AGARD-AG-238
(Addendum)

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.238

Addendum to

DESIGN MANUAL FOR IMPACT DAMAGE TOLERANT AIRCRAFT STRUCTURE

by

M.J.Jacobson
Northrop Corporation
Aircraft Division
Hawthorne, CA 90250, USA

This Addendum has been prepared at the request of the USAF for presentation to the Structures and Materials Panel of AGARD.

THE MISSION OF AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;
- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Exchange of scientific and technical information;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

Published March 1988

ISBN 92-835-0443-7

Set and printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

SUMMARY

Addendum to "Design Manual for Impact Damage Tolerant Aircraft Structure".

In 1981 the Structures and Materials Panel of AGARD published a Design Manual for Impact Damage Tolerant Aircraft Structures (AG 238). Since that date, there have been significant advances in design to resist impact damage. The Panel has therefore considered it appropriate to record this information in an addendum to the AGARDograph.

***

RESUME

Supplément au "Guide de conception de la tolérance des structures d'avion à l'endommagement dû à l'impact.

En 1981 le Panel des structures et matériaux de l'AGARD a publié un guide de conception de la tolérance des structures d'avion à l'endommagement dû à l'impact (AG 238). Depuis cette date, aucun progrès important n'est à signaler dans le domaine de la conception de la tolérance à l'endommagement dû à l'impact. Le Panel est donc de l'avis qu'il serait opportun d'en faire état sous forme de supplément à l'AGARDographie en question.

PREFACE

Aircraft must maintain structural integrity despite various sources of damage such as, for example, fatigue cracking or corrosion. Military aircraft must also withstand, as far as is practicable, damage inflicted by hostile military weapons. The resistance of the structure to the impact of projectiles is an important parameter in considerations of vulnerability. It is necessary to determine the impact failure characteristics of the structure under load, and its residual strength after damage. The detail design features of the structure are important in determining the spread of the damage. Where neighbouring systems or fuel tanks are vulnerable, the degree of penetration of the projectile into the structure is important. Hydrodynamic ram, blast and fragmentation effects must be considered.

An essential feature of AGARD activities is the pooling of relevant knowledge with the NATO community, aided by the bringing together of specialists for informed discussions. AGARDograph No.238 was, therefore, produced by the Structures and Materials Panel (largely through the efforts of J.G.Avery of the Boeing Company, Wichita, as coordinator, compiler and editor of the manual) to aid the designer in making assessments of the tolerance of the structure to various threats, and the probability of the aircraft surviving the impact, completing the mission and returning safely to base. It describes methods which exist to determine both the damage resulting from the impact of various types of projectiles and the resulting capabilities of the damaged structure. It also embraces an analogous problem, arising mainly on transport aircraft, of the resistance of the structure to impact of debris from engine disintegration.

Since AGARDograph No.238 was published in 1981, further work has been performed on the subjects which it addressed. Therefore, plans for preparing and publishing an addendum to AGARDograph No.238 were initiated, with M.J.Jacobson of Northrop Corporation, Hawthorne, acting as the U.S coordinator, and G.Kagerbauer of MBB acting as the European coordinator.

This document is the result of the SMP's more recent activities in this field, and it contains considerable information that is in written reports of (1) L.G.Kelly and G.J.Czarnecki of the USAF Wright Aeronautical Laboratories, Ohio (2) J.G.Avery, S.J.Bradley and M.R.Allen of the Boeing Military Airplane Co., Wichita, and (3) M.J.Jacobson, R.M.Heitz and J.R.Yamane of Northrop Corporation, Aircraft Division, Hawthorne, California.

Thanks are due to all the above contributors.

Otto Sensburg
Chairman, Sub-Committee on
Survivability of Battle Damaged
Composiste Structures

CONTENTS

LIST OF FIGURES

INTRODUCTION

Since the publication of the "Design Manual for Impact Damage Tolerant Aircraft Structure" AGARDograph No.238 in 1981, considerable activity in the NATO community has been performed to develop design concepts and analytical methods for composite aircraft structures (including fuel tanks) subjected to impacts from ballistic threats. Much of the activity had the principal objective of obtaining a better understanding of the damage modes and their effects on the survivability and repairability of the damaged vehicles. Although some of the activity featured the use of composite materials of the second generation (i.e. bismaleimides and toughened resins) and third generation (i.e. thermoplastics), the experimental data that were developed with these newer composites have generally been deemed proprietary and, therefore, have not been published in the open literature. On the other hand, information developed in programs featuring first generation composites and addressing topics such as the effects on composite aircraft structure of ballistic impacts, hydrodynamic ram and repairability are available and are presented in this document.

Effects of key structural design parameters and threat/tank encounter conditions on hydrodynamic ram damage and residual strength of composite fuel tanks impacted ballistically are presented in Section 1. Design guidelines for ballistically-survivable composite structure, in the absence of hydrodynamic ram effects, are presented in Section 2. In addition, brief comments on battle damage repairability, as influenced by structural design and rapid repair needs, are also presented in Section 2.

SECTION 1

HYDRODYNAMIC RAM

1.0 HYDRODYNAMIC RAM

The subject of hydrodynamic ram and its potential consequences (e.g. excessive fuel loss, structural failures, fire and explosions, and aircraft kill) were addressed in Section 2.2.4 of AGARDograph No.238 (Reference 1-1). Hydrodynamic ram is the phenomenon that occurs when one or more solid objects, such as missile warhead fragments and armour-piercing projectiles impact, penetrate, and traverse a fuel tank and generate intensive pressure waves that act on the fuel tank. Since Reference 1-1 was published, several hydrodynamic ram research programs have been performed to obtain a better understanding of different aspects of the technology and develop hardening concepts to reduce or eliminate the detrimental consequences of hydrodynamic ram.

A major portion of a pilot paper entitled "Damage Tolerant Composite Structure Development" addressed hydrodynamic ram and was presented by Mr Larry Kelly, USAF, to the Ad-hoc Group on Survivability of Battle-Damaged Composite Structures at the 60th Meeting of the AGARD Structures and Materials Panels in San Antonio, Texas, (April 22—24, 1985). Much of the pilot paper is incorporatedherein. Other recent reports (e.g. References 1-2 and 1-3) addressing hydrodynamic ram have been made available by AGARD.

1.1 OVERVIEW

Composite aircraft structural response to exploding warhead fragments and penetrating projectiles can vary significantly depending on the design approach employed, the amount and type of load being carried by the structure at time of impact, and whether the structure serves as a fuel container. In this latter case, a shock wave is generated at the impact site resulting in very high instantaneous dynamic pressures (>2,000 psi). These pressures are commonly referred to as hydrodynamic ram and can result in the delamination, brooming and spallation of large amounts of material from the fuel tank structure. In turn, these lead to significant fuel loss or even catastrophic reduction in the fuel tank strength and/or stiffness. The amount of damage caused by hydrodynamic ram effects is dependent not only on the fuel tank materials and type of construction, but also on the physical features of the fuel tank and many characteristics of the penetrating projectile. Several of the more important parameters have been evaluated through the design and ballistic testing of representative carbon/epoxy fuel tank structures. Results of this testing are presented herein to provide researchers in the field with the knowledge gained to date, and to provide military airframe designers with design concepts and techniques that can be utilized in the conceptual phase of a new airframe development. It is at the early design stage that more damage-tolerant designs or even hydrodynamic ram-tolerant fuel tank construction can be incorporated with minimal weight and overall system performance penalties.

1.2 KEY DESIGN PARAMETERS INFLUENCING DAMAGE SIZE AND TYPE

Current carbon/epoxy aircraft structure has been developed to achieve significant weight savings, especially when compared to conventional skin-stringer aluminium construction. Therefore, to obtain a feel for the response of carbon/epoxy composite material to hydrodynamic ram, 2024-T3 aluminium alloy and equivalent thickness carbon/epoxy (AS1/3501-5A) laminates were subjected to impact by 5/8-inch diameter steel spheres under simulated fuel tank test conditions in USAF tests. The visible damage in the composite laminates was orders of magnitude greater than the visible damage in the aluminium panels (Figure 1). These results were a stimulus for a series of programs evaluating the vulnerability of composite fuel tanks to hydrodynamic ram.

Pertinent test parameters for providing realistic simulation of actual operational conditions were identified and their effects were evaluated. The parameters were:

(1) Projectile shape, hardness and velocity
(2) Projectile kinetic energy and momentum
(3) Projectile incidence of impact

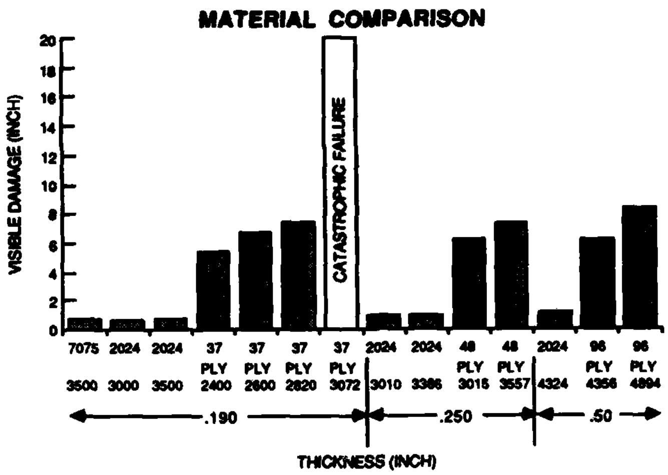


Figure 1. Aluminium and Carbon Epoxy Material Comparison.

(4) Amount of fuel tank ullage or fluid level
(5) Type of test fluid
(6) Tank geometry
(7) Panel attachment conditions
(8) Type of panel construction and thickness
(9) Temperature and moisture conditions of the composite
(10) Airflow

To evaluate the relative importance of these parameters numerous stiffened and unstiffened composite panels representative of current aircraft wing construction techniques and some baseline metallic panels were subjected to ballistic impact and hydrodynamic ram forces. Relevant results are contained in the following presentation.

1.2.1 Stiffener Attachment

Stiffener attachment was a very important variable. Stiffeners were either bonded, bolted or stitched to flat panels (Figures 2 and 3) in a manner representative of typical wing cover to spar construction. These panels formed one side of a simulated fuel tank test fixture. All panels were impacted with 5/8 inch diameter steel spheres, weighing 250 grains, (437.5 grains = 1 ounce) at varying velocities. Panel response varied from almost complete stiffener separation to confinement of the total visible damage between the spars. All panels experienced extensive internal delamination. The order of increasing survivability (measured by total visible damaged area) was:

Bonded	(stiffeners disbonded at low projectile velocity)
Bolted	(fastener pull-through and large area damage)
Through the Skin Tows	(pull-through of the tows)
Stitched	(some damage under stiffener)
Double Stitched	(visible damage contained between stiffeners and some internal damage under stiffener)

1.2.2 Panel Edge Conditions:

Three panel edge conditions were evaluated under a USAF contract with the Northrop Corp. (Reference 1-4): (1) simply supported, (2) fully clamped and (3) clamped-sliding. The contractor tested 48-ply ($0_{20}/+45_{10}/-45_{10}/90_{8}$) AS1/3501-6 carbon/epoxy unstiffened panels without mechanical preloads. When attached to the test tank, an 18 by 8 inch central zone of each panel was in contact with the liquid. The panel boundary conditions were applied at the edge of the 18 by 8 inch central zone. The panels were impacted as entry panels in hydrodynamic ram tests with 129 grain spheres and cubes at 4,300 and 5,200 fps and normal incidence (0 degree obliquity). Edge conditions simulating simply supported conditions were achieved by attaching an edge flexibility frame between the test panel and the adapter plate on the test fixture. Following the hydrodynamic ram tests, a 7 inch wide hydrodynamic ram-damaged section of each panel was tested for residual tension strength. The range of values obtained for each support condition is presented in Figure 4.

There was less entry-panel damage with simply-supported edge conditions. There was only minimal tear-through of the panels at the joints with the supporting structure for simply-supported edge conditions in contrast with much greater panel tear-through at the panel boundaries with the clamped and clamped-sliding edge conditions. The clamped panels experienced delamination failures over the entire wetted test section whereas the simply-supported panels had intermittent delaminations.

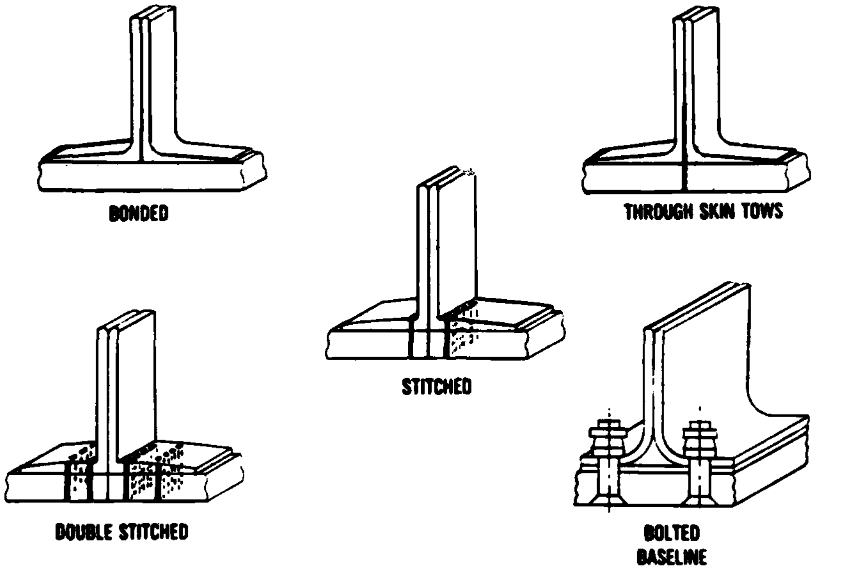


Figure 2. Stiffener Attachment Techniques.

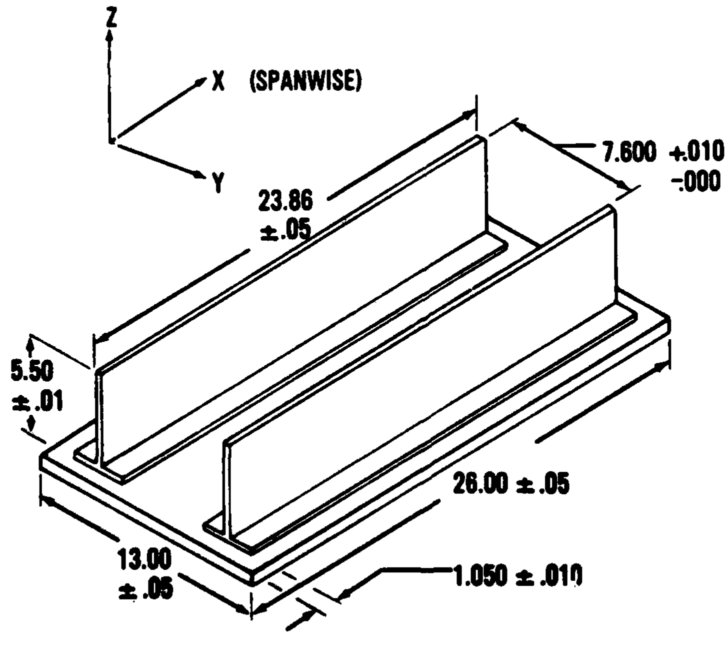


Figure 3. Test Panel Design Details.

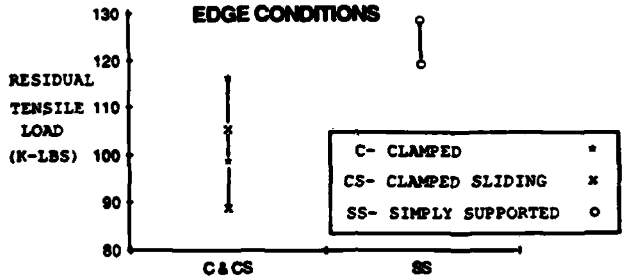


Figure 4. Effects of Panel Boundary Support.

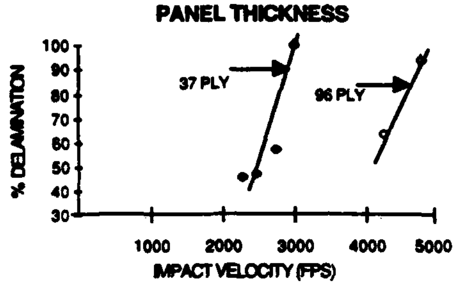


Figure 5. Effect of Panel Thickness on Panel Delamination (C-Scan Measurements).

The greater strains to failure and lesser hydrodynamic ram damage with simply-supported edge conditions were attributed to the greater in-plane flexibility of the support structure and therefore lesser membrane stresses during the hydrodynamic ram response. Analysis showed clamped conditions to be more representative of actual wing box structure.

1.2.3 Panel Thickness

Laminate thickness (i.e. number of plies) had a significant influence on damage size in USAF tests (Figure 5). Visible damage size in thin composite laminates (<40 plies) that were entry panels in hydrodynamic ram tests tended to conform to the shape of the projectile on the plane of the impacted laminates. Increased skin gauges can reduce the entry velocity of the projectile and thus reduce the resulting fluid pressure. Increased skin gauges can also reduce panel deformation due to ram induced wall loadings. However, intermediate thickness laminates can be extensively damaged as a result of delamination and rear surface spallation. Excessive gauges are required to minimise damage. Therefore, increasing skin thickness to prevent penetration is not an effective means of improving structural survivability. A more efficient approach is to design the structure to accept penetration damage by using damage tolerant concepts (see Hybrid Designs, Section 1.2.6). Tests conducted under the Northrop contract (Reference 1-4) showed no substantial difference in 0.25, 0.34, and 0.45 inch AS1/3501-6 panel damage in that C-scan detected damage was observed throughout the wetted areas of all the panels in the tests with 129 grain threats impacting the panels at velocities of 5,200 fps. There were no mechanical pre-loads applied to the test panels in any of the Northrop ballistic tests of Reference 1-4.

1.2.4 Projectile Incidence of Impact

Under the Northrop contract (Reference 1-4) the projectile impact angle was varied from 0 to 45 degrees in a series of tests with 129 grain steel spheres representing an exploding warhead fragment. Impact velocity was 5,200 fps. The residual strength (Figure 6) of the panels, measured by loading the panels to failure after impact, decreased substantially when the obliquity angle was increased from 0 to 45 degrees.

This indicates that entry panels of fuel tanks are more vulnerable to projectiles penetrating at high obliquity angles as opposed to normal incidence. High obliquity angles are known to cause far more delamination. The visible damage to an entry panel when a projectile entered at non-zero obliquity was not symmetrical about the entry location, but was very much greater in the direction of the projection on the panel of the projectile path through the liquid. This strongly implies that the concept of an instantaneous release of kinetic energy of the projectile as it impacts and/or traverses the liquid is generally invalid for use in the prediction of the structural response of the entry (or exit) panel.

In Reference 1-5 the extent of damage is estimated to vary inversely with the cosine of the angle of obliquity. The higher obliquity angles increase the distance the projectile travels before exiting and the more the projectile may deform. The larger

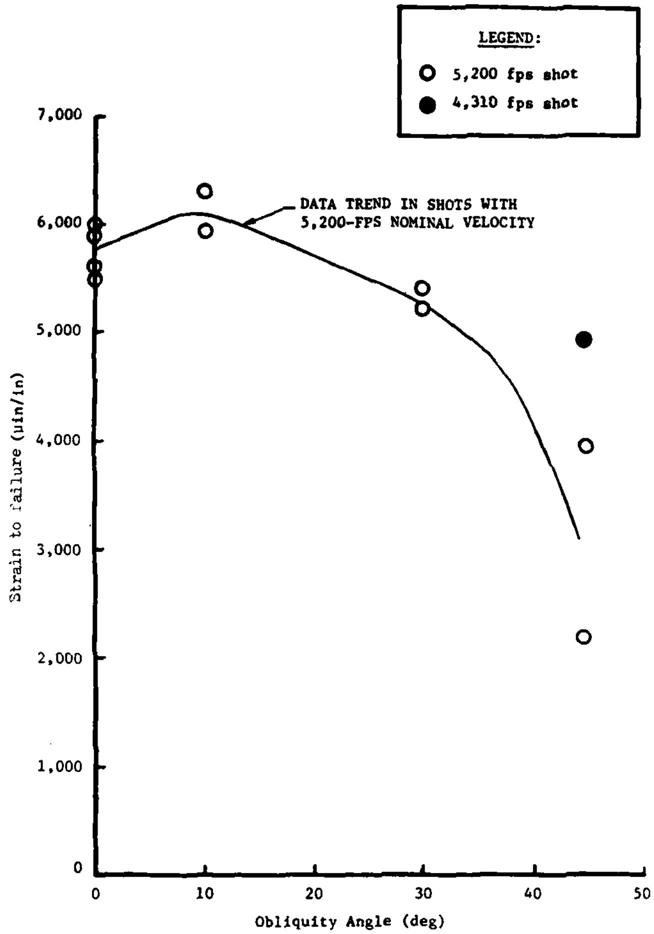


Figure 6. Effects of Projectile Incidence.

that the projectile cross-sectional area is, the greater the drag will be; therefore, there will be more kinetic energy transferred to the fluid. However, more kinetic energy transferred to the fluid will not always result in greater damage to a panel For example, if a tank is deep enough to slow down a projectile sufficiently so that it does not perforate an exit wall, the damage to the exit wall will be less severe than in cases when the exit panel is perforated and less projectile kinetic energy is transferred to the liquid.

1.2.5 Test Fluid

The Air Force tests showed a distinct difference (Figure 7) in the amount of damage area incurred on entry panels when water was substituted for fuel. However, in terms of residual strength the Northrop tests (Figure 8 from reference 1-4) did not substantiate the Air Force findings.

The Northrop tests employed AS1/3501-6 entry and exit panels. Residual tensile strengths were obtained after impact with spheres at a nominal velocity of 4,300 fps for both water and JP-4 test fluid. The lack of a discernible difference in damage was considered consistent with the finding that strains to failure were not sensitive to fragment impact velocity and the kinetic energy loss of the projectiles in traversing the liquids was essentially insensitive to the type of liquid. There were a number of differences in the Air Force and Northrop tests, including entry panel thickness, exit panel thickness and material type and test tank design. These variables are believed to cause the different test behaviour. Another reason could have been the fact that residual strength does not generally correlate with damage area but rather the damage extent transverse to the applied load. Because doubt remains as to the effect of test fluid it is recommended that only parameter screening be done with water as the test fluid for safety and expediency reasons. Final design verification testing of a hydrodynamic ram tolerant concept should be accomplished with the actual fuel as the test fluid. As an aside, it is noted that the USAF recommends that fuel simulants should not be substituted for JP-4 fuel in fuel leakage tests.

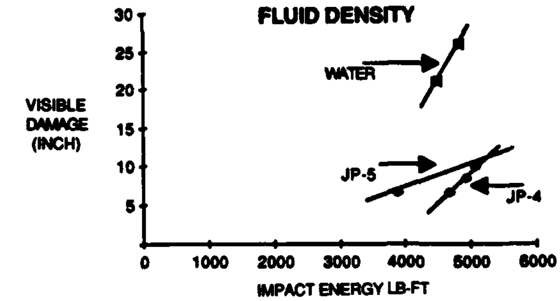


Figure 7. Effect of Fluid Density.

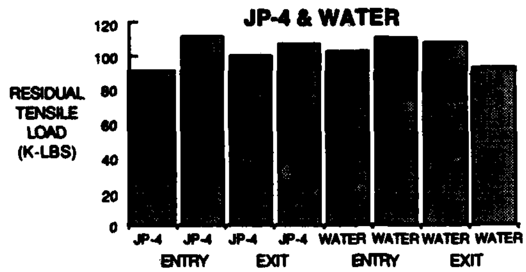


Figure 8. Northrop Tests.

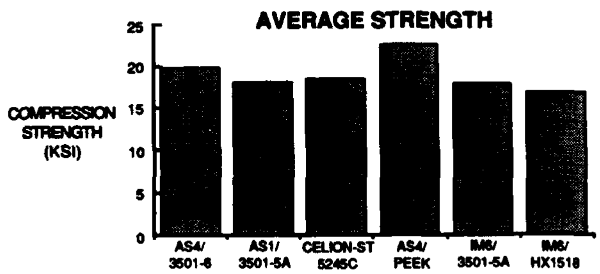


Figure 9. Residual Compression Strength.

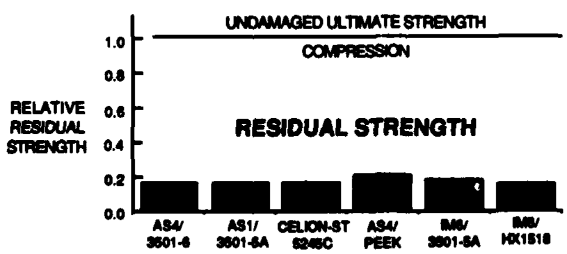


Figure 10. Relative Residual Compressive Strength.

1.2.6 Hybrid Designs

Many damage-tolerant enhancement design concepts have been proposed for use in carbon/epoxy primary structure. These generally take the form of various interply, intraply or parasitic damage containment additives. The additions are to provide crack arrestment or load path redundancy. In addition, the parasitic additions featuring foams are primarily intended to reduce peak hydrodynamic ram pressures. Hybridizing the laminate with plies of a more compliant material such as woven S-glass or Kevlar 29 is most common. In addition, higher strain to failure fibres and tougher resins have been employed. Interply hybrid laminates of S-glass and Kevlar 29 have not been very successful in containing damage from dynamic impact forces, however, nor has material substitution alone been very useful (Reference 1-6). The newer materials were stronger in compression for a given damage size but sustained greater damage for a given threat impact. Under the Boeing contract (Reference 1-5), six different materials were subjected to multiple impacts of three 230 grain fragments at 2,540 fps in dry shots and the residual compression stress measured. The results are shown in Figure 9 and the materials were as follows:

AS1/3501-5A	Current Carbon/Epoxy System
IM6/3501-5A	High Modulus Carbon/Epoxy
Celion-ST/5245	High Strain Carbon/Epoxy
IM6/HX1518	Carbon/Bismaleimide Resin
AS4/PEEK	Carbon/Thermoplastic Resin
AS4/3501-6	Current Carbon/Epoxy System

There was considerable variation in damage size obtained, but the compression residual stresses were relatively close considering the wide variation in materials tested. The best approach is to incorporate a crack-arrestment region through the use of buffer or crack-arrestment strips. This technique provides a region of lower stiffness/higher toughness than the carbon/epoxy primary laminate. As a crack approaches one of these regions, the stress intensity at the crack tip is reduced because of the lower stress in the buffer region which, combined with the higher toughness, prevents continued crack propagation.

Hydrodynamic ram damage to composites is too complex to model as a simple crack extension or damage zone propagation. Composites are intolerant of large out-of-plane deflections resulting from hydrodynamic ram pressures. Extensive ply delamination, along with laminate peeling and fibre breakage, can occur. Such damage results in significant compression strength loss. Figure 10 from Reference 1-5 shows that regardless of the material type, compression strength loss is dramatic under impact forces. In addition, the strength loss is augmented when the structure is already stressed by operational loads at the time the impact and/or ram pressures forces are applied.

Tensile or compressive fracture can occur at impact even though the applied stress is below that static residual strength corresponding to the damage size induced. The applied stress level at which this type of fracture occurs is called the "impact fracture threshold". The impact fracture threshold for composite laminates containing 0-deg plies impacted with non-exploding projectiles is 80% of the average residual strength of impacted panels that are unstressed (Reference 1-6). This level was obtained from single ballistic impacts of tensile loaded panels and found to correlate with low velocity impact data. Recently (Reference 1-5), this 80% threshold was extended to compression-loaded panels subjected to multiple ballistic impacts. If hydrodynamic ram pressure load damage mechanisms are coupled with already augmented strength loss, dramatic changes in design concepts are required for damage containment to be realised. Using composites that are tougher and/or with higher strains to failure or tailoring the laminate orientation has not proven to be adequate in increasing residual compression strength (Figure 10). Vulnerability reduction from hydrodynamic ram-induced threats requires the incorporation of damage-containment principles in the initial design process. Selectively employed hybrid materials can permit built-in break points for a "blow out panel" that prevents pressure damage to the primary load-carrying structure. Examples of some hybridizing materials that have shown promise from the Northrop contract (Reference 1-4) are woven Kevlar fabric 49 and 29. In addition, parasitic rigidized reticulated foam and ballistic foam resulted in reduced hydrodynamic ram pressures and greater residual strengths of the entry panels (Figure 11). The test results of Figure 11 were obtained in tension tests and may not be applicable quantitatively and/or qualitatively in compression tests. Further tests are needed to augment the meagre amount of available compression data for hydrodynamic ram-damaged panels. The more promising approaches for reducing hydrodynamic ram effects have been those that provide significant energy absorption and/or controlled damage confinement. The best design concepts create a tolerable failure path within the structure by directing the failure along defined boundaries selected so that critical adjacent structural elements remain undamaged. An example is the double-stitched concept in Figure 2. With this approach the induced damage is confined primarily to the skin between intermediate spars and ribs, so that failure of the spar/skin attachment is reduced. When hybrid materials are applied with skin pads at ribs and spars, the propagating fracture damage is stopped, providing a battle-damage-tolerant skin.

Typically, exit panels experienced much greater hydrodynamic ram damage than entry panels in the vicinity of the projectile perforation site in 0-degree obliquity shots. The difference in the typical hydrodynamic ram damage near the fragment perforation site of the entry versus exit composite panels is attributed to the following factors: (1) The entry panels in the vicinity of the fragment perforation site were somewhat shielded from the hydrodynamic ram pressures by the cavity, visible in high speed films, in the wake of fragments that penetrated the panels and (2) the exit panels of full tanks and some partially-filled tanks were continuously subjected to extremely high pressures due to the liquid compression as the fragments traversed the last few inches of liquid immediately before perforating the exit panels.

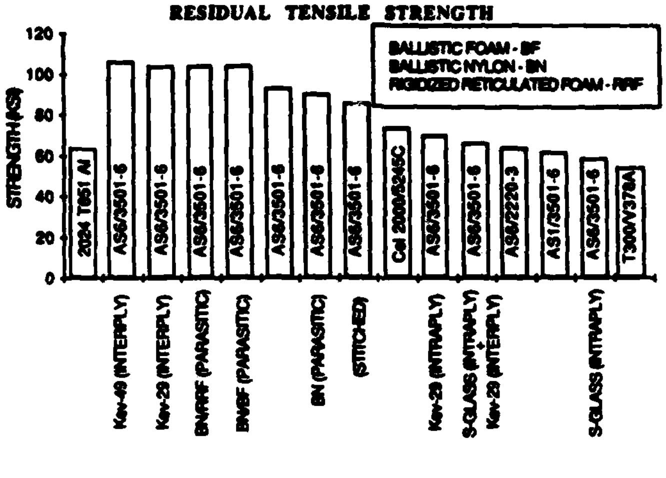


Figure 11. Hybrid Composite Residual Tensile Strength.

1.2.7 Projectile Shape

Soft steel cubes and soft and hard steel spheres were used as the projectile types in Northrop tests (Reference 1-4). The weight of each projectile was 129 grains. AS1/3501-6 graphite/epoxy and 2024-T851 aluminium alloy entry and exit panels of 0.25 inch thickness and with clamped edge conditions were used in these tests. These shots were all at normal incidence and projectile velocities ranged from 4,000 to 6,000 fps. The following items were the principal results of this testing.

The scatter in strain-to-failure data and visible damage data of hydrodynamic ram-damaged AS1/3501-6 entry and exit panels was independent of the projectile type (i.e. spheres versus cubes). Strains to failure of AS1/3501-6 entry panels impacted by cubes were generally substantially less than when impacted by spheres (Figure 12). Strains to failure of AS1/3501-6 exit panels impacted by cubes were generally substantially greater than when impacted by spheres (Figure 13). In shots with AS1/3501-6 entry and exit panels the strain to failure of the entry panel impacted by cubes was generally substantially less than that of the entry panel. Only at the greatest fragment velocity (6,000-fps shots) were the strains to failure of AS1/3501-6 exit panels substantially less than those of the AS1/3501-6 entry panels. In shots with the 129 grain spheres in the 4,000 to 5,200 fps range, the strain to failure of the AS1/3501-6 entry and exit panels penetrated by spheres were in the same range.

The failure modes of the AS1/3501-6 entry panels included panel tear-through at the edge clamps when the impact velocity exceeded a threshold of 4,600 fps. As the fragment impact velocity increased, the tear-throughs at the entry panel edges became a prominent failure mode. The failure mode at the AS1/3501-6 exit panels included massive damage in the form of brooming and delamination on the dry side of the panels in the vicinity (e.g. a 5 inch diameter zone) of the fragment penetration site and usually no evidence of even partial panel tear-throughs at the edge clamps. Delaminations of the AS1/3501-6 entry and exit panels, detected by C-scans, were throughout the panel zones that were in contact with the liquid prior to the shots.

The visible damage of the 2024-T851 entry panels was confined to the fragment penetration site in normal incidence shots and was a relatively clean hole in all the shots. The spheres and cubes generally did not completely penetrate the 2024-T851 exit panels. Generally, the residual tensile strengths of the 2024-T851 entry and exit panels remained essentially constant as the fragment velocity at the impact with the entry panel increased from 4,000 to 6,000 fps.

The test results led to the following conclusions. It does not appear necessary to simulate cubes with spheres (note that cubes generally simulate missile warhead fragments better than spheres) in the hydrodynamic ram tests of panels of 0.25 inch thickness without mechanical preloads since the data scatter of strains to failure was approximately the same for both projectile types. An adjusted velocity of a sphere cannot generally be achieved that will simultaneously produce entry panel damage and exit panel damage that would have resulted from a shot with a cube. Based on the visible damage and strain-to-failure data, the AS1/3501-6 panels of 0.25 inch thickness generally were substantially more vulnerable to the 129 grain threats than the 2024-T851 aluminium alloy panels if the fragment velocity at the entry panel exceeded approximately 4,000 fps. However, until the fragment impact velocity at the entry panel reached approximately 6,000 fps, the strains to failure of the AS1/3501-6 laminates exceeded 4,000 micro-in/in, which typically is the design limit strain for such laminates.

1.2.8 Constant Projectile Kinetic Energy and Momentum

Hydrodynamic ram tests with AS1/3501-6 entry and exit panels of water-filled tanks were performed by Northrop (Reference 1-4) with spheres having different combinations of projectile mass and velocity that would produce a constant kinetic energy of the sphere at its impact with the entry panel. In other hydrodynamic ram tests in this test series, the mass and velocity combinations of the spheres were adjusted to produce a constant fragment momentum at the entry panel. Fragment

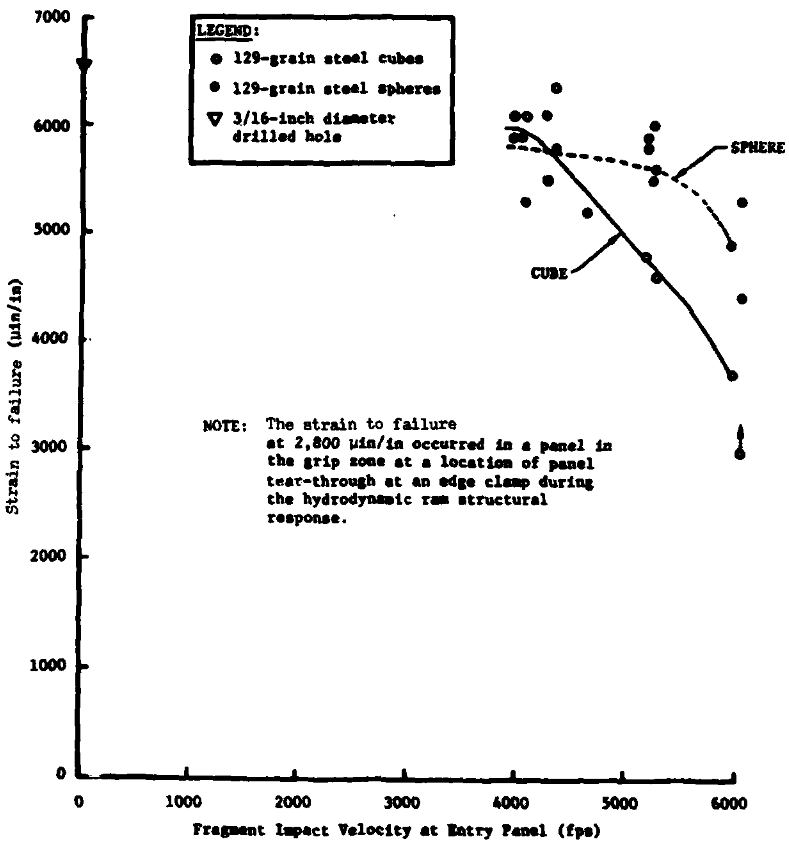


Figure 12. Effect of Fragment Shape and Velocity on AS1/3501-6 Entry Panels.

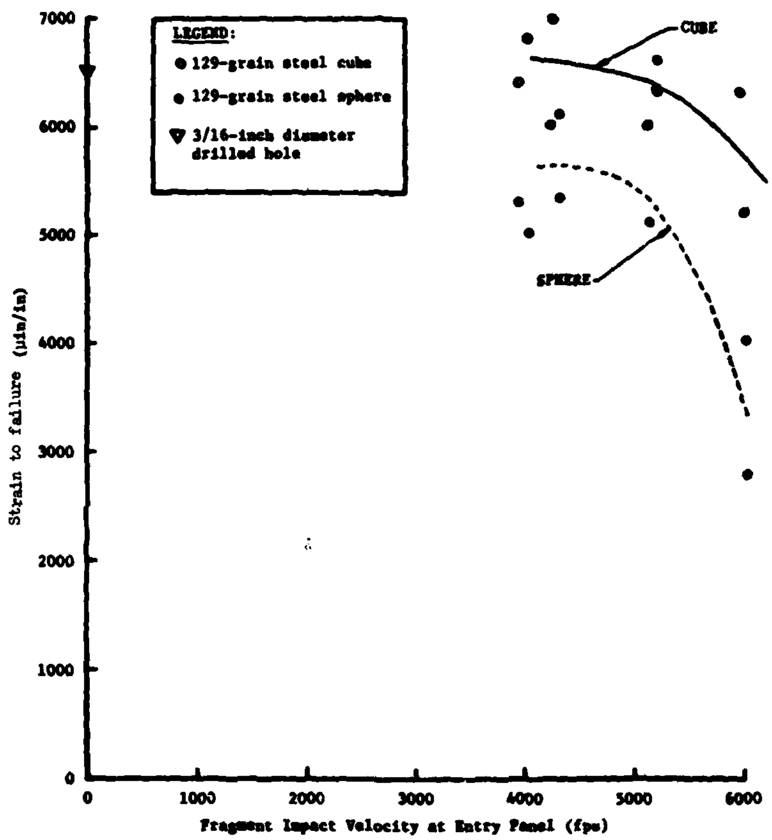


Figure 13. Effect of Fragment Shape and Velocity on AS1/3501-6 Exit Panels.

mass and velocity combinations were 252 grains at 3,070 fps, 129 grains at 4,300 fps, and 87 grains at 5,200 fps in constant kinetic energy tests and were 129 grains at 4,000 fps and 87 grains at 5,930 fps in constant momentum tests. In these tests all projectile impacts were at normal incidence.

The principal test result was that the strains to failure were not overly sensitive to different mass and velocity combinations in the constant fragment kinetic energy tests and in the constant fragment momentum tests. Since hydrodynamic ram tests with spheres at an arbitrary constant fragment kinetic energy resulted in average strains to failure within a range of approximately 10%, it was concluded that strains to failure may be reported on the basis of fragment kinetic energy at the entry panel. It is anticipated that the same conclusion would be reached if the spheres were replaced by cubes in hydrodynamic ram tests. However, this conjecture has not been verified by tests.

1.2.9 Fluid Levels

The effects of fluid levels (Reference 1-4) were investigated in upward vertical shots, in horizontal shots simulating the upward vertical shots, and in horizontal shots simulating downward vertical shots. Horizontal shots simulating upward and downward shots were performed because a missile detonation may occur above or below an aircraft in level flight. In all the shots, the distance between the entry and exit panels (i.e., the tank depth) was 7.6 inches and the projectile impacts were at normal incidence.

The strains to failure following the upward vertical shots into the tank with AS1/3501-6 panels and the horizontal shots simulating the vertical shots were within a 20% range and are not considered to be overly sensitive to the liquid levels in vertical shots and simulated liquid levels in horizontal shots of 2.0, 3.8, 5.8 and 7.6 inches. In the horizontal shots with 129 grain spheres fired at 5,200 fps, panel tear-throughs at edge clamps that occurred in shots into liquid-filled tanks did not occur in shots into simulated partially-filled tanks.

In horizontal shots at normal incidence and simulating a missile detonation above an aircraft, liquid levels of 2.5, 3.5, and 4.5 inches were simulated in the 7.6 inch deep test tank with AS1/3501-6 exit panels. The hydrodynamic ram damage to the exit panels in the shots with the 2.5 and 3.5 inch simulated liquid level was substantially greater than that experienced by any other 0.25 inch thick test panels in the Northrop tests of Reference 1-4. The strains to failure of these panels dropped below 2,000 micro-inch/inch (Figure 14) and were substantially less than all the other strains to failure obtained in the tests of Reference 1-4.

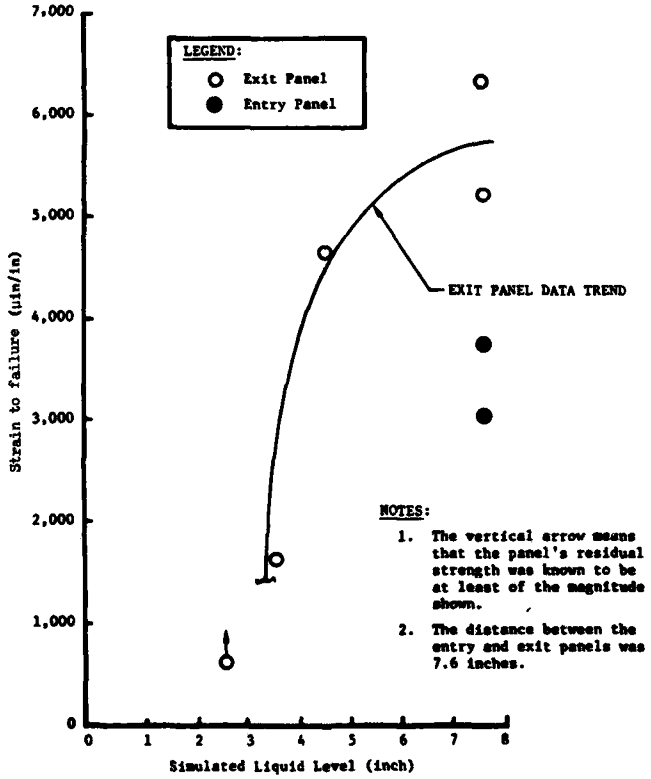


Figure 14. Effect of Simulated Liquid Level Following Simulated Detonations Above an Aircraft

The results in this test series led to the following conclusions: The hypothesis that an integral tank is more vulnerable to a missile detonation below the aircraft than above the aircraft and that the compression skin is always more vulnerable than the tension skin to warhead fragment encounters may have to be reversed to account for the damage in tension skins of tanks with certain liquid levels (e.g., approximately 2 to 4 inches) if the detonation occurs above the aircraft. The residual strength of a tension skin of an integral tank an aircraft may not be increased substantially if the tank is penetrated in a partly-filled condition (i.e. >2 inches of liquid) rather than a full condition.

1.2.10 Stacking Sequence (No Air Flow)

AS1/3501-6 entry panels of 0.25 inch thickness with two different stacking sequences were subjected to hydrodynamic ram tests in Northrop tests without air flow followed by residual tensile stength tests (Reference 1-4). There was no effect of the stacking sequence on the residual tensile strength in the absence of air flow. However, stacking sequence may have a profound effect on residual strength when there is air flow, as noted subsequently in Section 1.2.12.

1.2.11 Temperature and Moisture

Hydrodynamic ram tests and residual strength tests of AS1/3501-6 panels were conducted by Northrop (Reference 1-4) with water as the test fluid with the external surface of the entry panels heated to 180°F in two of four tests. The other two tests were conducted at ambient temperature. The panels had been conditioned to a moisture content of 1.1% for the tests at 180°F.

The principal result of these tests was that the strains to failure of the AS1/3501-6 panels were essentially insensitive to the environmental conditions. The principal conclusion is that the ambient temperature test conditions of the other tests of AS1/35016 panels of Reference 1-4 produced strain-to-failure data applicable to the conditions of elevated temperature up to approximately 180°F and moisture contents up to 1.1%.

1.2.12 Airflow

When a composite wing's fuel tank is impacted by a high-velocity projectile, hydrodynamic ram combines with projectile damage causing bundles of delaminated fibres to protrude. Therefore, a sensitivity study was conducted by the Flight Dynamics Laboratory (AFWAL/FIES) at Wright-Patterson AFB to determine the effects of high speed airflow (400 knots) over battle-damaged composite surfaces. Using an A-7 airfoil section as the test bed, effects of airflow were monitored as a function of the following parameters: material type, threat, impact location, ply stacking sequence, fluid level, fluid type, panel thickness, static tank pressure, and tank volume.

Material types evaluated were graphite/epoxy (AS4/3502) similar to that used on a wing now in service, aluminium (2024 and 7075), and graphite/bismaleimide (T300/V378A). The composite skins sustained significantly more damage than their aluminium counterparts, with airflow increasing the original level of projectile/hydrodynamic ram damage in most instances. Protruding fibrous material was torn back toward the wing's trailing edge. Woven E-glass outer surface coatings, designed to attentuate delamination cause by low velocity impacts such as tool drops, proved detrimental to structural survivability. Caught in airflow, the relatively ductile woven material tended to hold together and be torn off in one large piece. Along with the E-glass, many adhering subsurface plies were peeled back until reaching an edge, where they separated from the structure.

Test panels were subjected to threats ranging in magnitude from 12.7 mm armour-piercing incendiary (API) to the 30 mm high-explosive incendiary (HEI). Of all threats, only the 12.7 mm API created damage so insignificant as to disallow the occurrence of airflow effects. Thus, composite aircraft that have been designed to survive the 12.7 mm and lesser threats will be extremely vulnerable in a realistic hostile environment where the 23 mm and 30 mm threats abound.

The impact location significantly affected the amount of airflow damage received. Composite skin panels were found vulnerable to airflow when impacted near their leading edges. Delamination spread easily along this discontinuous edge, allowing the airflow to wedge the plies apart and peel them back.

Stacking sequence changes affected the shape of original damage and the extent of subsequent damage. Damage on panels having a quasi-isotropic lay-up was somewhat circular, whereas on panels having an anisotropic lay-up, the damage spread perpendicular to the airflow stream (increasing the potential for airflow effects).

The effects of hydrodynamic ram and airflow remained proportional to the fluid level when the tank was more than half full. The extent of ram/airflow damage was not affected when the panel thickness was increased by one-third.

1.2.13 Simulation of Ullage

When horizontal shots are performed in tests to simulate vertical shots, there is a need to simulate ullage (i.e. airspace above the fuel of partially-filled fuel tanks). The motivation for conducting horizontal shots to simulate vertical shots is that at many test facilities it is much easier and less costly to conduct the horizontal shots.

Hydrodynamic ram tests with vertical and horizontal shots were conducted by Northrop (Reference 1-4) with 7475-T61 aluminium alloy panels of 0.085 inch thickness and AS1/3501-6 graphite-epoxy panels of 0.25 inch thickness. Encapsulated rigidized reticulated foam, encapsulated non-rigidized reticulated foam, and styrofoam were used to simulate the air gap in the cases when a horizontal shot was performed to simulate a vertical shot. The encapsulation was performed to keep the reticulated foams dry prior to the shots. The horizontal shots simulated missile detonations below an aircraft in level flight. All vertical shots were upward.

Vertical shots with 129 grain spheres fired at 5,200 fps nominal velocity in the tests of the 7475-T61 panels of 0.085 inch thickness resulated in catastrophic exit panel failures when there was 1 inch of ullage but not when there were 2 inches of ullage. The non-catastrophic and catastrophic failures of 7475-T61 exit panels obtained in the vertical shots with ullages of 1 and 2 inches, respectively, were replicated when horizontal shots were performed and the ullage was simulated by encapsulated rigidized reticulated foam. However, when styrofoam was used to replace the encapsulated rigidized reticulated foam, there were catastrophic failures of 7475-T61 exit panels in the shots with both 1 and 2 inches of ullage. The rigidized reticulated foam was less stiff in flatwise compression, but heavier than the styrofoam.

The entry panel damage in horizontal shots simulating vertical shots with a 1.8 inch ullage (i.e. a 5.8 inch liquid level) was insensitive to the use of encapsulated rigidized reticulated foam versus styrofoam in simulating the ullage. However, in the vertical shots with 5.8 inch liquid level the entry panels experienced tear-throughs along their long clamped edges in contrast to the absence of tear-throughs at clamped panel edges in all the horizontal shots with a 5.8 inch simulated liquid level.

The test results led to the following conclusions. A minimum amount of ullage, which is dependent on panel geometry (especially on panel thickness) and material, tank depth, and threat encounter conditions is needed to prevent a catastrophic failure of panels above the ullage in upward shots. The cause of AS1/3501-6 panel tear-throughs at the edge clamps that occurred in the vertical shots with a 5.8 inches of liquid is not clearly understood, but is being attributed principally to pre-loads due to the cantilevered tank arrangement and the somewhat different cantilevered edge conditions in the vertical versus horizontal shots. There were no entry panel tear-throughs at edge clamps in vertical shots with liquid levels of 2.0 and 3.8 inches and in the horizontal shots simulating these vertical shots. The need for applying pre-loads to panels in horizontal shots versus vertical shots should be further investigated. The air gaps in vertical shots can be simulated with encapsulated rigidized reticulated foam or styrofoam in horizontal shots. The encapsulated rigidized reticulated foam will provide a somewhat better simulation of the air gaps, but the styrofoam is somewhat less costly and is easier to work with. Encapsulated non-rigidized reticulated foam should not be used to simulate the ullage since it crushes due to static liquid presures.

1.3 HYDRODYNAMIC RAM ANALYSIS

The HRSR finite element code is a promising analytic tool for predicting Hydrodynamic Ram Structural Response that couples a fluid pressure analysis method developed by E.Lundstrom at the Naval Weapons Center with the BR-1FC finite element code developed by Boeing for structural response to highly transient loading (see paragraphs 2.2.4.3.1 and 2.2.2.2.3.1 of Reference 1-1). The HRSR code was used satisfactorily in Reference 1-4 to predict the transient nature of hydrodynamic ram structural response. However, the HRSR code has not resulted in accurate predictions of the extent of hydrodynamic ram damage, which is needed for subsequent predictions of residual strength.

Furthermore, no analysis methods for predicting the extent of hydrodynamic ram structural failures for arbitrary problems have been developed. Hence, general techniques of predicting residual strength of battle-damaged structure, such as presented in Section 2, have not yet been developed for application to hydrodynamic ram-damaged structure.

1.4 CONCLUDING COMMENTS

Key conclusions that have been presented are summarised below.

(1) Current carbon/epoxy construction in aircraft can be intolerant to ballistic damage and hydrodynamic ram if not designed to survive such threats.

(2) Improvements in composite materials, both in terms of increased fibre strain capability and tougher resins, have not produced a corresponding increase in ballistic damage tolerance as measured by the failure strain of impacted compression-loaded panels.

(3) To survive the very high pressure forces created by hydrodynamic ram, damage containment concepts have to be incorporated into the structural design from the start.

(4) Stitching of stiffener elements to the panels provides transverse reinforcement and prevents local buckling prior to failure and has been successful in resisting propagation of delamination damage.

(5) The shape (e.g. sphere versus cube) of a simulated missile warhead fragment may have a substantial effect on the hydrodynamic ram structural response of a fuel tank panel because of the resulting effect of the fragment shape on fluid drag pressure.

(6) In hydrodynamic ram tests of liquid-filled tanks perforated near the centre of a tank wall by a simulated warhead fragment, the very severe structural damage of graphite/epoxy exit panels was concentrated in the vicinity of the fragment perforation sites, whereas the very severe damage of the entry panels was in the vicinity of both the panel joints and the fragment perforation sites. Hydrodynamic ram damage increased and residual tensile strength of the damaged panels decreased experimentally with increasing kinetic energy of the simulated warhead fragments.

(7) A missile detonation above an aircraft in level flight may result in massive damage to the exit panels of fuel tanks if there is a critical depth of the fuel. This critical depth depends on factors such as panel geometry and missile fragment weight and obliquity, and may be less than three inches of fuel.

(8) In cases when missile detonations occur beneath an aircraft in level flight, the hydrodynamic ram damage of composite entry panels will not vary greatly as a function of liquid level if the liquid level exceeds a critical depth (e.g., approximately two inches, depending on panel geometry, the encounter conditions, etc.). The hydrodynamic ram damage will increase substantially with increasing fragment obliquity angles greater than approximately ten degrees when the liquid level is not a variable.

(9) In general, the stacking sequence (especially of the surface plies) of composite panels will have a substantial effect on the extent of hydrodynamic ram damage when the panels are subjected to airflow conditions, inasmuch as the airflow tends to greatly enhance damage characterized by fibres with loose ends in the airstream.

(10) Elevated temperatures of 180°F and a 1.1% moisture content of AS1/3501-6 panels do not appear to influence substantially the hydrodynamic ram damage and resulting residual strength of the damaged panels.

(11) The effect of water versus JP-4 fuel as the fluid in hydrodynamic ram tests is not completely understood. Until further tests are evaluated, water is recommended for safety reasons in hydrodynamic ram screening tests, and JP-4 fuel is recommended for the final hydrodynamic ram testing. JP-4 fuel, rather than its simulants, are recommended for fuel leakage tests.

(12) If horizontal shots are to be performed to simulate vertical shots in hydrodynamic ram tests, simulating the ullage with encapsulated rigidized reticulated foam is generally preferable to simulations with styrofoam. Simulations of the ullage with encapsulated non-rigidized reticulated foam should be avoided.

(13) The research and development needed to establish clear design guidelines for hydrodynamic ram-tolerant composite fuel tanks is still in its early stages and much more work needs to be done.

REFERENCES FOR SECTION 1

1-1 J.G.Avery, "Design Manual for Impact Damage Tolerant Aircraft Structure," AGARDograph No.238, October 1981.

1-2 G.Kagerbauer, D.Weisburger, and O.Sensberg, "Improvement of Battle Damage Tolerance for Composite Structures," *Impact Damage Tolerance to Composite Structures*, AGARD Report No.729, February 1986.

1-3 T.E.Hess, "Ballistic Survivability Considerations for Aircraft Structures," *Impact Damage Tolerance to Composite Structures*, AGARD Report No.729, February 1986.

1-4 M.J.Jacobson, R.M.Heitz, and J.R.Yamane, "Survivable Composite Integral Fuel Tanks," Contract F33615-82-C-3212, AFWAL-TR-85-3085, January 1986.

1-5 "Survivable Characteristics of Composite Compression Structure," Contract F33615-83-C-3228, Boeing Miltary Airplane Co.

1-6 S.J.Bradley and J.G.Avery, "Design Guide for Survivable Structure in Combat Aircraft," Contract F33615-80-C-3411, AFWAL-TR-84-3015, April 1984.

SECTION 2

DESIGN GUIDELINES FOR SURVIVABLE AIRCRAFT STRUCTURE

2.0 DESIGN GUIDELINES FOR SURVIVABLE AIRCRAFT STRUCTURE

The topics of structural damage and residual strength resulting from projectiles perforating composite structures, mainly in the absence of hydrodynamic ram effects, were addressed in Reference 2-1. The data available to develop semi-empirical relations to predict damage and residual strength were very limited. Subsequently, the USAF sponsored a program, (Reference 2-2) conducted by Boeing, with a major objective of updating the semi-empirical methods of Reference 2-1 for damage and residual strength. The overall objectives of the program were to extend design technology for achieving combat-survivable structure and to prepare an engineering design guide for implementing the technology on new aircraft. The program primarily investigated fibre composites subjected to conventional weapon threats. Research in the area of metallic structure was limited to the incorporation of pre-existing analysis methods and threat effects into the design guide. The program included an extensive weapon effects and residual strength test program employing graphite/epoxy and hybrid structural elements damaged by machined flaws, ballistic perforations or blast overpressures. The test results were used to finalize analytical models for predicting damage size and structural degradation in fibre composites impacted by small arms projectiles, AAA high-explosive projectiles and missile warhead fragments. The test program consisted of over 360 tests designed to rectify previously identified deficiencies, and included a warhead arena test to investigate the effects of warhead detonation on composite structural elements and components and to validate the fragment damage simulation methods used in the laboratory.

2.1 MATERIALS AND TEST METHODS

Figure 15 shows an overview of the test program. There were three phases involving non-exploding penetrators, high-explosive AAA projectiles, and the fragmentation warhead.

AS4/3501-6 grade 145 tape was selected as the graphite/epoxy product for the test specimens, and grade 145 S-glass/3501-6 and Kevlar 49/3501-6 were utilized for hybrid specimens. The nominal ply thicknesses of all the products was 0.0055-in/ply.

Ply orientations of 0, +45 and 90 degrees were employed. Thirteen different graphite/epoxy laminate configurations and three hybrid laminate configurations were tested, as shown in Figure 16. Specimen thicknesses ranged from 8 plies to 96 plies.

2.2 TEST RESULTS AND DISCUSSION

The following paragraphs summarize the significant conclusions drawn from analysis of test data obtained under this program and from other sources.

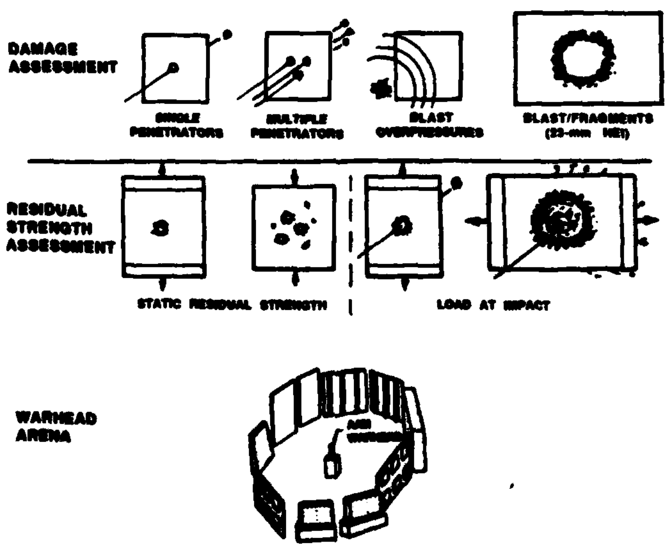


Figure 15. Overview of Survivability Testing of Advanced Composites.

Designation	Layup	Ply orientations			No. of plies	Nominal thickness (0.0055 in/ply)
		%0	%±45	%90		
G1	$[(0/\pm45/90)_N]_s$	25.0	50	25.0	16, 48, 96	0.088, 0.264, 0.528
G2	$(0_2/\pm45/0_2/90/0)_s$	62.5	25	12.5	16	0.0880
G2R	$(90_2/\pm45/90_2/0/90)_s$	12.5	25	62.5	16	0.0880
G3	$[(90/\pm45_2)_2]_s$	0.0	80	20.0	20	0.1100
G3R	$[(0/\pm45_2)_2]_s$	20.0	80	0.0	20	0.1100
G4	$[(\pm45)_N]_s$	0.0	100	0.0	16, 48	0.0880, 0.2640
G5	$\pm45_2/90/\pm45_2$	0.0	89	11.0	9	0.0495
G5R	$\pm45_2/0/\pm45_2$	11.0	89	0.0	9	0.0495
G6	$[(90/+45/90/-45)_2]_s$	0.0	50	50.0	16	0.0880
G6R	$[(0/+45/0/-45)_2]_s$	50.0	50	0.0	16	0.0880
G7	$(90_2/+45/90_2/-45)_s$	0.0	33	67.0	12	0.0660
G7R	$(0_2/+45/0_2/-45)_s$	67.0	33	0.0	12	0.0660
G8	0_8	100.0	0	0.0	8	0.0440

Designation	Layup	Ply orientations					No. of plies	Nominal thickness (0.0055 in/ply)
		%0			%±45	%90		
		SGL	KEV	GR				
GS1	$(0/\pm45/0_{SGL}/90)_s$	20	0	20	40	20	10	0.055
GS2	$(0/+45/0_{2\ SGL}/-45/90)_s$	33	0	17	33	17	12	0.066
GK1	$(0/\pm45/0_{KEV}/90)_s$	0	20	20	40	20	10	0.055

Legend:
s: Symmetrical.
N: Repetitions to achieve total ply count.
SGL: S-glass.
KEV: Kevlar.

Figure 16. Ply Orientations Included in Composite Survivability Test Program.

2.2.1 Characterization of Ballistic Damage in Graphite/Epoxy Laminates

Data from several hundred ballistic test firings were analysed to characterise ballistic damage in graphite/epoxy laminates and to develop predictive models. These included 150 tests using non-exploding projectiles, including compact fragments (4 to 250 grain cubes) and small-arms projectiles (.30 and .50 calibre, aligned and tumbled). There were 10 firings of 23 mm HEI projectiles against 21 targets, and 26 static charge detonation tests for blast response. The warhead arena test employed 32 composite targets and seven metal targets. Results of these tests and the associated analysis are summarised below:

a) The testing verified that the most significant parameters influencing ballistic penetration damage size are projectile presented length, impact angle (obliquity), and laminate thickness. This result pertains to impacts by non-exploding projectiles at velocities well above the ballistic limit.

b) As a consequence of a), the penetration damage size from compact fragments and small-arms projectiles can be predicted using a ballistic damage model in closed form. The model for the median visible damage size in graphite/epoxy is shown in Figures 17 and 18 and below:

$$D_v = (1.5L_p/\cos\theta) + 2.6\,t$$

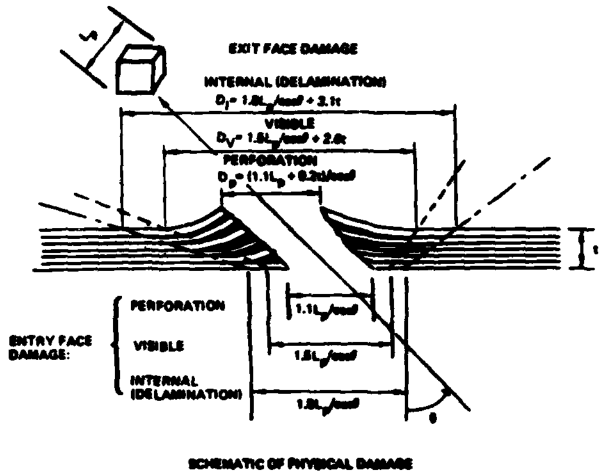


Figure 17. Physical Aspects of Ballistic Damage in Graphite/Epoxy Laminates.

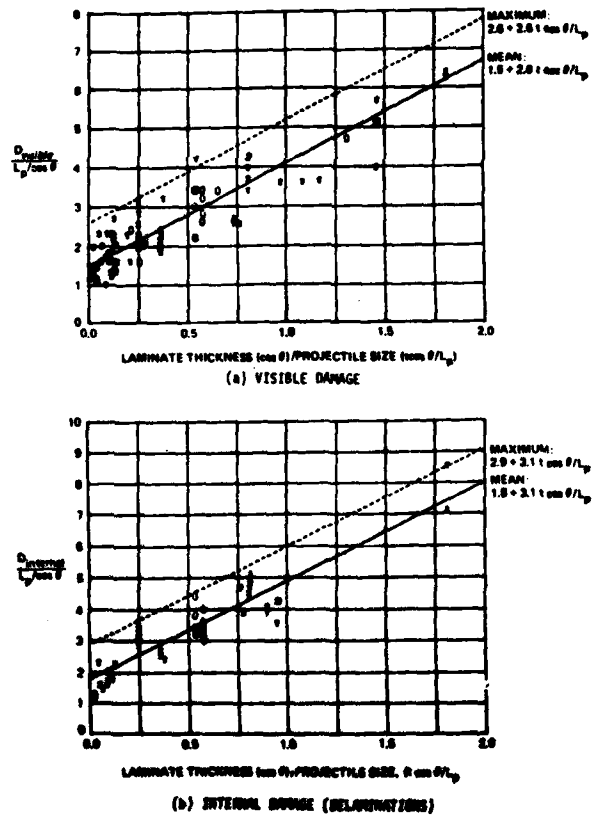


Figure 18. Predictive Models for Physical Damage Resulting from Penetration of Graphite/Epoxy Laminates by Non-Exploding Projectiles.

where: D_v = maximum extent of visible damage including extended peeling of the surface ply;

L_p = projectile presented length;

θ = obliquity angle;

t = laminate thickness.

c) The extent of internal damage surrounding the visible damage (consisting of delamination revealed by ultrasonic scan), depends upon the same parameters as visible damage (defined in (a) above), but internal damage size increases with laminate thickness at a faster rate than visible damage. The predictive model developed for internal damage in graphite/epoxy is shown in Figures 17 and 18(b) and is given below:

$$D_i = (1.8\, L_p/\cos\theta) + 3.1\, t$$

where: D_i = maximum extent of internal damage, consisting of delamination revealed by ultrasonic scan.

d) For graphite/epoxy laminates, the extent of significant damage is relatively independent of ply orientation except that peeling of the surface ply in laminates fabricated from tape is always most extensive in the direction of the surface ply.

e) Visible damage induced in graphite/epoxy laminates which are under an applied load at the time of impact does not differ significantly from damage induced in unloaded laminates if the applied load is below the threshold for fracture at impact (see Section 2.2.2, Residual Strength, for additional comments).

f) Ballistic damage due to multiple impacts does not differ significantly from single impact damage unless the spacing between impacts is such that the damage regions overlap. This was verified for simultaneous impact by HE projectile fragments and by simultaneous impact of warhead fragments.

g) Ballistic damage in thin Kevlar 49-graphite hybrids is similar in size and character to damage in all-graphite/epoxy laminates of the same thickness. However, damage induced in thin S-glass-graphite laminates is larger than all-graphite/epoxy laminates. Figure 19 illustrates these effects.

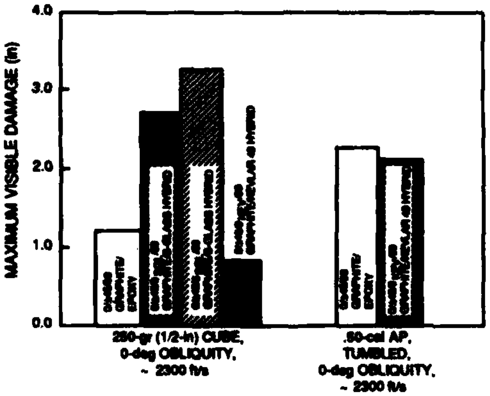


Figure 19. Comparison of Ballistic Damage in Hybrid and All-Graphite Laminates.

h) The damage size induced by contact-detonating superquick fused 23 mm HEI projectiles is a function of projectile impact velocity as shown in Figure 20. At 2,200 fps and 0-degree obliquity, a six-inch diameter hole is produced, with one to three additional inches of delamination around the hole. The hole size is of primary significance in strength degradation (as discussed subsequently under Section 2.2.2, Residual Strength).

i) The large base and fuse fragments from a 23 mm HEI projectile, which typically weight over 40 grains, have been shown to penetrate laminates up to 0.5 inch thick. Most side-spray fragments, which typically weigh less than 40 grains, can be stopped by laminates of 0.2 inches thick.

j) Threshold stand-off distances for inducing damage due to the blast effects of enemy 23 mm HEI projectiles were estimated for 0/±45/90 and ±45 laminates. Bare charges consisting of 210 grains of Composition C-4 were detonated in proximity to the laminates for this assessment. The ±45 laminates resist blast pressures better than 0/±45/90 laminates of the same thickness. Blast overpressure can induce delamination in thick 0/±45/90 laminates even when there is no visible external damage. This non-visible damage can severely degrade compression strength.

2.2.2 Residual Strength of Ballistic Damaged Graphite/Epoxy

More than 130 tension and compression residual strength tests were performed with specimens containing machined flaws, ballistic damage, 23 mm HEI damage, and blast damage. In addition, residual shear strength results were analysed. Conclusions drawn from these tests are summarised below.

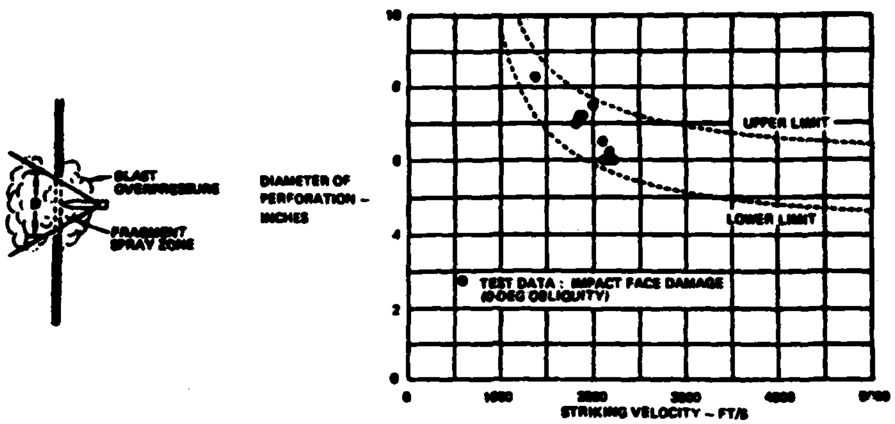


Figure 20. Damage from Superquick-Fused 23-mm HEI Projectiles, Graphite/Epoxy Laminates, 0.05 to 0.50-in Thicknesses.

2.2.2.1 Effective Flaw

The fasibility of the effective flaw concept for predicting the residual strength of ballistic-damaged composite laminates was established. This concept correlates ballistic damage with idealized flaws of a shape and size which produce the same strength degradation as the ballistic damage. Once this correlation has been established, conventional analysis methods such as linear elastic fracture mechanics can be used for residual strength prediction, employing the effective flaw size as the characteristic flaw dimension.

The results obtained from more than 100 residual strength tests with single penetrators and machined flaws verified the following items. The appropriate effective flaw shape for ballistic damage in graphite/epoxy is a sharp-edged through-crack. The effective flaw size is a function of laminate thickness, projectile size and impact angle, and is insensitive to ply orientation.

The predictive model developed for the size of the effective flaw resulting from non-explosive penetrators is given by the relationship:

$$D_{eff} = (0.8\, L_p/\cos\theta) + 4.3\, t$$

where: D_{eff} = effective flaw size, i.e. length of a sharp-edged through-crack causing the same strength degradation as the ballistic flaw;

L_p = projectile presented length;

θ = obliquity angle;

t = laminate thickness.

The data used to develop the model and applications of the model for common threats are shown in Figures 21, 22, and 23.

For 23 mm HEI contact detonations, it was established by testing that the effective flaw is approximately the diameter of the perforation. Based on limited tests employing 23 mm HEI standoff detonations, the effective flaw appeared to be the width of the region intercepted by fragments spaced such that overlapping damages occur. In theory, at certain critical combinations of projectile velocity and stand-off distance, this region can be as wide as 20 inches. However, these conditions represent extremes that have not been demonstrated.

Figure 24 shows application of the effective flaw concept in predicting the residual tension, compression and shear strength of ballistic-damaged panels. Effective flaw sizes were computed using the model presented above and used with a modified version of the Whitney-Nuismer point stress failure prediction method. These predictions are in good agreement with the residual strength test results, as indicated in the figures. Figure 25 demonstrates applicability for a range of ply orientations.

2.2.2.2 Applied Load Effects

For non-exploding projectiles, unstable crack propagation can initiate at impact in certain laminates if the tension applied load is above 80% of the static residual strength. This result applies to laminates containing plies parallel to the principal load direction (0 degree plies in end-loaded panels, for example). If loaded below this threshold at impact, these laminates can exhibit reduced static residual strength when loaded to failure after impact. Reductions of up to 15% were observed, as shown in Figure 26.

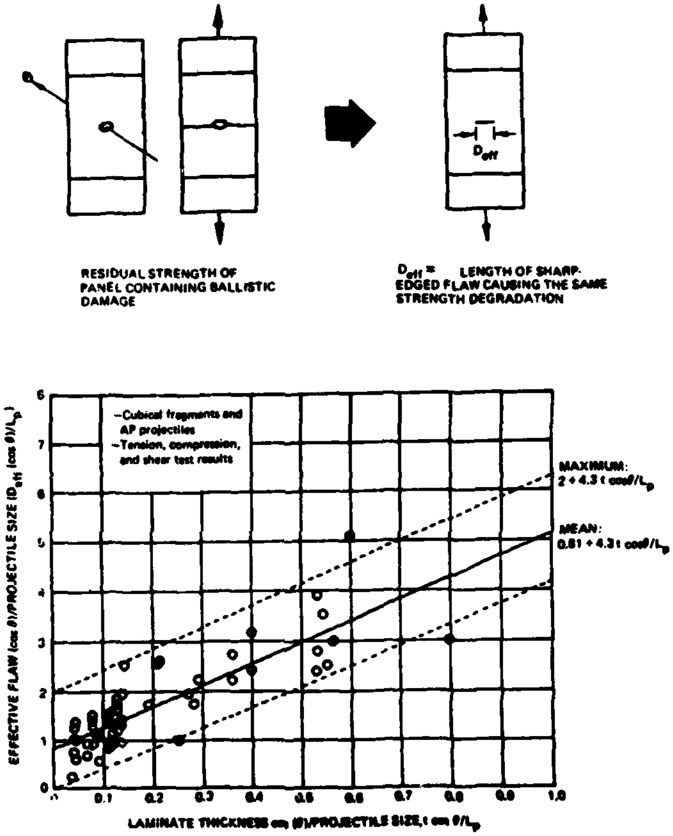


Figure 21. Effect of Laminate and Threat Parameters on Effective Flaw Size.

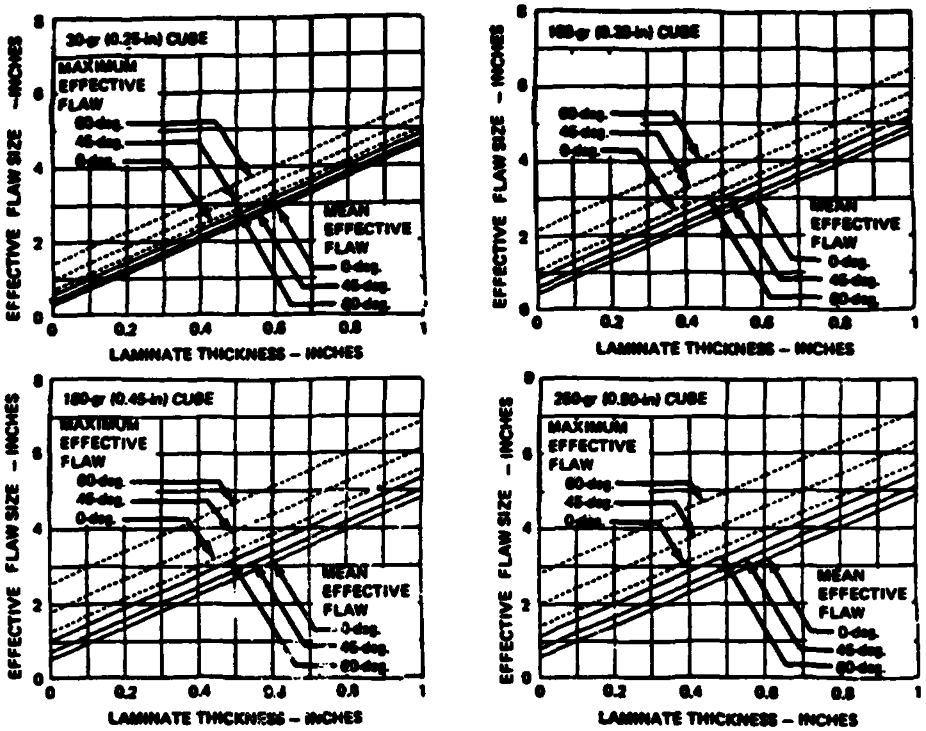


Figure 22. Effective Flaws for Cubical Fragments Impacting Graphite/Epoxy Laminates.

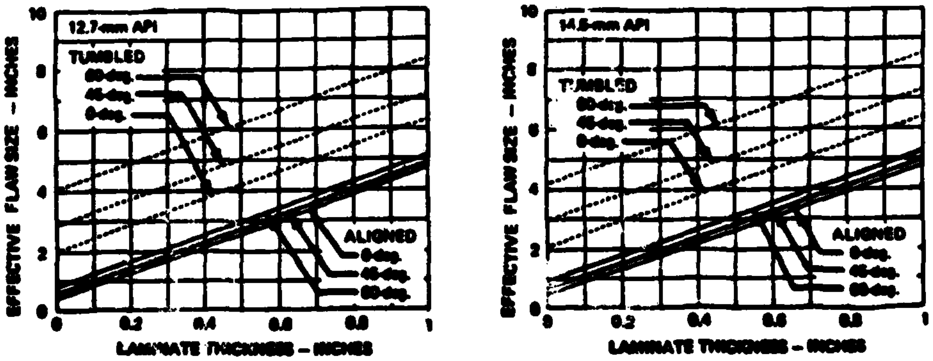


Figure 23. Effective Flaws for Aligned and Tumbled Armor-Piercing Projectiles Impacting Graphite/Epoxy.

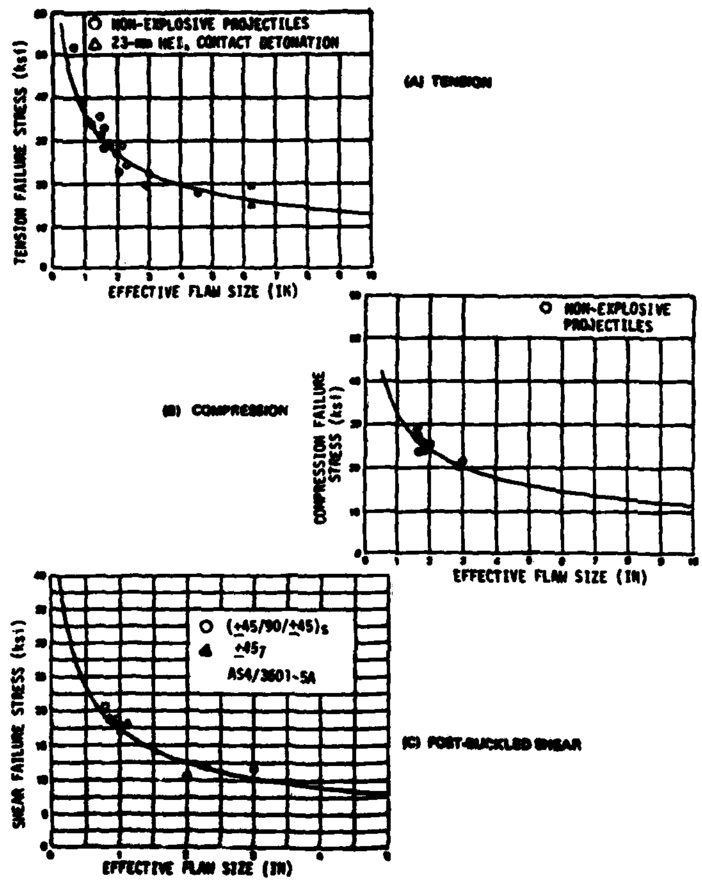


Figure 24. Correlations of Test Data with Residual Strength Predictions Using Effective Flaw Concept.

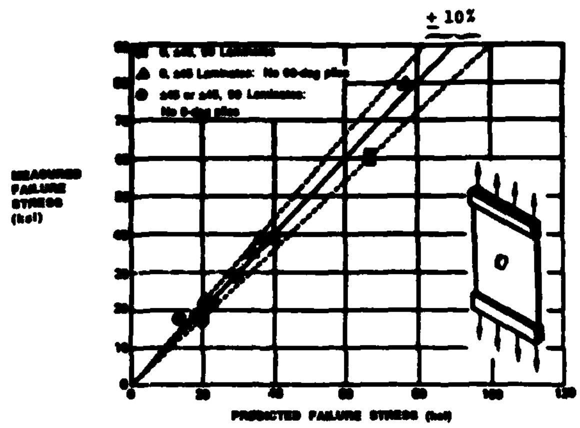


Figure 25. Correlation of Residual Tension Strength Prediction for 13 Laminates Using Effective Flaws.

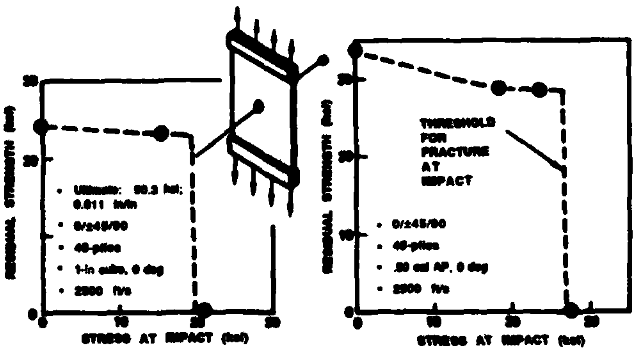


Figure 26. Effect of Stress at Impact on Residual Strength and Fracture at Impact (48 Ply 0/±45/90 GR/EP).

Laminates with only ±45 degree plies loaded in tension do not exhibit either of the above degradations due to the load when impacted by non-exploding projectiles, and will survive impact at loads up to the static residual strength level.

High-explosive 23 mm HEI projectiles can initiate failure at impact at applied tensile loads between one-third and one-half of the static residual strength of the laminate. This is shown in Figure 27 for contact detonation.

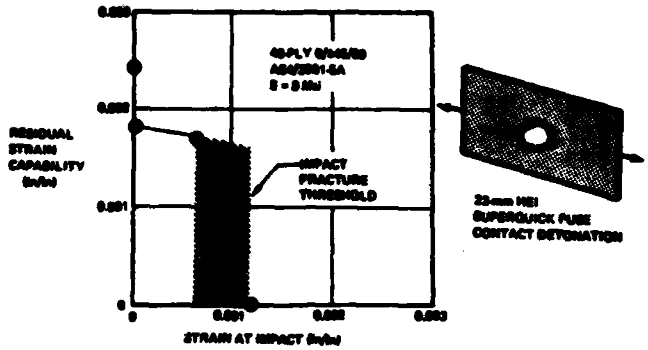


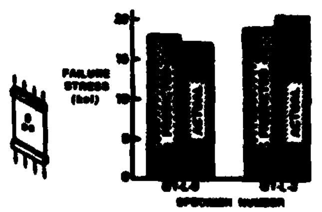
Figure 27. Effect of Load at Impact on Residual Strain Capability, 23-mm HEI Damage.

2.2.3 Analysis Verification — Warhead Arena Test

A warhead arena test was conducted to establish the response of composite structural elements and components to a fragmentation warhead, and to verify the damage response and residual strength predictive models developed from laboratory testing. In the test arrangement, composite panels were arranged in a 12 foot radius around the warhead. Figure 28 shows a comparison of predicted and measured damage sizes and residual strengths for two sections of 0/±45/90 40 ply panels. The good correlation is evident.

FRAGMENT TYPE	VISIBLE DAMAGE (in)		INTERNAL DAMAGE (in)	
	MEASURED	PREDICTED	MEASURED	PREDICTED
30-gr CUBE	0.8	0.9	1.1	1.2
30-gr CUBE	0.7	0.9	1.1	1.2
30-gr CUBE	0.8	0.8	1.1	1.7
[illegible] LENS	2.0	2.7	2.3	3.5
[illegible] LENS	2.4	2.2	2.7	2.6
INTERSTITIAL	2.2	2.1	2.2	2.6

(a) CORRELATION OF DAMAGE PREDICTIONS



(b) CORRELATION OF RESIDUAL STRENGTH PREDICTIONS

Figure 28. Damage and Residual Strength Analysis Methods were Validated by Warhead Arena Test Results.

2.3 REPAIRABILITY

The establishment of repair concepts for composite structures is of great important since ill-conceived repair concepts may result in the loss of both substantial weight savings and increased aircraft performance, which together have been the driving force for the development and use of composite aircraft structures. Another factor that has affected the development of repair concepts is the need for rapid repairs of battle damage in order to return aircraft to flight and sustain the sortie rate of the fleet in a short war.

Thus, it is becoming increasingly apparent that the design of repairable composite structure should be addressed early in the design stage of future aircraft. Structural analysis methods to be used for evaluating repair concepts range from large finite element programs to interactive computer programs. The finite element programs are most advantageously used at an aircraft depot or at the aircraft manufacturer's facility in the verification of the adequacy of a repair. Interactive computer programs are being developed for use in the field in establishing a suitable rapid repair of a battle-damaged aircraft.

Inasmuch as the damage repair that will be needed is influenced by the initial design, it is desirable that the following items be considered in establishing future aircraft designs and repair concepts for current aircraft. It is generally more difficult, with current composite repair concepts, to repair highly anisotropic structure than mildly anisotropic structure. Co-cured parts are more difficult to repair than conventional bolted metallic skin-stringer construction. Honeycomb construction poses particular repair problems (e.g. moisture-related problems, such as skins blowing off, may result from poor repair concepts). Metallic versus composite sub-structure, as well as the types of joints, may have a substantial impact on battle damage propagation (especially in the cases of hydrodynamic ram and blasts), the extent of the damage and the resulting repairs. Failures (e.g. delamination and fastener pull-throughs) of composite sub-structure when hydrodynamic ram and blast pressures are transferred from aircraft skins to the sub-structure, are generally of much more concern than failures of metallic sub-structure.

Numerous composite repair concepts have been investigated. For example, thick composite structures generally necessitate bolted repairs (too much material would have to be removed to obtain a satisfactory bonded repair), whereas bonded repairs are generally suitable for thinner structure. All of the concepts must, of necessity, address the following factors: (1) the equipment needed to ascertain the damage extent, (2) the repair criteria (e.g. aerodynamic smoothness, flutter, etc.) and the repair concept (e.g. bolted repair, external bonded patch, flush scarf bonded patch, etc.), and (3) the site selection for the repair (e.g. depot versus field repair).

All of the aforementioned issues are being addressed (e.g. Reference 2-3) by aircraft repair specialists and designers in the further development of the aircraft repair technology. The continual evolution of the repair technology is proceeding to ensure that the most satisfactory use of composites to reduce structural weight and the part count of military aircraft will be achieved.

REFERENCES FOR SECTION 2

2-1 J.G.Avery, "Design Manual for Impact Damage Tolerant Aircaft Structure," AGARDograph No.238, October 1981.

2-2 S.J.Bradley and J.G.Avery, "Design Guide for Survivable Structure in Combat Aircraft," Contract F33615-80-C-3411, AFWAL-TR-84-3015, April 1984.

2-3 L.G.Kelly, Composite Structure Repair, AGARD Report No.716, February 1984.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AG-238 (Addendum)	ISBN 92-835-0443-7	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	ADDENDUM TO "DESIGN MANUAL FOR IMPACT DAMAGE TOLERANT AIRCRAFT STRUCTURE"
7. Presented at	

8. Author(s)/Editor(s)	9. Date
M.J.Jacobson	March 1988

10. Author's/Editor's Address	11. Pages
Northrop Corporation Aircraft Division Hawthorne, CA 90250, USA	34

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Airframes	Vulnerability
Impact	Design
Damage	Manuals

14. Abstract

In 1981 the Structures and Materials Panel of AGARD published a Design Manual for Impact Damage Tolerant Aircraft Structures (AG 238). Since that date, there have been significant advances in design to resist impact damage. The Panel has therefore considered it appropriate to record this information in an addendum to the AGARDograph.

This Addendum has been prepared at the request of the USAF for presentation to the Structures and Materials Panel of AGARD.

AGARDograph No.238 (Addendum)
Advisory Group for Aerospace Research and Development, NATO
ADDENDUM TO DESIGN MANUAL FOR IMPACT DAMAGE TOLERANT AIRCRAFT STRUCTURE
by M.J.Jacobson
Published March 1988
34 pages

In 1981 the Structures and Materials Panel of AGARD published a Design Manual for Impact Damage Tolerant Aircraft Structures (AG 238). Since that date, there have been significant advances in design to resist impact damage. The Panel has therefore considered it appropriate to record this information in an addendum to the AGARDograph.

P.T.O

AGARD-AG-238
(Addendum)

Airframes
Impact
Damage
Vulnerability
Design
Manuals

AGARDograph No.238 (Addendum)
Advisory Group for Aerospace Research and Development, NATO
ADDENDUM TO DESIGN MANUAL FOR IMPACT DAMAGE TOLERANT AIRCRAFT STRUCTURE
by M.J.Jacobson
Published March 1988
34 pages

In 1981 the Structures and Materials Panel of AGARD published a Design Manual for Impact Damage Tolerant Aircraft Structures (AG 238). Since that date, there have been significant advances in design to resist impact damage. The Panel has therefore considered it appropriate to record this information in an addendum to the AGARDograph.

P.T.O

AGARD-AG-238
(Addendum)

Airframes
Impact
Damage
Vulnerability
Design
Manuals

AGARDograph No.238 (Addendum)
Advisory Group for Aerospace Research and Development, NATO
ADDENDUM TO DESIGN MANUAL FOR IMPACT DAMAGE TOLERANT AIRCRAFT STRUCTURE
by M.J.Jacobson
Published March 1988
34 pages

In 1981 the Structures and Materials Panel of AGARD published a Design Manual for Impact Damage Tolerant Aircraft Structures (AG 238). Since that date, there have been significant advances in design to resist impact damage. The Panel has therefore considered it appropriate to record this information in an addendum to the AGARDograph.

P.T.O

AGARD-AG-238
(Addendum)

Airframes
Impact
Damage
Vulnerability
Design
Manuals

AGARDograph No.238 (Addendum)
Advisory Group for Aerospace Research and Development, NATO
ADDENDUM TO DESIGN MANUAL FOR IMPACT DAMAGE TOLERANT AIRCRAFT STRUCTURE
by M.J.Jacobson
Published March 1988
34 pages

In 1981 the Structures and Materials Panel of AGARD published a Design Manual for Impact Damage Tolerant Aircraft Structures (AG 238). Since that date, there have been significant advances in design to resist impact damage. The Panel has therefore considered it appropriate to record this information in an addendum to the AGARDograph.

P.T.O

AGARD-AG-238
(Addendum)

Airframes
Impact
Damage
Vulnerability
Design
Manuals

This Addendum has been prepared at the request of the USAF for presentation to the Structures and Materials Panel of AGARD.

ISBN 92-835-0443-7

This Addendum has been prepared at the request of the USAF for presentation to the Structures and Materials Panel of AGARD.

ISBN 92-835-0443-7

This Addendum has been prepared at the request of the USAF for presentation to the Structures and Materials Panel of AGARD.

ISBN 92-835-0443-7

This Addendum has been prepared at the request of the USAF for presentation to the Structures and Materials Panel of AGARD.

ISBN 92-835-0443-7