastic. Sometimes used specifically in reference to the enclosure of capacitors or circuit board modules.

epoxy plastic A polymerizable thermoset polymer containing one or more epoxide groups and curable by reaction with amines, alcohols, phenols, carboxylic acids, acid anhydrides, and mercaptans. An important matrix resin in composites and structural adhesive.

exotherm heat The heat given off as the result of the action of a catalyst on a resin.

F

failure criterion Empirical description of the failure of composite materials subjected to complex state of stresses or strains. The most commonly used are the maximum stress, the maximum strain, and the quadratic criteria.

failure envelope Ultimate limit in combined stress or strain state defined by a failure criterion.

fairing A member or structure, the primary function of which is to streamline the flow of a fluid by producing a smooth outline and to reduce drag, as in aircraft frames and boat hulls.

fatigue The failure or decay of mechanical properties after repeated applications of stress. Fatigue tests give information on the ability of a material to resist the development of cracks, which eventually bring about failure as a result of a large number of cycles.

fatigue life The number of cycles of deformation required to bring about failures of the test specimen under a given set of oscillating conditions (stresses or strains).

fatigue limit The stress limit below which a material can be stressed cyclically for an infinite number of times without failure.

fatigue strength The maximum cyclical stress a material can withstand for a given number of cycles before failure occurs. The residual strength after being subjected to fatigue.

faying surface The surfaces of materials in contact with each other and joined or about to be joined together.

felt A fibrous material made up of interlocking fibers by mechanical or chemical action, pressure or heat. Felts may be made of cotton, glass or other fibers.

fiber A general term used to refer to filamentary materials. Often, fiber is used synonymously with filament. It is a general term for a filament with a finite length that is at least 100 times its diameter, which is typically 0.004 to 0.005 inches. In most cases it is prepared by drawing from a molten bath, spinning, or deposition on a substrate. A whisker, on the other hand, is a short single-crystal fiber or filament made from a variety of materials, with diameters ranging from 40 to 1400 micro inches and aspect ratios between 100 and 15000. Fibers can be continuous or specific short lengths (discontinuous), normally less than 1/8 inch.

fiber content The amount of fiber present in a composite. This is usually expressed as a percentage volume fraction or weight fraction of the composite.

fiber count The number of fibers per unit width of ply present in a specified section of a composite.

fiber direction The orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.

fiberglass An individual filament made by drawing molten glass. A continuous filament is a glass fiber of great or indefinite length. A staple fiber is a glass fiber of relatively short length, generally less than 17 inches, the length related to the forming or spinning process used.

fiberglass reinforcement Major material used to reinforce plastic. Available as mat, roving, fabric, and so forth, it is incorporated into both thermosets and thermoplastics.

fiber-reinforced plastic (FRP) A general term for a composite that is reinforced with cloth, mat, strands or any other fiber form.

fiberglass chopper Chopper guns, long cutters and roving cutters cut glass into strands and fibers to be used as reinforcement in plastics.

Fick's equation Diffusion equation for moisture migration. This is analogous to the Fourier's equation of heat conduction.

filament The smallest unit of fibrous material. The basic units formed during drawing and spinning, which are gathered into strands of fiber for use in composites. Filaments usually are of extreme length and very small diameter, usually less than 1 mil. Normally, filaments are not used individually. Some textile filaments can function as a yarn when they are of sufficient strength and flexibility.

filament winding A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape or other) either previously impregnated with a matrix material or impregnated during the winding, are placed over a rotating and removable form or mandrel in a prescribed way to meet certain stress conditions. Generally, the shape is a surface of revolution and may or may not include end closures. When the required number of layers is applied, the wound form is cured and the mandrel is removed.

fill Yarn oriented at right angles to the warp in a woven fabric.

filler A relatively inert substance added to a material to alter its physical, mechanical, thermal, electrical and other properties or to lower cost or density. Sometimes the term is used specifically to mean particulate additives.

fillet A rounded filling or adhesive that fills the corner or angle where two adherends are joined.

filling yarn The transverse threads or fibers in a woven fabric. Those fibers running perpendicular to the warp. Also called weft.

finish A mixture of materials for treating glass or other fibers. It contains a coupling agent to improve the bond of resin to the fiber, and usually includes a lubricant to prevent abrasion, as well as a binder to promote strand integrity. With graphite or other filaments, it may perform any or all of the above functions.

first-ply-failure First ply or ply group that fails in a multidirectional laminate. The load corresponding to this failure can be the design limit load.

flame retardants Certain chemicals that are used to reduce or eliminate the tendency of a resin to burn.

fish eye A circular separation in a gel coat film generally caused by contamination such as silicone, oil, dust or water.

flammability Measure of the extent to which a material will support combustion.

flexural modulus The ratio, within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outermost fibers of the specimen.

flexural strength The maximum stress that can be borne by the surface fibers in a beam in bending. The flexural strength is the unit resistance to the maximum load before failure by bending, usually expressed in force per unit area.

flow The movement of resin under pressure, allowing it to fill all parts of the mold. The gradual but continuous distortion of a material under continued load, usually at high temperatures; also called creep.

foam-in-place Refers to the deposition of foams when the foaming machine must be brought to the work that is "in place," as opposed to bringing the work to the foaming machine. Also, foam mixed in a container and poured in a mold, where it rises to fill the cavity.

fracture toughness A measure of the damage tolerance of a material containing initial flaws or cracks. Used in aircraft structural design and analysis.

G

gel The initial jellylike solid phase that develops during the formation of a resin from a liquid. A semisolid system consisting of a network of solid aggregates in which liquid is held.

gelation time That interval of time, in connection with the use of synthetic thermosetting resins, extending from the introduction of a catalyst into a liquid adhesive system until the start of gel formation. Also, the time under application of load for a resin to reach a solid state.

gel coat A quick setting resin applied to the surface of a mold and gelled before lay-up. The gel coat becomes an integral part of the finish laminate, and is usually used to improve surface appearance and bonding.

glass finish A material applied to the surface of a glass reinforcement to improve the bond between the glass and the plastic resin matrix.

glass transition The reversible change in an amorphous polymer or in an amorphous regions of a partially crystalline polymer from, or to, a viscous or rubbery condition to, or from, a hard to a relatively brittle one.

graphite To crystalline allotropic form of carbon.

Green strength The ability of a material, while not completely cured, set or sintered, to undergo removal from the mold and handling without distortion.

H

hand lay-up The process of placing (and working) successive plies of reinforcing material of resin-impregnated reinforcement in position on a mold by hand.

hardener A substance or mixture added to a plastic composition to promote or control the curing action by taking part in it.

harness satin Weaving pattern producing a satin appearance. "Eight-harness" means the warp tow crosses over seven fill tows and under the eighth (repeatedly).

heat build-up The temperature rise in part resulting from the dissipation of applied strain energy as heat.

heat resistance The property or ability of plastics and elastomers to resist the deteriorating effects of elevating temperatures.

homogeneous Descriptive term for a material of uniform composition throughout. A medium that has no internal physical boundaries. A material whose properties are constant at every point, that is, constant with respect to spatial coordinates (but not necessarily with respect to directional coordinates).

honeycomb Manufactured product of resin impregnated sheet material (paper, glass fabric and so on) or metal foil, formed into hexagonal-shaped cells. Used as a core material in sandwich constructions.

hoop stress The circumferential stress in a material of cylindrical form subjected to internal or external pressure.

hull liner A separate interior hull unit with bunks, berths, bulkheads, and other items of outfit preassembled then inserted into the hull shell. A liner can contribute varying degrees of stiffness to the hull through careful arrangement of the berths and bulkheads.

hybrid A composite laminate consisting of laminae of two or more composite material systems. A combination of two or more different fibers, such as carbon and glass or carbon and aramid, into a structure. Tapes, fabrics and other forms may be combined; usually only the fibers differ.

hygrothermal effect Change in properties due to moisture absorption and temperature change.

hysteresis The energy absorbed in a complete cycle of loading and unloading. This energy is converted from mechanical to frictional energy (heat).

I

ignition loss The difference in weight before and after burning. As with glass, the burning off of the binder or size.

impact strength The ability of a material to withstand shock loading. The work done on fracturing a test specimen in a specified manner under shock loading.

impact test Measure of the energy necessary to fracture a standard notched bar by an impulse load.

impregnate In reinforced plastics, to saturate the reinforcement with a resin.

inclusion A physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material. Inclusions are often capable of transmitting some structural stresses and energy fields, but in a noticeably different degree from the parent material.

inhibitor A material added to a resin to slow down curing. It also retards polymerization, thereby increasing shelf life of a monomer.

injection molding Method of forming a plastic to the desired shape by forcing the heat-softened plastic into a relatively cool cavity under pressure.

interlaminar Descriptive term pertaining to an object (for example, voids), event (for example, fracture), or potential field (for example, shear stress) referenced as existing or occurring between two or more adjacent laminae.

interlaminar shear Shearing force tending to produce a relative displacement between two laminae in a laminate along the plane of their interface.

intralaminar Descriptive term pertaining to an object (for example, voids), event (for example, fracture), or potential field (for example, temperature gradient) existing entirely within a single lamina without reference to any adjacent laminae.

isotropic Having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.

Izod impact test A test for shock loading in which a notched specimen bar is held at one end and broken by striking, and the energy absorbed is measured.

K

kerf The width of a cut made by a saw blade, torch, water jet, laser beam and so forth.

Kevlar® An organic polymer composed of aromatic polyamides having a para-type orientation (parallel chain extending bonds from each aromatic nucleus).

knitted fabrics Fabrics produced by interlooping chains of yarn.

L

lamina A single ply or layer in a laminate made up of a series of layers (organic composite). A flat or curved surface containing unidirectional fibers or woven fibers embedded in a matrix.

laminae Plural of lamina

laminate To unite laminae with a bonding material, usually with pressure and heat (normally used with reference to flat sheets, but also rods and tubes). A product made by such bonding.

lap joint A joint made by placing one adherend partly over another and bonding the overlapped portions.

lay-up The reinforcing material placed in position in the mold. The process of placing the reinforcing material in a position in the mold. The resin-impregnated reinforcement. A description of the component materials, geometry, and so forth, of a laminate.

load-deflection curve A curve in which the increasing tension, compression, or flexural loads are plotted on the ordinate axis and the deflections caused by those loads are plotted on the abscissa axis.

loss on ignition Weight loss, usually expressed as percent of total, after burning off an organic sizing from glass fibers, or an organic resin from a glass fiber laminate.

low-pressure laminates In general, laminates molded and cured in the range of pressures from 400 psi down to and including pressure obtained by the mere contact of the plies.

M

macromechanics Structural behavior of composite laminates using the laminated plate theory. The fiber and matrix within each ply are smeared and no longer identifiable.

mat A fibrous material for reinforced plastic consisting of randomly oriented chopped filaments, short fibers (with or without a carrier fabric), or swirled filaments loosely held together with a binder. Available in blankets of various widths, weights and lengths. Also, a sheet formed by filament winding a single-hoop ply of fiber on a mandrel, cutting across its width and laying out a flat sheet.

matrix The essentially homogeneous resin or polymer material in which the fiber system of a composite is embedded. Both thermoplastic and thermoset resins may be used, as well as metals, ceramics and glass.

mechanical adhesion Adhesion between surfaces in which the adhesive holds the parts together by interlocking action.

mechanical properties The properties of a material, such as compressive or tensile strength, and modulus, that are associated with elastic and inelastic reaction when force is applied. The individual relationship between stress and strain.

mek peroxide (MEKP) Abbreviation for Methyl Ethyl Ketone Peroxide; a strong oxidizing agent (free radical source) commonly used as the catalyst for polyesters in the FRP industry.

micromechanics Calculation of the effective ply properties as functions of the fiber and matrix properties. Some numerical approaches also provide the stress and strain within each constituent and those at the interface.

mil The unit used in measuring the diameter of glass fiber strands, wire, etc. (1 mil = 0.001 inch).

milled fiber Continuous glass strands hammer milled into very short glass fibers. Useful as inexpensive filler or anticrazing reinforcing fillers for adhesives.

modulus of elasticity The ratio of stress or load applied to the strain or deformation produced in a material that is elasticity deformed. If a tensile strength of 2 ksi results in an elongation of 1%, the modulus of elasticity is 2.0 ksi divided by 0.01 or 200 ksi. Also called Young's modulus.

moisture absorption The pickup of water vapor from air by a material. It relates only to vapor withdrawn from the air by a material and must be distinguished from water absorption, which is the gain in weight due to the take-up of water by immersion.

moisture content The amount of moisture in a material determined under prescribed conditions and expressed as a percentage of the mass of the moist specimen, that is, the mass of the dry substance plus the moisture present.

mold The cavity or matrix into or on which the plastic composition is placed and from which it takes form. To shape plastic parts or finished articles by heat and pressure. The assembly of all parts that function collectively in the molding process.

mold-release agent A lubricant, liquid or powder (often silicone oils and waxes), used to prevent the sticking of molded articles in the cavity.

monomer A single molecule that can react with like or unlike molecules to form a polymer. The smallest repeating structure of a polymer (mer). For additional polymers, this represents the original unpolymerized compound.

N

netting analysis Treating composites like fibers without matrix. It is not a mechanical analysis, and is not applicable to composites.

non-air-inhibited resin A resin in which the surface cure will not be inhibited or stopped by the presence of air. A surfacing agent has been added to exclude air from the surface of the resin.

nondestructive evaluation (NDE) Broadly considered synonymous with nondestructive inspection (NDI). More specifically, the analysis of NDI findings to determine whether the material will be acceptable for its function.

nondestructive inspection (NDI) A process or procedure, such as ultrasonic or radiographic inspection, for determining the quality of characteristics of a material, part or assembly, without permanently altering the subject or its properties. Used to find internal anomalies in a structure without degrading its properties.

nonwoven fabric A planar textile structure produced by loosely compressing together fibers, yarns, rovings, etc. with or without a scrim cloth carrier. Accomplished by mechanical, chemical, thermal, or solvent means and combinations thereof.

non-volatile material Portion remaining as solid under specific conditions short of decomposition.

normal stress The stress component that is perpendicular to the plane on which the forces act.

notch sensitivity The extent to which the sensitivity of a material to fracture is increased by the presence of a surface nonhomogeneity, such as a notch, a sudden change in section, a crack or a scratch. Low notch sensitivity is usually associated with ductile materials, and high notch sensitivity is usually associated with brittle materials.

O

orange peel Backside of the gel coated surface that takes on the rough wavy texture of an orange peel.

orthotropic Having three mutually perpendicular planes of elastic symmetry.

P

panel The designation of a section of FRP shell plating, of either single-skin or sandwich construction, bonded by longitudinal and transverse stiffeners or other supporting structures.

peel ply A layer of resin-free material used to protect a laminate for later secondary bonding.

peel strength Adhesive bond strength, as in pounds per inch of width, obtained by a stress applied in a peeling mode.

permanent set The deformation remaining after a specimen has been stressed a prescribed amount in tension, compression or shear for a definite time period. For creep tests, the residual unrecoverable deformation after the load causing the creep has been removed for a substantial and definite period of time. Also, the increase in length, by which an elastic material fails to return to original length after being stressed for a standard period of time.

permeability The passage or diffusion (or rate of passage) of gas, vapor, liquid or solid through a barrier without physically or chemically affecting it.

phenolic (phenolic resin) A thermosetting resin produced by the condensation of an aromatic alcohol with an aldehyde, particularly of phenol with formaldehyde. Used in high-temperature applications with various fillers and reinforcements.

pitch A high molecular weight material left as a residue from the destructive distillation of coal and petroleum products. Pitches are used as base materials for the manufacture of certain high-modulus carbon fibers and as matrix precursors for carbon-carbon composites.

plasticity A property of adhesives that allows the material to be deformed continuously and permanently without rupture upon the application of a force that exceeds the yield value of the material.

plain weave A weaving pattern in which the warp and fill fibers alternate; that is, the repeat pattern is warp/fill/warp/fill. Both faces of a plain weave are identical. Properties are significantly reduced relative to a weaving pattern with fewer crossovers.

ply In general, fabrics or felts consisting of one or more layers (laminates). The layers that make up a stack. A single layer of prepreg.

Poisson's ratio The ratio of the change in lateral width per unit width to change in axial length per unit length caused by the axial stretching or stressing of the material. The ratio of transverse strain to the corresponding axial strain below the proportional limit.

polyether etherketone (PEEK) A linear aromatic crystalline thermoplastic. A composite with a PEEK matrix may have a continuous use temperature as high as 480°F.

polymer A high molecular weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit, the mer. Examples include polyethylene, rubber and cellulose. Synthetic polymers are formed by addition or condensation polymerization of monomers. Some polymers are elastomers, some are plastics and some are fibers. When two or more dissimilar monomers are involved, the product is called a copolymer. The chain lengths of commercial thermoplastics vary from near a thousand to over one hundred thousand repeating units. Thermosetting polymers approach infinity after curing, but their resin precursors, often called prepolymers, may be a relatively short six to one hundred repeating units before curing. The lengths of polymer chains, usually measured by molecular weight, have very significant effects on the performance properties of plastics and profound effects on processibility.

polymerization A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called copolymerization.

polyurethane A thermosetting resin prepared by the reaction of disocyanates with polols, polyamides, alkyd polymers and plyether polymers.

porosity Having voids; i.e., containing pockets of trapped air and gas after cure. Its measurement is the same as void content. It is commonly assumed that porosity is finely and uniformly distributed throughout the laminate.

postcure Additional elevated-temperature cure, usually without pressure, to improve final properties and/or complete the cure, or decrease the percentage of volatiles in the compound. In certain resins, complete cure and ultimate mechanical properties are attained only by exposure of the cured resin to higher temperatures than those of curing.

pot life The length of time that a catalyzed thermosetting resin system retains a viscosity low enough to be used in processing. Also called working life.

prepreg Either ready-to-mold material in sheet form or ready-to-wind material in roving form, which may be cloth, mat, unidirectional fiber, or paper impregnated with resin and stored for use. The resin is partially cured to a B-stage and supplied to the fabricator, who lays up the finished shape and completes the cure with heat and pressure. The two distinct types of prepreg available are (1) commercial prepregs, where the roving is coated with a hot melt or solvent system to produce a specific product to meet specific customer requirements; and (2) wet prepreg, where the basic resin is installed without solvents or preservatives but has limited room-temperature shelf life.

pressure bag molding A process for molding reinforced plastics in which a tailored, flexible bag is placed over the contact lay-up on the mold, sealed, and clamped in place. Fluid pressure, usually provided by compressed air or water, is placed against the bag, and the part is cured.

pultrusion A continuous process for manufacturing composites that have a constant cross-sectional shape. The process consists of pulling a fiber-reinforcing material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured.

Q

quasi-isotropic laminate A laminate approximating isotropy by orientation of plies in several or more directions.

R

ranking Ordering of laminates by strength, stiffness or others.

reaction injection molding (RIM) A process for molding polyurethane, epoxy, and other liquid chemical systems. Mixing of two to four components in the proper chemical ratio is accomplished by a high-pressure impingement-type mixing head, from which the mixed material is delivered into the mold at low pressure, where it reacts (cures).

reinforced plastics Molded, formed filament-wound, tape-wrapped, or shaped plastic parts consisting of resins to which reinforcing fibers, mats, fabrics, and so forth, have been added before the forming operation to provide some strength properties greatly superior to those of the base resin.

resin A solid or pseudosolid organic material, usually of high molecular weight, that exhibits a tendency to flow when subjected to stress. It usually has a softening or melting range, and fractures conchoidally. Most resins are polymers. In reinforced plastics, the material used to bind together the reinforcement material; the matrix. See also polymer.

resin content The amount of resin in a laminate expressed as either a percentage of total weight or total volume.

resin-rich area Localized area filled with resin and lacking reinforcing material.

resin-starved area Localized area of insufficient resin, usually identified by low gloss, dry spots, or fiber showing on the surface.

resin transfer molding (RTM) A process whereby catalyzed resin is transferred or injected into an enclosed mold in which the fiberglass reinforcement has been placed.

roving A number of yarns, strands, tows, or ends collected into a parallel bundle with little or no twist.

S

sandwich constructions Panels composed of a lightweight core material, such as honeycomb, foamed plastic, and so forth, to which two relatively thin, dense, high-strength or high-stiffness faces or skins are adhered.

scantling The size or weight dimensions of the members which make up the structure of the vessel.

secondary bonding The joining together, by the process of adhesive bonding, of two or more already cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself.

secondary structure Secondary structure is considered that which is not involved in primary bending of the hull girder, such as frames, girders, webs and bulkheads that are attached by secondary bonds.

self-extinguishing resin A resin formulation that will burn in the presence of a flame but will extinguish itself within a specified time after the flame is removed.

set The irrecoverable or permanent deformation or creep after complete release of the force producing the deformation.

set up To harden, as in curing of a polymer resin.

S-glass A magnesium aluminosilicate composition that is especially designed to provide very high tensile strength glass filaments. S-glass and S-2 glass fibers have the same glass composition but different finishes (coatings). S-glass is made to more demanding specifications, and S-2 is considered the commercial grade.

shear An action or stress resulting from applied forces that causes or tends to cause two contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact. In interlaminar shear, the plane of contact is composed primarily of resin.

shell The watertight boundary of a vessel's hull.

skin Generally, a term used to describe all of the hull shell. For sandwich construction, there is an inner and outer skin which together are thinner than the single-skin laminate that they replace.

skin coat A special layer of resin applied just under the gel coat to prevent blistering. It is sometimes applied with a layer of mat or light cloth.

shear modulus The ratio of shearing stress to shearing strain within the proportional limit of the material.

shear strain The tangent of the angular change, caused by a force between two lines originally perpendicular to each other through a point in a body. Also called angular strain.

shear strength The maximum shear stress that a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original cross-sectional area of the specimen.

shear stress The component of stress tangent to the plane on which the forces act.

sheet molding compound (SMC) A composite of fibers, usually a polyester resin, and pigments, fillers, and other additives that have been compounded and processed into sheet form to facilitate handling in the molding operation.

shelf life The length of time a material, substance, product, or reagent can be stored under specified environmental conditions and continue to meet all applicable specification requirements and/or remain suitable for its intended function.

short beam shear (SBS) A flexural test of a specimen having a low test span-to-thickness ratio (for example, 4:1), such that failure is primarily in shear.

size Any treatment consisting of starch, gelatin, oil, wax, or other suitable ingredient applied to yarn or fibers at the time of formation to protect the surface and aid the process of handling and fabrication or to control the fiber characteristics. The treatment contains ingredients that provide surface lubricity and binding action, but unlike a finish, contains no coupling agent. Before final fabrication into a composite, the size is usually removed by heat cleaning, and a finish is applied.

skin The relatively dense material that may form the surface of a cellular plastic or of a sandwich.

S-N diagram A plot of stress (S) against the number of cycles to failure (N) in fatigue testing. A log scale is normally used for N. For S, a linear scale is often used, but sometimes a log scale is used here, too. Also, a representation of the number of alternating stress cycles a material can sustain without failure at various maximum stresses.

specific gravity The density (mass per unit volume) of any material divided by that of water at a standard temperature.

spray-up Technique in which a spray gun is used as an applicator tool. In reinforced plastics, for example, fibrous glass and resin can be simultaneously deposited in a mold. In essence, roving is fed through a chopper and ejected into a resin stream that is directed at the mold by either of two spray systems. In foamed plastics, fast-reacting urethane foams or epoxy foams are fed in liquid streams to the gun and sprayed on the surface. On contact, the liquid starts to foam.

spun roving A heavy, low-cost glass fiber strand consisting of filaments that are continuous but doubled back on each other.

starved area An area in a plastic part which has an insufficient amount of resin to wet out the reinforcement completely. This condition may be due to improper wetting or impregnation or excessive molding pressure.

storage life The period of time during which a liquid resin, packaged adhesive, or prepreg can be stored under specified temperature conditions and remain suitable for use. Also called shelf life.

strain Elastic deformation due to stress. Measured as the change in length per unit of length in a given direction, and expressed in percentage or in./in.

stress The internal force per unit area that resists a change in size or shape of a body. Expressed in force per unit area.

stress concentration On a macromechanical level, the magnification of the level of an applied stress in the region of a notch, void, hole, or inclusion.

stress corrosion Preferential attack of areas under stress in a corrosive environment, where such an environment alone would not have caused corrosion.

stress cracking The failure of a material by cracking or crazing some time after it has been placed under load. Time-to-failure may range from minutes to years. Causes include molded-in stresses, post fabrication shrinkage or warpage, and hostile environment.

stress-strain curve Simultaneous readings of load and deformation, converted to stress and strain, plotted as ordinates and abscissae, respectively, to obtain a stress-strain diagram.

structural adhesive Adhesive used for transferring required loads between adherends exposed to service environments typical for the structure involved.

surfacing mat A very thin mat, usually 7 to 20 mils thick, of highly filamentized fiberglass, used primarily to produce a smooth surface on a reinforced plastic laminate, or for precise machining or grinding.

symmetrical laminate A composite laminate in which the sequence of plies below the laminate midplane is a mirror image of the stacking sequence above the midplane.

T

tack Stickiness of a prepreg; an important handling characteristic.

tape A composite ribbon consisting of continuous or discontinuous fibers that are aligned along the tape axis parallel to each other and bonded together by a continuous matrix phase.

tensile strength The maximum load or force per unit cross-sectional area, within the gage length, of the specimen. The pulling stress required to break a given specimen.

tensile stress The normal stress caused by forces directed away from the plane on which they act.

thermoforming Forming a thermoplastic material after heating it to the point where it is hot enough to be formed without cracking or breaking reinforcing fibers.

thermoplastic polyesters A class of thermoplastic polymers in which the repeating units are joined by ester groups. The two important types are (1) polyethylene terphthalate (PET), which is widely used as film, fiber, and soda bottles; and (2) polybutylene terephthalate (PBT), primarily a molding compound.

thermoset A plastic that, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material.

thermosetting polyesters A class of resins produced by dissolving unsaturated, generally linear, alkyd resins in a vinyl-type active monomer such as styrene, methyl styrene, or diallyl phthalate. Cure is effected through vinyl polymerization using peroxide catalysts and promoters or heat to accelerate the reaction. The two important commercial types are (1) liquid resins that are cross-linked with styrene and used either as impregnants for glass or carbon fiber reinforcements in laminates, filament-wound structures, and other built-up constructions, or as binders for chopped-fiber reinforcements in molding compounds, such as sheet molding compound (SMC), bulk molding compound (BMC), and thick molding compound (TMC); and (2) liquid or solid resins cross-linked with other esters in chopped-fiber and mineral-filled molding compounds, for example, alkyd and diallyl phthalate.

thixotropic (thixotropy) Concerning materials that are gel-like at rest but fluid when agitated. Having high static shear strength and low dynamic shear strength at the same time. To lose viscosity under stress.

tooling resin Resins that have applications as tooling aids, coreboxes, prototypes, hammer forms, stretch forms, foundry patterns, and so forth. Epoxy and silicone are common examples.

torsion Twisting stress

torsional stress The shear stress on a transverse cross section caused by a twisting action.

toughness A property of a material for absorbing work. The actual work per unit volume or unit mass of material that is required to rupture it. Toughness is proportional to the area under the load-elongation curve from the origin to the breaking point.

tow An untwisted bundle of continuous filaments. Commonly used in referring to manmade fibers, particularly carbon and graphite, but also glass and aramid. A tow designated as 140K has 140,000 filaments.

tracer A fiber, tow, or yarn added to a prepreg for verifying fiber alignment and, in the case of woven materials, for distinguishing warp fibers from fill fibers.

transfer molding Method of molding thermosetting materials in which the plastic is first softened by heat and pressure in a transfer chamber and then forced by high pressure through suitable sprues, runners, and gates into the closed mold for final shaping and curing.

transition temperature The temperature at which the properties of a material change. Depending on the material, the transition change may or may not be reversible.

U

ultimate tensile strength The ultimate or final (highest) stress sustained by a specimen in a tension test. Rupture and ultimate stress may or may not be the same.

ultrasonic testing A nondestructive test applied to materials for the purpose of locating internal flaws or structural discontinuities by the use of high-frequency reflection or attenuation (ultrasonic beam).

uniaxial load A condition whereby a material is stressed in only one direction along the axis or centerline of component parts.

unidirectional fibers Fiber reinforcement arranged primarily in one direction to achieve maximum strength in that direction.

urethane plastics Plastics based on resins made by condensation of organic isocyanates with compounds or resins that contain hydroxyl groups. The resin is furnished as two component liquid monomers or prepolymers that are mixed in the field immediately before application. A great variety of materials are available, depending upon the monomers used in the prepolymers, polyols, and the type of diisocyanate employed. Extremely abrasion and impact resistant. See also polyurethane.

V

vacuum bag molding A process in which a sheet of flexible transparent material plus bleeder cloth and release film are placed over the lay-up on the mold and sealed at the edges. A vacuum is applied between the sheet and the lay-up. The entrapped air is mechanically worked out of the lay-up and removed by the vacuum, and the part is cured with temperature, pressure, and time. Also called bag molding.

veil An ultrathin mat similar to a surface mat, often composed of organic fibers as well as glass fibers.

vinyl esters A class of thermosetting resins containing esters of acrylic and/or methacrylic acids, many of which have been made from epoxy resin. Cure is accomplished as with unsaturated polyesters by copolymerization with other vinyl monomers, such as styrene.

viscosity The property of resistance to flow exhibited within the body of a material, expressed in terms of relationship between applied shearing stress and resulting rate of strain in shear. Viscosity is usually taken to mean Newtonian viscosity, in which case the ratio of shearing stress to the rate of shearing strain is constant. In non-Newtonian behavior, which is the usual case with plastics, the ratio varies with the shearing stress. Such ratios are often called the apparent viscosities at the corresponding shearing stresses. Viscosity is measured in terms of flow in Pa · s (P), with water as the base standard (value of 1.0). The higher the number, the less flow.

void content Volume percentage of voids, usually less than 1% in a properly cured composite. The experimental determination is indirect, that is, calculated from the measured density of a cured laminate and the "theoretical" density of the starting material.

voids Air or gas that has been trapped and cured into a laminate. Porosity is an aggregation of microvoids. Voids are essentially incapable of transmitting structural stresses or nonradiative energy fields.

volatile content The percent of volatiles that are driven off as a vapor from a plastic or an impregnated reinforcement.

volatiles Materials, such as water and alcohol, in a sizing or a resin formulation, that are capable of being driven off as a vapor at room temperature or at a slightly elevated temperature.

W

warp The yarn running lengthwise in a woven fabric. A group of yarns in long lengths and approximately parallel. A change in dimension of a cured laminate from its original molded shape.

water absorption Ratio of the weight of water absorbed by a material to the weight of the dry material.

weathering The exposure of plastics outdoors. Compare with artificial weathering.

weave The particular manner in which a fabric is formed by interlacing yarns. Usually assigned a style number.

weft The transverse threads or fibers in a woven fabric. Those running perpendicular to the warp. Also called fill, filling yarn, or woof.

wet lay-up A method of making a reinforced product by applying the resin system as a liquid when the reinforcement is put in place.

wet-out The condition of an impregnated roving or yarn in which substantially all voids between the sized strands and filaments are filled with resin.

wet strength The strength of an organic matrix composite when the matrix resin is saturated with absorbed moisture, or is at a defined percentage of absorbed moisture less than saturation. (Saturation is an equilibrium condition in which the net rate of absorption under prescribed conditions falls essentially to zero.)

woven roving A heavy glass fiber fabric made by weaving roving or yarn bundles.

Y

yield point The first stress in a material, less than the maximum attainable stress, at which the strain increases at a higher rate than the stress. The point at which permanent deformation of a stressed specimen begins to take place. Only materials that exhibit yielding have a yield point.

yield strength The stress at the yield point. The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, the material is viscous. Often defined as the stress needed to produce a specified amount of plastic deformation (usually a 0.2% change in length).

Young's modulus The ratio of normal stress to corresponding strain for tensile or compressive stresses less than the proportional limit of the material. See also modulus of elasticity.

Chapter References

1-1 "Aerospace Composites Technology is Finding New Applications." Reinforced Plastics, Vol. 27 (No. 8), Aug. 1983, p. 243-248, in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-2 "GRP Proves Its Worth in Tough-Going Powerboat Race." Reinforced Plastics, Vol. 29 (No. 4), April 1985, p. 106-107, in Engineering College, "Marine Applications," in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-3 "Composite Material Study: Maturity of Technology Materials and Fabrication," F.I.T. Structural Composites Laboratory technical report prepared for UNISYS Corporation and U.S. Navy, March 1988, Distribution Limited.

1-4 Guide for Building and Classing Offshore Racing Yachts, American Bureau of Shipping, 1986, Paramus, New Jersey.

1-5 Shuttleworth, J. "Spectrum 42 Production Catamaran," Multihull Int., Vol. 18 (No. 207), April 1985, p. 91-94, in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-6 Doyle, J.F. and L. Hadley-Coates. "Distortion of Thin Shells Due to Rapid Temperature Changes," Ocean Eng., Vol. 13 (no. 2), 1986, p. 121-129, in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-7 Pittman, L.L. "Breaking the Old Moulds," Sail, Jan. 1985, P. 76-81, in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-8 Florida Today, November 7, 1989, article by Catherine Liden.

1-9 Summerscales, John. Royal Naval Engineering College, "Marine Applications," in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-10 Second International Conference on Marine Applications of Composite Materials, March 1988; Invited Paper: "The High Speed Passenger Ferry SES Jet Rider." S. Hellbratt and O. Gullberg, Karlskronavarvet AB, Karlskrona, Sweden.

1-11 "Italcraft M78." Boat Int. No. 7, 1985, p. 91, in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-12 "Extensive Use of GRP for Tomorrow's Undersea Craft." Reinforced Plastics, Vol. 27, No. 9 (Sept. 1983), p. 276, in Engineered Materials Handbook, Vol. 1, Composites, ASM International 1987.

1-13 "Composite Hull Increases Submarine's Range of Action." Composites, Vol. 14, No. 3 (July 1983) p. 314, in Engineered Materials Handbook, Vol. 1, Composites, ASM International, 1987.

1-14 IBID ref. [1-9].

1-15 Heller, S.R. Jr. "The Use of Composite Materials In Naval Ships." Mechanics of Composite Materials, Proceedings of the Fifth Symposium on Structural Mechanics, 8-10 May, 1967, Phil., PA.

1-16 Landford, Benjamin W. Jr. and J. Angerer. "Glass Reinforced Plastic Developments for Application to Minesweeper Construction." Naval Engineers Journal, (Oct. 1971) p.13-26.

1-17 Olsson, Karl-Axel. "GRP Sandwich Design and Production in Sweden Development and Evaluation." The Royal Institute of Technology, Stockholm, Sweden, Report 86-6, 1986.

1-18 Ellis, R.W. and Sridharan, N.S. General Dynamics Land Systems Division, Troy, MI, "Combat Vehicles for New Design Environment for Composites." Advanced Composites Conference Proceedings, 2-4 Dec. 1985, Dearborn, MI, 1985.

1-19 Kariya, B. and J. Hill, FMC Corporation, San Jose, CA. "Implementation of Composite Materials in Ground Combat Vehicles." Advanced Composites III Expanding the Technology, Proceedings, Third Annual Conference on Advanced Composites, 15-17 September 1987, Detroit, MI.

1-20 Ostberg, Donald T., U.S. Army Tank Automotive Command, Warren, MI. "Military Vehicles Composite Applications." Advanced Composites III Expanding the Technology, Proceedings, Third Annual Conference on Advanced Composites, 15-17 September 1987, Detroit, MI.

1-21 Fishman, N. "Structural Composites: a 1995 Outlook." Modern Plastics, (July 1989), p. 72-73.

1-22 Margolis, J.M. "Advanced Thermoset Composites Industrial and Commercial Applications." Van Nostrand Reinhold Company, N.Y., 1986.

1-23 Koster, J., MOBIK GmbH, Gerlingen, West Germany. "The Composite Intensive Vehicle - A Third Generation of Automobiles! A Bio-Cybernetical Approach to Automotive Engineering?" May, 1989.

1-24 Engineers' Guide to Composite Materials. American Society for Metals, 1987, Abstracted from "Composite Driveshafts - Dream or Reality." D.R. Sidwell, M. Fisk and D. Oeser. Merlin Technologies, Inc., Campbell, CA. New Composite Materials and Technology, The American Institute of Chemical Engineers, p. 8-11, 1982.

1-25 Engineers' Guide to Composite Materials. American Society for Metals, 1987, Abstracted from "A Composite Rear Floor Pan." N.G. Chavka and C.F. Johnson, Ford Motor Co. Proceedings of the 40th Annual Conference, Reinforced Plastics/Composites Institute, 28 Jan.-1 Feb. 1985, Session 14-D. The Society of the Plastics Industry, Inc., p. 1-6.

1-26 Modern Plastics, April 1989, Plastiscope feature article.

1-27 Modern Plastics, September 1989, various articles.

1-28 Reinforced Plastics for Commercial Composites, American Society for Metals Source Book, 1986.

1-29 Dickason, Richard T., Ford Motor Company, Redford, MI. "HSMC Radiator Support." Reinforced Plastics for Commercial Composites, American Society for Metals: Metals Park, OH, 1986.

1-30 Johnson, Carl F., et al. Ford Motor Company, Dearborn, MI and Babbington, Dorothy A., Dow Chemical Company, Freeport, TX. "Design and Fabrication of a HSRTM Crossmember Module." Advanced Composites III Expanding the Technology, Proceedings, Third Annual Conference on Advanced Composites, 15-17 September 1987, Detroit, MI.

1-31 "Materials Substitution in Automotive Exterior Panels (1989-1994)." Philip Townsend Associates, Inc., Marblehead, MA.

1-32 Farris, Robert D., Shell Development Center, Houston, TX. "Composite Front Crossmember for the Chrysler T-115 Mini-Van." Advanced Composites III Expanding the Technology, Proceedings, Third Annual Conference on Advanced Composites, 15-17 September 1987, Detroit, MI.

1-33 Engineers' Guide to Composite Materials. American Society for Metals, 1987. Abstracted from "Design and Development of Composite Elliptic Springs for Automotive Suspensions." P.D. Mallick, University of Michigan-Dearborn, Dearborn, MI. Proceedings of the 40th Annual Conference, Reinforced Plastics/Composites Institute, 28 Jan.-1 Feb. 1985, Session 14-c, The Society of the Plastics Industry, Inc., p. 1-5.

1-34 Engineers' Guide to Composite Materials. American Society for Metals, 1987. Abstracted from "Composite Leaf Springs in Heavy Truck Applications." L.R. Daugherty, Exxon Enterprises, Greer, SC. Composite Materials: Mechanics, Mechanical Properties, and Fabrication. Proceedings of Japan-U.S. Conference, 1981, Tokyo, Japan: The Japan Society for Composite Materials, p. 529-538, 1981.

1-35 Engineers' Guide to Composite Materials, American Society for Metals, 1987. Abstracted from "Composite Truck Frame Rails." Gerald L. May, GM Truck and Coach Division, and Curtis Tanner, Convair Division of General Dynamics. Automotive Engineering, p. 77-79, Nov. 1979.

1-36 Sea, M.R., Kutz, J. and Corriveau, G., Vehicle Research Institute, Western Washington University, Bellingham, WA. "Development of an Advanced Composite Monocoque Chassis for a limited Production Sports Car." Advanced Composites: The Latest Developments. Proceedings of the Second Conference on Advanced Composites, 18-20 Nov. 1986, Dearborn, MI, 1986.

1-37 Modern Plastics, July 1989, article by A. Stuart Wood.

1-38 Shook, G.D. Reinforced Plastics for Commercial Composites, Metals Park, OH: American Society for Metals, 1986.

2-1 Engineers' Guide to Composite Materials, Metals Park, OH: American Society for Metals, 1987 ed.

2-2 Feichtinger, K.A. Methods of Evaluation and Performance of Structural Core Materials Used in Sandwich Construction. Proc. of the 42nd Annual Conference SPI Reinforced Plastics/Composites Institute. 2-6 Feb., 1987.

2-3 Johannsen, Thomas J. One-Off Airex Fiberglass Sandwich Construction. Buffalo, NY: Chemacryl, Inc., 1973.

2-4 Hexcel. HRH-78 Nomex Commercial Grade Honeycomb Data Sheet 4400. Dublin, CA., 1989.

2-5 Rules for Building and Classing Reinforced Plastic Vessels. By the American Bureau of Shipping. New York, 1978.

2-6 Guide for Building and Classing Offshore Racing Yachts. By the American Bureau of Shipping. Paramus, New Jersey, 1986.

2-7 Chammis, C.C. "Mechanics of Composite Materials: Past, Present, and Future." Journal of Composites Technology & Research, JCTRER, Vol. 11, No. 1 (Spring 1989), pp. 3-14.

3-1 Principles of Naval Architecture. By the Society of Naval Architects and Marine Engineers. New York, 1967.

3-2 Engineers' Guide to Composite Materials. By the American Society for Metals. Metals Park, OH, 1987.

3-3 Evans, J. Harvey. Ship Structural Design Concepts. Cambridge, MD: Cornell Maritime Press, 1975.

3-4 Noonan, Edward F. Ship Vibration Design Guide. Washington, D.C.: Ship Structure Committee, 1989.

3-5 Guide for Building and Classing Offshore Racing Yachts. By the American Bureau of Shipping. Paramus, NJ, 1986.

3-6 Proposed Guide for Building and Classing High-Speed and Displacement Motor Yachts. By the American Bureau of Shipping. New York, 1989.

3-7 Heller, S.R. and N.H. Jasper. "On the Structural Design of Planing Craft." Transactions, Royal Institution of Naval Architects, (1960) p.49-65.

3-8 Smith, C.S. "Buckling Problems in the Design of Fiberglass-Reinforced Plastic Ships." Journal of Ship Research, (Sept. 1972) p.174-190.

3-9 Schwartz, Mel M. Composite Materials Handbook. New York: McGraw Hill, 1984.

3-10 Tsai, Stephen W. Composites Design. Third ed. Tokyo: Think Composites, 1987.

3-11 Owens-Corning Fiberglas Corp. "The Hand Lay-Up Spray-Up Guide." Toledo, OH, 1988.

3-12 Owens-Corning Fiberglas Corp. "Design Properties of Marine Grade Fiberglass Laminates." Toledo, OH, 1978.

3-13 Gibbs & Cox, Inc. "Marine Design Manual for Fiberglass Reinforced Plastics," New York: McGraw Hill, 1960.

3-14 "Guide for Selection of Fiberglass Reinforced Plastics for Marine Structures." Society of Naval Architects and Marine Engineers, Hull Structure Committee Panel HS-6, Bulletin 2-12, 1965.

3-15 Owens-Corning Fiberglas Corp. Report. "Feasibility Study for Application of Reinforced Plastic Construction to Minesweepers." Navy Dept. - Bureau of Ships, Contract NObs-4671 - Materials Test Program - Phase 1.

3-16 "An Analysis of the Causes of Variability in the Hand Lay-Up Process." OCF Report TC/RPL/67/24.

3-17 "Effect of Fill-Warp Ratio on Woven Roving Laminate Flexural Properties." OCF Report TR/RPL/68/22.

3-18 "Optimum Laminate Study of Typical Marine Constructions," OCF Report TC/RPL/65/11.

3-19 Laminate property data on panels cut from boat hulls in conjunction with the Survey of U.S. Navy Glass Reinforced Plastic Small Craft conducted by Gibbs & Cox, Inc.

3-20 "Woven Roving and Glass Fiber Mat Reinforced Plastic Laminates - Basic Strength Properties." V.S Ristic, 26th Annual Conference of the SPI (Canada) June, 1968.

3-21 Reichard, Ronnal P. FRP Sailboat Structural Design: Details Make the Difference. Proc. of the 17th AIAA/SNAME Symposium on the Aero/Hydronautics of Sailing: The Ancient Interface. Voi. 34. 31 Oct.-1 Nov. 1987.

3-22 Owens-Corning Fiberglas Corp. "Joint Confirguration and Surface Preparation Effect on Bond Joint Fatigue in Marine Application." Toledo, OH, 1973.

3-23 Della Rocca, R.J. & R.J. Scott. "Materials Test Program for Application of Fiberglass Reinforced Plastics to U.S. Navy Minesweepers." 22nd Annual Technical Conference, The Society of the Plastics Industry, Inc.

3-24 USCG NVIC No. 8-87. "Notes on Design, Construction, Inspection and Repair of Fiber Reinforced Plastic (FRP) Vessels." 6 Nov. 1987.

3-25 Rules for Building and Classing Reinforced Plastic Vessels. By the American Bureau of Shipping. New York, 1978.

4-1 Hashin, Z. "Fatigue Failure Criteria for Unidirectional Fiber Composites." Journal of Applied Mechanics, Vol. 38, (Dec. 1981), p. 846-852.

4-2 Kim, R.Y. "Fatigue Behavior." Composite Design 1986, Section 19, S.W. Tsai, Ed., Think Composites: Dayton, Ohio, 1986.

4-3 Goetchius, G.M. "Fatigue of Composite Materials." Advanced Composites III Expanding the Technology, Third Annual Conference on Advanced Composites, Detroit, Michigan, 15-17 September 1987, p.289-298.

4-4 Salkind, M.J. "Fatigue of Composites." Composite Materials: Testing and Design (Second Conference), ASTM STP 497, 1972, p. 143-169.

4-5 Chang, F.H., Gordon, D.E., and Gardner, A.H. "A Study of Fatigue Damage in Composites by Nondestructive Testing Techniques." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 57-72.

4-6 Kasen, M.B., Schramm, R.E., and Read, D.T. "Fatigue of Composites at Cryogenic Temperatures." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 141-151.

4-7 Porter, T.R. "Evaluation of Flawed Composite Structure Under Static and Cyclic Loading." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 152-170.

4-8 Ryder, J.T., and Walker, E.K. "Effects of Compression on Fatigue Properties of a Quasi-Isotropic Graphite/Epoxy Composite." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 3-26.

4-9 Sendeckyj, G.P., Stalnaker, H.D., and Kleismit, R.A. "Effect of Temperature on Fatigue Response on Surface- Notched $[(0/\pm45/0_S]_3$ Graphite/Epoxy Laminate." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 123-140.

4-10 Sims, D.F., and Brogdon, V.H. "Fatigue Behavior of Composites Under Different Loading Modes." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 185-205.

4-11 Sun, C.T., and Roderick, G.L. "Improvements of Fatigue Life of Boron/Epoxy Laminates By Heat Treatment Under Load." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 89-102.

4-12 Sun, C.T., and Chen, J.K. "On the Impact of Initially Stressed Composite Laminates." Journal of Composite Materials, Vol. 19 (Nov. 1985).

4-13 Roderick, G.L., and Whitcomb, J.D. "Fatigue Damage of Notched Boron/Epoxy Laminates Under Constant-Amplitude Loading." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 73-88.

4-14 Highsmith, A.L., and Reifsnider, K.L. "Internal Load Distribution Effects During Fatigue Loading of Composite Laminates." Composite Materials: Fatigue and Fracture, ASTM STP 907, H.T. Hahn, Ed., American Society for Testing and Materials, Philadelphia, PA, 1986, p.233-251.

4-15 Reifsnider, K.L., Stinchcomb, W.W., and O'Brien, T.K. "Frequency Effects on a Stiffness-Based Fatigue Failure Criterion in Flawed Composite Specimens." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society for Testing and Materials, 1977, p. 171-184.

4-16 Hahn, H.T. "Fatigue of Composites." Composites Guide, University of Delaware, 1981.

4-17 Kundrat, R.J., Joneja, S.K., and Broutman, L.J. "Fatigue Damage of Hybrid Composite Materials." National Technical Conference On Polymer Alloys, Blends, and Composites, The Society of Plastics Engineering, Bal Harbour, Fl, Oct. 1982.

4-18 Kim, R.Y. "Fatigue Strength." Engineered Materials Handbook ,Volume 1, Composites, ASM International, Materials Park, Ohio, 1987.

4-19 Talreja, R. "Estimation of Weibull Parameters for Composite Material Strength and Fatigue Life Data." Fatigue of Composite Materials, Technomic Publishing : Lancaster, PA, 1987.

4-20 Sims, D.F., and Brogdon, V.H. "Fatigue Behavior of Composites Under Different Loading Modes." Fatigue of Filamentary Composite Materials, ASTM STP 636, K.L. Reifsnider and K.N. Lauraitis, Eds., American Society ıor Testing and Materials, 1977, p. 185-205.

4-21 Engineers' Guide to Composite Materials. By the American Society for Metals. Metals Park, OH, 1987.

4-22 Burrel, et al. "Cycle Test Evaluation of Various Polyester Types and a Mathematical Model for Projecting Flexural Fatigue Endurance." Reprinted from: 41st Annual, 1986, SPI Conference, Section Marine I, Session 7-D.

4-23 Konur, O. and L. Mathews. "Effect of the Properties of the Constituents on the Fatigue Performance of Composites: A Review." Composites, Vol. 20, No. 4 (July, 1989), p. 317-328.

4-24 Jones, David E. "Dynamic Loading Analysis and Advanced Composites." SNAME SE Section, May 1983.

4-25 O'Brien, T. Kevin. Delamination Durability of Composite Materials for Rotorcraft. U.S. Army Research and Technology Activity, Langley, VA. LAR-13753.

4-26 Springer, G.S. Environmental Effects on Composite Materials. Technomic Publishing: Lancaster, PA, 1984.

4-27 Leung, C.L. and D.H. Kaelble. Moisture Diffusion Analysis for Composite Microdamage. Proc. of the 29th Meeting of the Mechanical Failures Prevention Group. 23-25 May 1979, Gaithersburg, MD.

4-28 Pritchard, G. and S.D. Speake. "The Use of Water Absorption Kinetic Data to Predict Laminate Property Changes." Composites, Vol. 18 No. 3 (July 1987), p. 227-232.

4-29 Crump, Scott. A Study of Blister Formation in Gel Coated Laminates. Proc. of the International Conference Marine Applications of Composite Materials. 24-26 Mar. 1986. Melbourne,FL: Florida Institute of Florida.

4-30 Marino, R., et al. The Effect of Coatings on Blister Formation. Proc. of the International Conference Marine Applications of Composite Materials. 24-26 Mar. 1986. Melbourne, FL: Florida Institute of Technology.

4-31 Kokarakis, J. and Taylor, R. Theoretical and Experimental Investigations of Blistered Fiberglass Boats. Proc. of the Third International Conference on Marine Application of Composite Materials. 19-21 Mar. 1990. Melbourne, FL: Florida Institute of Technology.

4-32 Smith, James W. Cracking of Gel Coated Composites 1: Microscopic and Fractrographic Analysis. Proc. of the 43rd Annual Conference of the Composites Institute, The Society of the Plastics Industry, Inc. 1-5 February, 1988.

4-33 Blackwell, E., et al. Marine Composite Structures Failures and Their Causes. Proc. of the Atlantic Marine Surveyors, Inc. Blistering and Laminate Failures in Fiberglass Boat Hulls. 9-10 Feb. 1988. Miami, FL.

4-34 USCG NVIC No. 8-87. "Notes on Design, Construction, Inspection and Repair of Fiber Reinforced Plastic (FRP) Vessels." 6 Nov. 1987.

4-35 Owens-Corning Fiberglas. "Fiber Glass Repairability: A Guide and Directory to the Repair of Fiber Glass Commercial Fishing Boats." No. 5-BO-12658. Toledo, OH, 1984.

4-36 Repair Manual for Boats and Other Fiber Glass Reinforced Surfaces. PPG Industries: Pittsburgh, PA.

4-37 Proc. of Atlantic Marine Surveyors, Inc. Two Day Seminar Blistering and Laminate Failures in Fiberglass Boat Hulls. 9-10 Feb. 1988. Miami, FL.

5-1 "How to Build a Mold." Marine Resin News. Reichhold Chemicals, Inc. Research Triangle Park, NC, 1990.

5-2 Reichard, R. and S. Lewit. The Use of Polyester Fabric to Reduce Print-Through. Proc. of the SNAME Powerboat Symposium. 15 Feb. 1989. Miami, FL.

5-3 "JIT Delivery Plan Set for RP Fabricators." Modern Plastics, (1989), p. 18.

5-4 Zenkert D. and Groth H.L. "Sandwich Constructions 1." Proceedings of the 1st Intl. Conference on Sandwich Constructions, edited by K.A. Olsson, et al., EMAS, 1989, p. 363-381.

5-5 Venus-Gusmer Catalog. 5th Ed. Kent, WA, 1988.

5-6 Health, Safety and Environmental Manual. FRP Supply. Ashland Chemical, Richmond, VA, 1989.

5-7 Safe Handling of Advanced Composite Materials Components: Health Information. Suppliers of Advanced Composite Materials Association, Arlington, VA, 1989.

5-8 "FFA Considers OSHA Proposed Agreement." Fabrication News, Vol. 11, No. 11 (Nov. 1989), p. 12-13.

5-9 Martinsen, S. and C. Madsen. Production, Research and Development in GRP Materials. Proc. of the 3rd International Conference on Marine Applications of Composite Materials. 19-21 March 1990. Melbourne, FL: Florida Institute of Technology, 1990.

5-10 Walewski L. and S. Stockton. "Low-styrene Emission Laminating Resins Prove it in the Workplace." Modern Plastics, (Aug. 1985), p. 78-79.

5-11 Seemann, Bill. Letter to Eric Greene. 11 April, 1990. Seemann Composites, Inc., Gulfport, MS.

5-12 Miller B. "Hybrid Process Launches New Wave in Boat-Building." Plastics World, (Feb. 1989), p. 40-42.

5-13 Gougeon Brothers Inc. GLR125 Epoxy Resin/GLH226 Hardener Gougeon Laminating Epoxy. Bay City, MI, 1987.

5-14 Thomas, Ronald and Christopher Cable. "Quality Assessment of Glass Reinforced Plastic Ship Hulls In Naval Applications." Diss. MIT 1985. Alexandria, VA:Defense Technical Information Center, 1985.

5-15 U.S. Navy. MIL-C-9084C. Military Specification Cloth, Glass, Finished, for Resin Laminates. Engineering Specifications & Standards Department Code 93, Lakehurst, NJ. 9 June 1970.

5-16 Proposed Guide for Building and Classing High-Speed and Displacement Motor Yachts. By the American Bureau of Shipping. Paramus, NJ, Nov. 1989 Draft.

6-1 Reichard, R.P. and T. Gasparrini. "Structural Analysis of a Power Planing Boat." SNAME Powerboat Symposium, Miami Beach, FL, Feb. 1984.

6-2 Reichard, R.P. "Structural Design of Multihull Sailboats." First International Conference on Marine Applications of Composite Materials. Melbourne, FL: Florida Institute of Technology, March 1986.

6-3 1988 Annual Book of ASTM Standards, Vols. 8.01, 8.02, 8.03, 15.03, ASTM, 1916 Race St., Philadelphia, PA 19103.

6-4 Weissman-Berman, D. "A Preliminary Design Method for Sandwich-Cored Panels." Proceedings 10th Ship Technology and Research (STAR) Symposium, SNAME SY-19, Norfolk, VA, May 1985.

6-5 Sponberg, E.W. "Carbon Fiber Sailboat Hulls: How to Optimize the Use of an Expensive Material." J. Marine Tech., 23(2) (April 1986).

6-6 Riley, Craig and F. Isley. "Application of Bias Fabric Reinforced Hull Panels." First International Conference on Marine Applications of Composite Materials. Melbourne, FL: Florida Institute of Technology, March 1986.

6-7 Naval Sea System Command (NAVSEA). Military Standard Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems Used in Hull, Machinery, and Structural Applications Inside Naval Submarines, MIL-STD-X108(SH). Dept. of the Navy, Washington, D.C. 11, July 1989.

6-8 Schwartz, M.M. "Nondestructive Composites Testing." International Product News, (Sept./Oct., 1989), p. 28.

6-9 Engineered Materials Handbook, Vol. 1, Composites. By the American Society of Metals International. Metals Park, OH, 1987.

7-1 Watson, James A. and William Hayden. "Overview of Coast Guard Plan Review for High-Tech Ship Design." Marine Technology, Vol. 27, No. 1 (Jan. 1990) p. 47-55.

7-2 Curry, Robert. The Small Craft Industry and ABS: The Last Ten Years and the Future. Proc. of the Third International Conference on Marine Applications of Composite Materials. 19-21 March, 1990. Melbourne, FL: Florida Institute of Technology, 1990.

7-3 Heller, S.R. & Jasper, N.H., "On the Structural Design of Planing Craft." Transactions, RINA, 1960.

7-4 Savitsky, D. and Brown, P. W., "Procedures for Hydrodynamic Evaluation of Planing Hulls, in Smooth and Rough Water." Marine Technology, (October 1976).

7-5 Allen, R.G. and Jones, R.R., "A Simplified Method for Determing Structural Design-Limit Pressures on High Performance Marine Vehicles." AIAA 1987.

7-6 Spencer, J.S., "Structural Design of Alumminum Crewboats." pp 267-274, Marine Technology, New York, (1975).

INDEX

A

B

C

D

E

O

P

Q

R

S

T

U

V

W

Y

END