Composite Materials and Sandwich Structures – A Primer

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1. INTRODUCTION

Improving the performance of aircraft and other military hardware is of prime concern to designers. The designers strive to build the military hardware which is light with improved performance and at the same time have low acquisition and life cycle costs. Recent developments in structures and materials technologies along with advancements in propulsion and flight control systems has resulted in quantum advancements in the performance of aircraft and other military structures. Current military hardware has greater reliability and low maintenance cost.

The major factors contributing to the improved performance of military hardware have been advanced materials and new structural concepts. New materials such as composites and structural concepts such as sandwich construction have resulted in lighter structural designs with superior performance.

The development of composite materials over last few decades has influenced every field of human life be it civilian or military. In military arena, one finds application of composites in almost every aerospace structure, ships, tanks, and marine structures. On civilian side one finds use of composites in bridges, sporting goods, repair of existing steel and concrete structures, enhancing earthquake resistance of existing structures, etc.

Elements of composite and sandwich structures are discussed here. It is not possible to cover every aspect of this vast subject. The purpose here is to impart the basic knowledge so that the people involved in the structural repairs will have better understanding of the repair processes.

2. COMPOSITE MATERIALS

A composite material consists of two or more constituent materials combined in such a way that the resulting material has more useful applications than the constituent materials alone. The constituent materials play a key role in the development of the final material properties. Advanced composite materials used in structural applications are obtained by reinforcing a matrix material with continuous fibers having high strength and stiffness properties. The selection of a composite material for any application will involve selection of reinforcing fiber and matrix, and their fractional volume in the resulting material. A properly selected combination will give a composite material with following advantages:

- High strength and stiffness-to-weight ratio;
- Low weight;
- Excellent corrosion resistance;
- Excellent fatigue resistance ;
- Can be “tailored to fit”.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
MAY 2010	**N/A**	**-**

4. TITLE AND SUBTITLE	
Composite Materials and Sandwich Structures A Primer	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **R-Tec 28441 Highridge Road, Suite 530 Rolling Hills Estates, CA 90274-4886, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA564486. Battle Damage Repair Techniques and Procedures on Air Vehicles - Lessons Learned and Prospects. RTO-EN-AVT-156

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2.1. Fiber Forms

Many types of reinforcement fibers are currently available. The fibers that have been used include: glass, aramid, carbon (graphite) and boron (Ref. 1-2). Reinforcements like ceramic fibers, metallic fibers, and whiskers have also been used in specific applications.

Glass fibers are produced by mixing various ingredients in specific proportions, melting the mixture in a furnace, and drawing molten glass in the form of filaments. The proportions of various ingredients depend on the product form desired. E glass fibers are used in electrical applications and S glass fibers are used in strength critical situations. S glass fibers are sometimes woven in composite materials to increase toughness and impact resistance.

Carbon or graphite fibers are produced by pyrolytic degradation of an organic precursor material. The commonly used precursor materials include polyacrilonitrile (PAN), rayon and pitch. The fibers produced from PAN precursor are high strength and low modulus, whereas pitch fibers are high modulus and low strength. Carbon fibers contain 92 to 99 percent carbon and graphite fibers contain 99 percent carbon.

Aramid fibers are aromatic polyamide fibers made from a polymer solution that is pressure extruded into a chemical bath by a procedure standard for synthetic textiles fibers. Commercially available fibers are Kevlar 29, Kevlar 49 and Nomex.

Boron fibers are obtained by depositing elemental boron over a tungsten substrate, using chemical vapor plating. Boron fibers are larger in size as compared to glass, carbon and aramid fibers. Hence, difficult to work with in the fabrications process.

The reinforcement fibers are generally available in the form of a tow, or in a band as shown in Figure 1a. A woven form of the reinforcements (Figure 1b) is also used in certain cases, depending on the application of the composite.

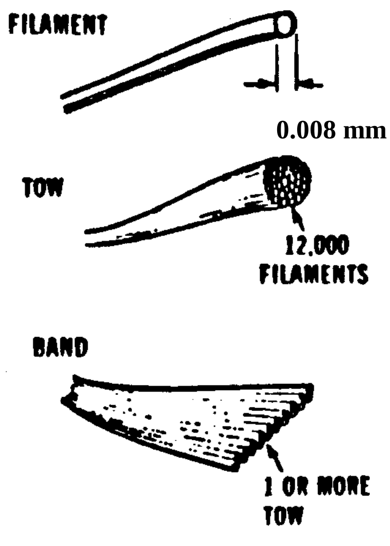


Figure 1a- Fiber Forms

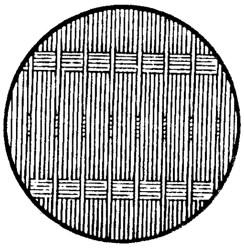


Figure 1b- Unidirectional Weave

A comparison of important properties of typical fiber reinforcements are shown in Table 1. Glass fibers have low modulus as compared to boron and graphite fibers. Glass fibers have high tensile strength as compared to graphite fibers.

2.2. Matrix Materials

There are mainly three different types of matrix materials- organic polymers, ceramics and metals. The majority of composites currently used are polymeric matrix composites. The selection of the matrix material is primarily governed by the service temperature. Polymeric matrices are useful up to temperatures of about 2500C. Most of the aluminum metal matrices are good for temperatures up to 2500C. Titanium matrices are good for temperatures up to 3500C. Ceramics can withstand temperatures exceeding 10000C.

Fiber/ Wire	Density ρ (kN/m^3)	Tensile Strength S (MPa)	S/ρ (km)	Tensile Modulus (GPa)	E/ρ (Mm)
Aluminum	26.3	620	24	73	2.8
Titanium	46.1	1,930	42	115	2.5
Steel	76.6	4,100	54	207	2.7
E-glass	25.0	3,500	140	72	2.9
S-glass	24.4	4,800	197	86	3.5
Carbon	13.8	1,700	123	186	13.5
Boron	25.2	3,450	137	400	15.9
Graphite	13.8	1,700	123	255	18.5

Table 1: Fiber Properties

Polymeric matrices have lowest density, hence, produce lightest composite materials. For applications where temperatures are below 2500C these matrices are best suited. In the majority of civil and military aircraft applications, the service temperatures are below 1200C. In supersonic aircraft, engine components, and the areas near exhaust temperatures are likely to be high. In such cases polymeric matrices may not be suitable.

A major consideration in the selection of matrices is the processing requirement of the selected material. Polymers, ceramics and metals have different processing requirements that affect manufacturing costs. Developments in the processing of polymeric composites have made these materials most suitable for manufacturing advanced composite components.

2.3. Definition of Commonly used Terms

A-Stage- An early stage in the reaction of a thermosetting resin in which the material is still soluble and fusible.

Bleeder Cloth- A non-structural 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 cure and does not form a part of the composite part. The bleeder ply is separated from the laminate by a porous release ply which is discarded after the part fabrication.

Breather Cloth- An open weave material which acts as a path for trapped air and volatile materials which are drawn out under vacuum. Breather cloth is the last layer applied under vacuum bag.

B-Stage- An intermediate stage in the reaction of a thermosetting resin in which the material softens when heated and swells in contact with certain solvents but does not entirely fuse or dissolve. Materials are usually procured in this stage to facilitate handling and processing prior to final cure.

C-Stage- The final stage of the curing of a thermosetting resin in which the material has become infusible and insoluble in common solvents. Fully cured thermosets are in this stage.

Cure- A process of changing the properties of thermo-setting resin irreversibly by chemical reaction. Cure may be accomplished by addition of curing (cross-linking) agents with or without catalyst, and with or without heat.

Cocuring- The act of curing a composite laminate and simultaneously bonding it to some other prepared surface during the same cure cycle.

Delamination- The separation of the layers of material in a laminate. The delamination may be local or cover a large area of a laminate. It may occur during cure, fabrication or service life of a laminate.

Disbonding- A lack of proper adhesion in a bonded joint. A disbond may be in local area or over a large region of the joint. It may occur during fabrication process or during the service life of a joint.

Hand Layup- A process in which components are placed in a mold, and the composite is built up and worked by hand.

Hybrid- A composite laminate comprised of laminae of two or more composite materials.

Isotropic- Having uniform properties in all directions.

Lamina (Plural Laminae) - A lamina is an arrangement of unidirectional or woven fibers in a matrix as shown in Figure 2. The principal axes of the lamina are along the fiber direction and perpendicular to fiber direction.

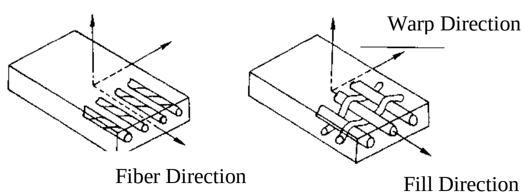


Figure 2- Types of Laminae

Laminate- A laminate is a built-up of a stack of laminae having fibers orientated in different directions. A lay-up of typical laminate is shown in Figure 3. A laminate having plies placed symmetrically about the centerline is termed as symmetric laminate as shown in Figure 3.

Prepreg, Pre-impregnated- A combination of mat, fabric, fibers with resin, advanced to B-stage, ready for curing.

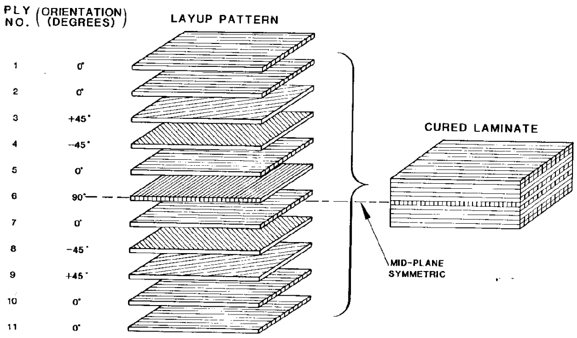


Figure 3- Typical Laminate Lay-up
(02/±45/0/90/0/±45/02) or (02/±45/0/90)S

Resin Content- Amount of matrix material present in a composite either by percent weight or volume.

Scrim (Glass Cloth, Carrier)- An open mesh woven fabric used in the processing of tape or other B-stage material to facilitate handling. Also, used in bonding process to control adhesive thickness.

Shelf Life- The length of time a material or a product can be stored under a specified environment without undergoing any degradation in properties required for the intended use.

Symmetrical Laminate- A composite laminate in which the ply orientation is symmetrical about the laminate mid- plane.

Thermoplastic- A plastic that can be repeatedly softened by heating, and hardened by cooling through a temperature range characteristic of the plastic. In the softened stage the plastic can be formed in a desired shape by molding or extrusion.

Thermoset- A plastic that is substantially infusible and insoluble after being cured by heat or other means.

Wet Lay-up- A method of making reinforced product by applying a liquid resin system while reinforcement is put in place.

2.4. Material Handling and Storage

Polymer matrix prepreg materials have to be handled properly and stored in proper environments to assure the quality of the material. The storage requirement and shelf-life are established by the manufacturer based on the chemical composition and mechanical properties at the time of storage in the controlled environments. Thermoset matrix composites and adhesives are stored in sealed bags at 00F (-180C). The storage process retards the “aging” or partial curing of polymer and extends the shelf-life. The sealed containers or bags prevent the condensation during the storage. When the prepreg is removed from the freezer for laminate fabrication, it is allowed to thaw in the sealed containers until it reaches ambient conditions.

Polymer matrix prepreg generally has a backing sheet that improves the handling quality and protects prepreg from handling damage. Non-woven unidirectional tapes can otherwise split between fibers. Clean, white lint-free cotton gloves are recommended when handling prepreg material to prevent transfer of skin oil to the material. Splinters are not present in the uncured prepreg; however, caution should be exercised to avoid penetration of small diameter fibers into the hand from prepreg edges.

A clean room environment similar to that for bonding process is required when prepreg is to be handled for fabricating laminates. Prepreg must be shielded from impurities and moisture. Fabrication area must be enclosed and doors to remain closed even when area is not in use. Temperature and humidity should be controlled within the limits shown in Figure 4 (Ref. 1).

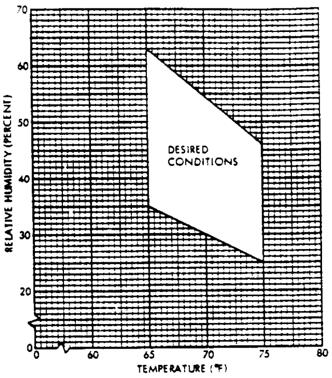


Figure 4- Composite Fabrication Area Requirements

2.5. Laminate Code

A laminate is designed to have specific lay-up or ply arrangement based on the design requirements. Laminates having no symmetry about mid-plane in lay-up are represented as total plies of the laminate. The fiber orientations of all the plies are sequentially written within brackets and are separated by a slash as shown in Figure 5. The plies having fibers orientated at 45 degrees may have fibers along +45 or -45 degrees with reference to the principal axes of the laminate. The use of ± prefix implies two plies one having fibers along +45 and other along -45. A subscript “T” is used after the closing bracket to denote the total laminate

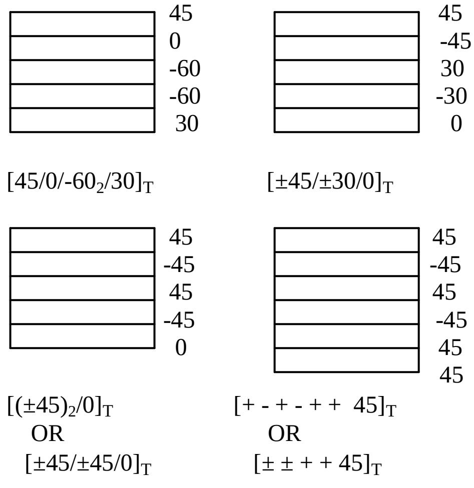
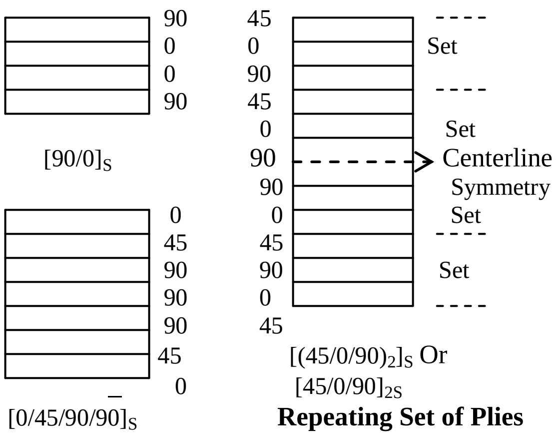


Figure 5- Total Laminate Definition

In some laminates the plies may be symmetrical about the mid-plane of the laminate. For a symmetrical lay-up the laminate code is shown in Figure 6 where only half the plies are represented for convenience. A subscript "S" is used after the closing brackets to denote the symmetric laminate.



2.6 Figure 6- Mid-plane Symmetry Laminate Definition

2.6. Lamina and Laminate Properties

The properties of a cured laminate depend on its individual lamina or ply properties and are computed from lamina properties using classical laminate plate theory. Hence, it is necessary to characterize properties of a cured lamina. The physical and mechanical properties of interest are obtained from sufficient number of replicate tests so that statistical analysis can be performed to account for any variation in test data. The current Military Handbook No. 17 (MIL-HDBK-17) recommends 6 tests each on 5 batches of material for each lamina property. This provides B-basis properties using statistical analysis of sets of 30 results for each property. A B-basis value is obtained by assuming 90 percent probability of occurrence with 95 percent confidence level. Table 2 shows typical lamina physical properties.

Property	**Graphite/epoxy (Tape)**
Ply Thickness (mm)	0.13
Fiber Volume	62 %
Void Content	0 %
Specific Gravity	1.56
Thermal Expansion Coefficient (μ(micro) m/m/^{0}C)	
Fiber Direction α_1	-0.38
Transverse Direction α_2	28.8

Table- 2 Typical Cured Lamina Physical Properties

Lamina mechanical properties that characterize a material are- fiber direction modulus, strength and failure strain; transverse direction modulus, strength and failure strain; in-plane shear modulus, shear strength and strain to failure; and major Poisson ratio. These properties are obtained under tension and compression loads under various environmental conditions. Standard ASTM tests are used to obtain these properties. Table 3 shows typical lamina mechanical properties for graphite/epoxy under Room Temperature Dry (RTD) conditions.

Lamina properties are generally used to obtain laminate properties using laminate plate theory. The laminate properties are shown in the form of carpet plots for various laminate lay-ups (e.g. various percentages of 0 degree, ±45 and 90 degree plies). Strength predictions are based on assumed failure criteria and are generally based on the first ply failure (fiber failure). A typical allowable strength plot for graphite/epoxy material is shown in Figure 7. Similar plots for other material properties are available in US Air Force design guide and FAA Handbook.

2.7. Manufacturing Operations

The manufacturing of composites involves several operations depending on available technology, facilities and personnel skills. Figure 8 shows an overview of the process. A typical manufacturing process starts with receiving the materials that may include tapes, broad goods, and adhesives. The materials are checked by quality assurance personnel to verify that the materials meet the necessary specifications. The materials are then stored in the freezer. As per the drawing requirements, the prepreg is cut to the required shape either manually with a knife or with a reciprocating cutter, or with a controlled knife. The required tooling is matched with the prepreg. The tooling undergoes preparation as per manufacturing requirements. The amount of time prepreg remains outside the freezer is closely recorded.

Property	**Graphite/Epoxy (Tape)**
Tension Ultimate Strength	
F^T_{11}	1724 MPa
F^T_{22}	55 MPa
Compression Ultimate Strength	
F^C_{11}	1586 MPa
F^C_{22}	241 MPa
Shear Ultimate Strength F^S_{12}	119 MPa
Interlaminar Shear Strength F^I	103 MPa
Tension Modulus	
E^T_{11}	129 GPa
E^T_{22}	13 GPa
Compression Modulus	
E^C_{11}	123 GPa
E^C_{22}	9 GPa
Shear Modulus G_{12}	4 GPa
Major Poisson Ratio ν_{12}	0.3
Tension Failure Strain	
ε^T_{11}	0.012
ε^T_{22}	0.005
Compression Failure Strain	
ε^C_{11}	0.017
ε^C_{22}	0.029
Shear Failure Strain ε_{12}	0.020

Table 3- Typical Room Temperature Dry Lamina (RTD) Mechanical properties

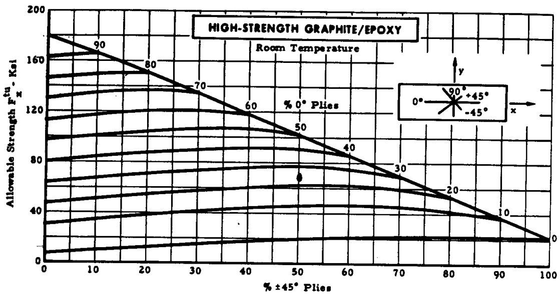


Figure 7- Allowable Strength F_x^{tu},

Graphite/Epoxy- ($0_i/\pm45_j/90_k$) Family

The tool, cut prepreg, and paperwork is taken to the lay-up area where the actual hands-on lay-up process takes place. Process coupons are simultaneously fabricated to investigate the fabrication quality by destructive tests. Quality assurance people check the lay-up prior to the bagging/sealing operation. The inspected bagged and sealed lay-up is placed in an autoclave for curing. After the cure, the part is separated from the tool.

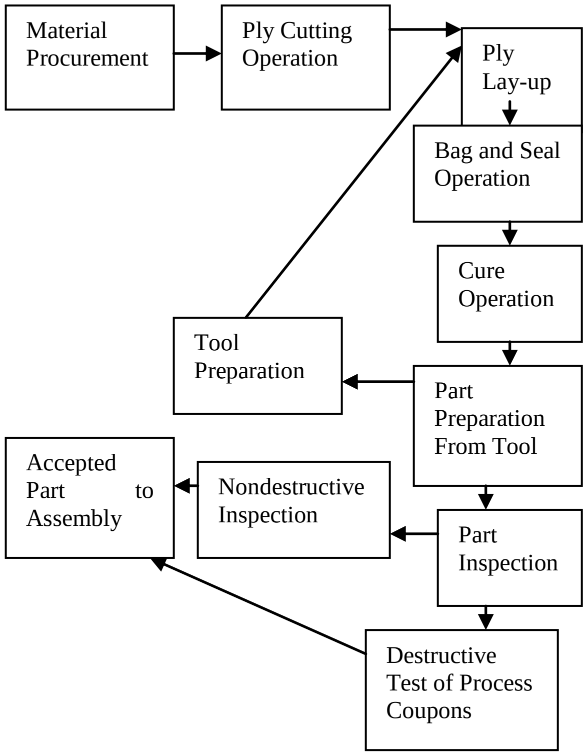


Figure 8-Overview of Manufacturing Process

Commonly used fabrication methods for composite parts are- 1) Vacuum bag processing, 2) Autoclave processing, 3) Compression molding, 4) Filament winding, 5) Pultrusion, and 6) Braiding.

Vacuum Bagging

This process uses a flexible film or rubber bag that covers the part lay-up. The bag allows the evacuation of air from the part to apply atmospheric pressure. Using the vacuum bag pressure for consolidation is a common practice. The only limitation of the vacuum bag process is the limited pressure that can be applied. In the autoclave process much higher pressure can be applied which may be necessary in fabrication of some complex parts. The bag in the vacuum bag process serves two purposes namely- 1) it removes volatiles during cure, and 2) It provides pressure of one atmosphere. Certain amounts of voids are present when plies of prepreg are laid on the lay-up tool. By applying vacuum bag on the tool, sealing it to the tool, and drawing a vacuum, a pressure of 15 psi (103 KPa) is created on the lay-up material. A proper vacuum bag process must meet the following requirements:

- Impervious to air passage
- Apply uniform pressure
- Must not leak
- Good vacuum path must be provided to evacuate air between the bag and tool

The most common vacuum bag process uses a disposal bag made of nylon or Kapton polyimide shown in Figure 9 (Ref. 1). Other process uses reusable silicone rubber bags.

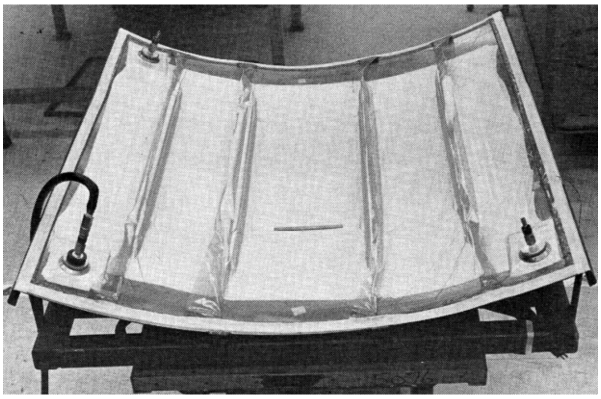


Figure 9- Disposal Vacuum Bag Process

Autoclave Process

An autoclave process uses a pressure chamber to apply heat and pressure during the consolidation and cure process. Autoclave method is the most common method used in the aerospace industry to make composite parts. The autoclave process is an economical method for making structural parts. The commonly used autoclave is capable of applying pressure of up to 200 psi (1400 KPa) and temperature of at least 350F (about 180C) and up to 600F (about 300C). The autoclaves are generally programmable and temperature/pressure history can be automated.

Compression Molding

The compression molding (matched die) process uses large presses to compress the prepreg material between two matched steel dies. The present use of this process is limited to discontinuous fiber composites. The process has application to the use of secondary structural parts. A typical compression molding press is shown in Figure 10.

Filament Winding

Filament winding is a mechanically automated process making parts of simple geometry by wrapping a male tool with filaments impregnated with matrix. This process is well suited for parts which are curved in shape (cylindrical or spherical). Filament winding process has been widely used in helicopter industry for making drive shafts, tail booms and rotor blades.

The filament winding process is named dry if it utilizes prepreg material and wet if it uses fibers passed through a resin bath. The fibers can be continuous fibers of glass, aramid or graphite. Figure 11 shows a typical dry filament winding process.

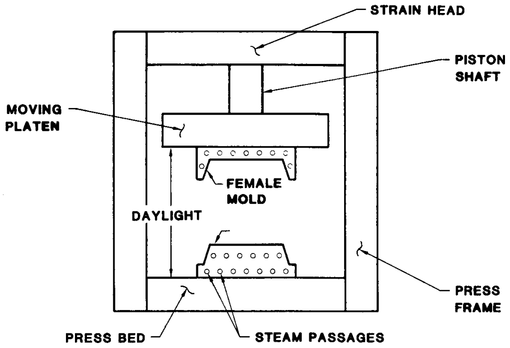


Figure 10- Compression Molding Press

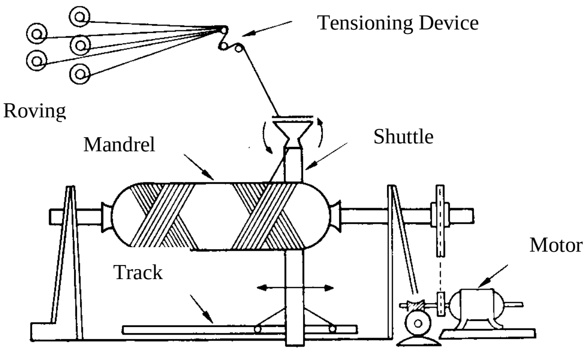


Figure 11- Filament Winding Process

Pultrusion

Pultrusion is a mechanically automated process used to produce shapes by pulling rovings through a shaped and heated die as shown in Figure 12. The process utilizes pre-impregnated rovings or rovings that are pulled through a resin bath to impregnate the fibers. The rovings go through a heated die that represents the cross section of the finished part. The curing is done by heating the die and /or microwave curing. The process is used to make shapes of constant shape such as I-beam, box or tube.

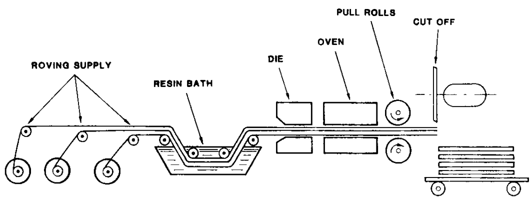


Figure 12- Continuous Pultrusion Process

Braiding

The braiding process involves the weaving of fibers into the shape by repeatedly crossing them back and forth over a mandrel. The method is a product of textile technology and uses equipment adapted from textile industry. The main advantage this process offers is a rapid, automated method for forming an interwoven structure.

2.8. Trimming and Machining of Composites

Special tools and operation techniques are needed to trim and machine composite materials. Special cutting equipment is required for hybrid composite structures (composite structures with layers of metallic materials). The proper trimming and machining operation should meet the requirements that there is no splintering or delamination of surfaces that can be seen visually, and no discoloration due to heating.

Specialized tooling and controlled feeds and speeds are needed to meet the machining requirements. Jobbers conventional carbide tipped or solid carbide drills are well suited. Recommended drilling speed depends on the hole diameter. For holes up to 0.25 inch (6.35 mm) a drilling speed of 3000 RPM is recommended and for larger diameter holes a reduced speed is suggested (e.g. for holes of 0.375 inch (9.5 mm) a speed of 1000 RPM).

For most cases drilling a hole in composites is a two step process. Plain hole or countersink hole is drilled initially and then a reaming operation follows. A coolant may be used to help flush chips from the drill. Some type of vacuum system is also required to contain dust generated by drilling operation.

Due to the brittle nature of composites some type of back-up support on drill exit side is required to prevent splintering of the material on exit side. Common back up materials are- fiberboard, fiberglass, wood, and aluminum. Even when drills or cutters are properly used, some burns or splinters occur. These are easily removed by sandpaper.

3. SANDWICH STRUCTURES

Sandwich construction has found extensive application in aircraft, missile and spacecraft structures due to high strength to weight ratio. This type of construction consists of thin, stiff and strong sheets of metallic or fiber composite material separated by a thick layer of low density material as shown in Figure 13. The thick layer of low density material commonly known as core material may be light foam type (e.g. Nomex core or Rohacell as shown in Figure 14a) or metallic honeycomb as shown in Figure 14b or corrugated core as shown in Figure 14c. The core material is generally adhesively bonded to the face sheets.

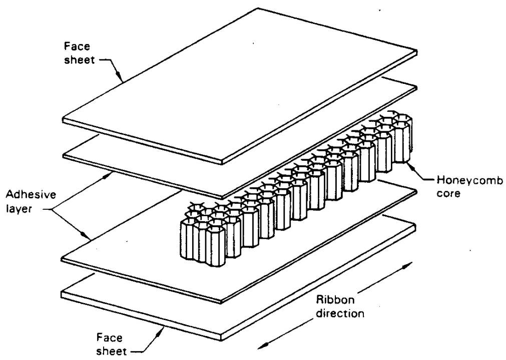
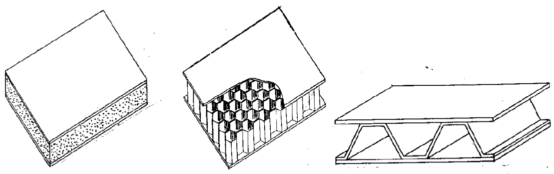


Figure 13- Honeycomb Construction



(a) Foam (b) Honeycomb (c) Corrugated

Figure 14- Types of Cores

In some sandwich construction the core may be made of metallic or composite material corrugations (Figure 14c). The corrugated core may be adhesively bonded, rivet bonded or weld bonded if the face sheets are metallic material. For sandwich construction using composite face sheets, the core may be bonded or co-cured with face sheets. A sandwich construction has following advantages-

- High ratio of bending stiffness to weight as compared to monolithic construction.
- High resistance to mechanical and sonic fatigue.
- Good damping characteristic.
- Improved thermal insulation.
- No mechanical fasteners, hence, no crack initiation sites.

The mains disadvantages of honeycomb construction are-

- In-service trapped moisture in the core material causes corrosion problems. Hence, degradation in the structural integrity of the parts.
- A good quality control is needed during the fabrication process to make sure that there is no disbonding in the adhesive layer.
- Disbonds may initiate and propagate in the adhesive layer during service and thereby reduce the load carrying capacity of structures.

3.1. Failure Modes

Failure modes in sandwich structures are different from those in monolithic structures. The general failure modes that might occur in sandwich structures, depending on the design and core material, are shown in Figure 15 (Ref. 3).

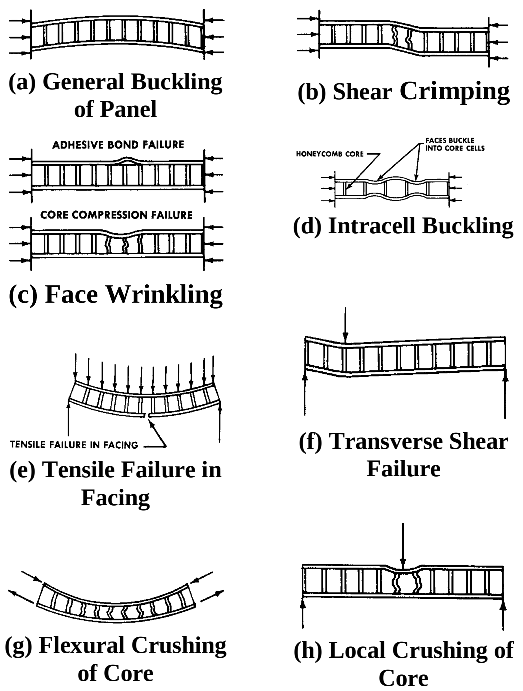


Figure 15- Failure Modes in Sandwich Structures

General Buckling- The general buckling of a panel might occur if the panel thickness is not sufficient or core rigidity is insufficient.

Shear Crimping- This occurs as a consequence of general buckling. It is caused by low core shear modulus or low adhesive shear strength.

Face Wrinkling- In this failure mode, a face sheet buckles acting as a "plate on an elastic foundation" with core acting as an elastic foundation. The wrinkling of face sheet may occur inwards or outwards depending on relative strength of core in compression and adhesive strength in tension.

Intracell Buckling (Dimpling) - This failure mode occurs in panels with cellular cores due to thin face sheets or large core cell size. This failure mode may propagate in adjoining cells and thus causing face sheet wrinkling.

Face Sheet Failure- This failure mode is caused by insufficient panel thickness, face sheet thickness or face sheet strength.

Transverse Shear Failure- This type of failure mode is caused by insufficient core shear strength or panel thickness.

Flexural Crushing of Core- This is caused by insufficient core compressive strength or excessive panel deflection.

Local Crushing of Core- This failure mode is caused by low core compressive strength.

3.2. Design Considerations

A sandwich structure is designed to make sure that it is capable of taking structural loads throughout its design life. In addition, it should maintain its structural integrity in the in-service environments. The structure should satisfy the following criteria:

- The face sheets should have sufficient stiffness to withstand the tensile, compressive, and shear stresses produced by applied loads.
- The core should have sufficient stiffness to withstand the shear stresses produced by applied loads.
- The core should have sufficient shear modulus to prevent overall buckling of the sandwich structure under loads.
- Stiffness of the core and compressive strength of the face sheets should be sufficient to prevent the wrinkling of the face sheets under applied loads.
- The core cells should be small enough to prevent inter-cell buckling of the face sheets under design loads.
- The core shall have sufficient compressive strength to prevent crushing due to applied loads acting normal to the face sheets or by compressive stresses produced by flexure.
- The sandwich structure should have sufficient flexural and shear rigidities to prevent excessive deflections under applied loads.
- Sandwich materials (face sheet, core and adhesive) should maintain the structural integrity during in-service environments.

4. SUMMARY

Composite materials technology has made tremendous strides in last couple of decades. Advanced resin systems, fibers, manufacturing technology, and new design concepts have been developed. Besides aerospace, the applications of composite materials has been extended to a number of fields such as sporting goods, civil engineering, army tanks, ships, strengthening of structures against earthquake damage, etc. It is not possible to cover in details all aspects of composite materials technology in this tutorial. Some basic knowledge of the technology is provided here to familiarize people who may be involved in repair technology.

5. REFERENCES

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