REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-R-729	ISBN 92-835-1517-X	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title

IMPACT DAMAGE TO COMPOSITE STRUCTURES

7. Presented at

8. Author(s)/Editor(s)

Various

9. Date

February 1986

10. Author's/Editor's Address

Various

11. Pages

40

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

Composite materials
Composite structures
Structural analysis
Mechanical properties
Impact strength
Damage

14. Abstract

The Structures and Materials Panel has instituted a Sub-Committee to study the Survivability of Battle-Damaged Composite Structures. This publication includes three papers heard by the Sub-Committee; they survey various aspects of the topic including theoretical analysis and experimentally simulated ballistic damage of test specimens.

This Report was sponsored by the Structures and Materials Panel of AGARD.

AGARD-R-729

AGARD-R-729

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT, Paris.

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD REPORT No.729

Impact Damage to Composite Structures

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY
ON BACK COVER

AGARD-R-729

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.729

IMPACT DAMAGE TO COMPOSITE STRUCTURES

This Report was sponsored by the Structures and Materials Panel of AGARD.

THE MISSION OF AGARD

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:

— Exchanging of scientific and technical information;

— 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;

— 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);

— 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;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

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.

The content of this publication has been reproduced
directly from material supplied by AGARD or the authors.

Published February 1986

ISBN 92-835-1517-X

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

CONTENTS

Improvement of Battle Damage Tolerance for Composite Structures

by
G. Kagerbauer, D. Weisgerber, O. Sensburg
Messerschmitt-Bölkow-Blohm GmbH
Helicopter and Aircraft Division
8000 München 80, P.O. Box 801160

Summary

The impact of ballistic penetrators in fuel filled tanks generates high dynamic pressure loading. This damage process is generally referred to as hydraulic ram.
Hydraulic ram in aircraft fuel tanks results in large damage of structural components, which in turn can lead to fuel loss or ingestion into engines, fire and explosion.
To determine the effect of hydraulic ram to an integral fuselage fuel tank with carbon/epoxy skin, a firing programme was established. Plane carbon/epoxy plates, bolted to an impact box, were impacted with single cuboid fragments. Different shock-absorbing materials to reduce hydraulic ram pressures on the impact plates, respectively to prevent propagation of the shock wave were investigated.
Multiple fragment impact on a fuel tank can result in extensive structural damage by the combined damage effects of fragments and the superposition of hydraulic ram pressures. Multiple fragments were projected against simulated fuel tank sections with carbon/epoxy skins of the cocured frame and sandwich design at a hit density of 25 fragments per square meter.

1. Introduction

Military aircraft have to operate in a man-made hostile environment created by small-arms weapons, anti-aircraft artillery and missile warheads, and a maximum of survivability is essential for successful mission performance. The survivability of an aircraft can be enhanced by reduced susceptibility and reduced vulnerability.

Susceptibility, i.e. the inability of an aircraft to avoid the hostile environment, is mainly affected by the aircraft's design, tactics and survivability equipment. Susceptibility can be reduced by the design to small size, high performance, good manoeuverability, or reduced signature, e.g. smokeless engines or reduced radar signature. Tactics should minimize the exposure of the aircraft to the threat and can include the capability for terrain masking for example. Susceptibility can also be reduced by the use of decoys, e.g. chaff and flares, electronic counter measures or active threat suppression by anti-radiation missiles.

The inability of an aircraft to withstand the damage mechanisms of the threat is considered as vulnerability. A hit to the aircraft should not result in a loss due to instant failure, but in a graceful degradation of the aircraft's structure and components. Vulnerability is mainly determined by design and can be reduced by component redundancy, component location or shielding, structural design to withstand, tolerate or control damage, and damage suppression, e.g. against fire and explosion.

2. Fuel tank vulnerability

Battle damage records of the conflicts in the past show that about fifty percent of aircraft losses after ballistic impact are contributed by the fuel system. The most important kinds of fuel tank vulnerability are:

- catastrophic fuel loss resulting in a significant reduction of available fuel
- fire and explosion inside the tank by ignition of the fuel-air-mixture in the ullage
- hydraulic ram, which is caused by the intense pressure waves generated by ballistic impact into filled tanks
- exterior fuel fire due to fuel spillage outside the fuel tank wall and subsequent ignition by incendiary particles, impact flash or hot surfaces
- fuel ingestion into air intakes and engines resulting in engine damage or explosion
- fire and explosions in void spaces or dry bays by fuel leakage and subsequent ignition

The fuel storage and distribution system generally represents the largest subsystem of an aircraft and is vulnerable to all damage mechanisms caused by the encountered threats. Nevertheless a significant reduction of fuel tank vulnerability can be achieved by proper design. Appropriate structural design and location of fuel tanks, i.e. compartmentation, reduction of vulnerable area or shielding by less critical components should be applied to avoid catastrophic fuel loss. Fire and explosion can be suppressed by installation of foams, inerting gas in the ullage or active/passive fire suppression systems. The use of self-sealing or bladder tanks prevents or minimizes fuel leakage and reduces the probability of secondary fires and fuel ingestion. The fuel system should also be designed to tolerate hydraulic ram.

3. Hydraulic ram

The dynamic pressure generated by the impact of projectiles or fragments into fluid filled tanks in generally referred to as hydraulic ram. The damage process is considered to consist of three phases, the shock phase, the drag phase and the cavity phase.

When the projectile, after penetration of the tank wall impacts the fluid, energy is transferred to the fluid and a strong hemispherical shock wave is formed. This causes a high dynamic pressure loading on the entry wall around the impact hole, which may cause extensive damage to the entry wall.
As the penetrator traverses the fluid its momentum is transferred to the fluid as it is decelerated. The fluid is displaced from the flight path of the projectile and an outward directed pressure field is generated. The peak pressures in the drag phase are much lower than in the shock phase, but the duration of the pressure pulse is considerably longer. The radial velocities imparted to the fluid during the drag phase lead to the formation of a cylindrical cavity behind the projectile, which is filled by air entering through the impact hole and vapor from the boundary of the cavity. As the fluid seeks to regain its undisturbed condition one or more oscillating vapor bubbles are formed which generate additional pressure pulses. These cavity oscillations are called the cavity phase.

The hydraulic ram loading on the tank structure can cause large damage, very much larger than that caused by the penetrator, and can also be transmitted through the fuel lines with subsequent failure or damage to the fuel supply system.

4. Threat characterisation

The conventional anti-aircraft threats can be grouped in four types:

- non-explosive projectiles (penetrators)
  fired from small arms and machine guns
- explosive projectiles
  fired from anti-aircraft artillery or aircraft guns
- warheads of missiles
  with fragments, blast or interaction of fragments and blast
- directed energy devices
  like laser or particle beam weapons.

For a fighter aircraft with mainly intercept missions the detonation of missile warheads was considered the threat most likely to encounter. This is based on the mission requirements and the premises that guided missiles in general are more lethal than gun projectiles and that an increasing number of anti aircraft missiles are available in defense inventories.

The majority of anti aircraft guided weapons are fitted with blast/fragmentation warheads of the preformed fragment or controlled fragmentation type and are usually proximity fuzed. The fragments have a mass of 2 to 7 grams and are generally ejected in beams with fairly well defined boundaries, dependent on warhead design. The shape of the fragments can be cuboid, diamond or random and their initial velocity ranges from 1500 to 3000 m/s. Fragment hit densities and the magnitude of the blast pressure are determined by the shape of the warhead, the size of the high explosive charge and the distance to the aircraft on detonation. The blast wave generated by the explosion of the warhead is usually the last damage mechanism to reach a target and enhances the damage caused by fragments.

5. Battle damage concept for a fuselage integral tank

A battle damage concept, Figure 1, for a fuselage integral fuel tank with carbon/epoxy skin, currently investigated, is based on the following features:

- compartmentation of fuel tank
- controlled damage and fracture of skin
- redundant load path

The centre fuselage fuel tank is divided by aluminium bulkheads and frames into several sections in longitudinal direction. Each section is designed to form three fuel compartments by the aluminium shear walls, air intake and tank floor panels. The carbon/epoxy skin with cocured frames and longerons is double riveted to the bulkheads, shear walls and tank floor. If a fuel compartment is impacted by a penetrator the carbon/epoxy skin on one side shall fracture at least at the rivets to reduce intense hydraulic ram pressures on internal structure. After failure of the load carrying skin a redundant load path by the tank shear walls, air intake and tank floor is provided.
The outer fuel compartments also serve as a protection system for the air intake and inner fuel compartments using the excellent capability of fuel to decelerate penetrators.
It is accepted, that part of the fuel is lost which may result in mission abort, but prevents loss of the aircraft.

6. Investigation of battle damage tolerance

To evaluate the damage mechanisms of fragment impact and hydraulic ram on the carbon/epoxy skin of a fuel tank a firing programme was carried out. The aim of the tests was to determine the damage size in composite material and the magnitude of hydraulic ram presures. Furthermore means to reduce the hydraulic ram pressures and damage containment features should be investigated.

6.1 Single fragment tests

Impact box

For single fragment tests an impact box made of 10 mm steel and 400 X 400 X 500 mm in size was used. On the front face of the box with a cut-out of 160 X 165 mm impact plates measuring 240 X 245 mm were fastened with 28 equally spaced 6 mm Hi Loks. To allow for the lower stiffness of a comparable aluminium structure the inner walls of the impact box were completely covered with 18 mm thick Rohacell foam. Through an orifice on top, the box was filled with water and, for some tests, with JP 4 fuel. The impact box is shown in Figure 2.

Impact plates

The impact plates, Figure 2, were flat unstiffened panels 240 x 245 x 4.25 mm in size. They were made of 34 plies of carbon/epoxy prepreg Fibredux 914C/T300 with about 6% plies in 0°-, 24% in 90°- and 70% in ± 45° -direction. For comparison 3 mm thick aluminium specimens made of 3.1364.4 (2024T3) were impacted.

Shock-absorbing material

To reduce the magnitude of hydraulic ram pressures on the impact plates, several shock absorbing materials were evaluated. For some tests air-buffer foil, Figure 3, with different size of air-buffers, and a rigid closed cell foam of 18 mm thickness was bonded to the back side of the impact plates. A sandwich specimen was manufactured with 6 mm NOMEX core bonded with 6 plies of carbon/epoxy fabric to the impact plate. Some tests were carried out with the impact box completely filled with a fibrous explosion suppression foam to prevent propagation of the hydraulic ram pressure front.

Fragment impact parameters

Cuboid fragments made of mild steel with a mass of 3.5 grams and 5.0 grams were fired from a 20 mm gun normal to the impact plate at a distance of 5 m. The test setup is shown in Figures 4 and 5. The impact velocity of the fragments was determined by two light screens, Figure 6, 665 mm apart and ranged from 540 to 1670 m/s.

Hydraulic ram pressure recording

Three lithium niobate pressure gauges were installed in the side wall of the impact box at distances of 212, 316 and 452 mm from the front face and 80 mm above the bottom, Figure 7. The pressure gauges protruded about 60 mm into the liquid. The signals from the pressure gauges were amplified by transient recorders and the pressure history was stored on a computer.

Impact test recording

The fragment impact on the impact plates was recorded by a LOCAM camera at 500 frames/sec and a HYCAM camera at 8000 frames/sec. The cameras and the pressure recording were triggered when the fragment hit a contact foil 300 mm in front of the impact box.

Damage assessment

The extent of damage in the impacted specimens was determined by ultrasonic and thermographic inspection techniques and photomicrographs at three different locations from the impact hole. In addition compression specimens were cut out of some impact plates.

6.2 Results of single fragment tests

A total of twenty single fragment firings were performed against carbon/epoxy and aluminium impact plates. Figure 8 tables some of the impact tests with fragments of 3.5 grams against the water filled impact box. The damage on the impacted carbon/epoxy plates is shown in Figures 9 to 32.
A fragment of 3.5 grams impacting at a velocity of 541 m/s causes an impact hole of about 15 mm, Figures 9 to 11. On the entrance side the first ply is peeled off for about 50 mm. Non destructive inspection showed a 15 mm circular delamination around the impact hole.
At a fragment velocity of 1027 m/s the impact hole is about 15 mm and the first plies on the entrance side are delaminated and cracked, Figures 12 to 14. Ultrasonic and thermographic inspection showed a circular delamination of about 40 mm in upper plies around

the impact hole and nearly complete delamination of inner plies.
Figures 15 to 17 show the damage after impact of a fragment with 1666 m/s. The impact plate was heavily damaged and ruptured in transverse direction. Hydraulic ram pressure resulted in bolt head pull through and complete delamination of the impact plate.

To reduce the damage on the impact plates by hydraulic ram pressures different shock-absorbing material was tested. Different sized air buffer foil and a rigid closed cell foam was bonded to the back side of the impact plates. The damage to the impact plate with 30 mm air buffer foil is shown in Figures 18 to 20. The fragment at 1528 m/s caused a circular impact hole of 12 mm. On the entrance side, the upper plies are delaminated on a length of 50 mm and 20 mm in width. On the side of the impact plate delaminations starting at the bolts were found. The damage inflicted by a fragment at 1647 m/s on an impact plate with 18 mm rigid closed cell foam bonded to the back side is shown in Figures 21 to 23. The impact hole has a diameter of 12 mm. Delaminations of first plies on the entrance side are about 30 mm long and 20 mm wide. A circular 40 mm delamination around the impact hole was detected by ultrasonic and thermographic inspection.
A sandwich impact plate with a Nomex core and six plies of graphite/epoxy fabric as outer skin was impacted by a fragment at a velocity of 1643 m/s. The impact hole had a diameter of 15 mm, Figures 24 to 26, and delaminations of first plies occurred at the entrance side. The outer skin and the honeycomb core were nearly completely destroyed. Delaminations starting at some bolts were found on one side of the impact plate. A comparison of all tests at fragment velocities of about 1650 m/s shows that damage size on the impact plates can be limited by the use of shock-absorbing material. Best results were achieved with close cell foam and sandwich type specimens. Hydraulic pressures inside the impact box were not affected by the use of shock-absorbing material and peak pressures recorded were about 35 MPa at a distance of 212 mm from the impact plate.

To prevent the hydraulic ram pressure from propagation the impact box was completely filled with a fibrous explosion suppression foam. The damage on an unprotected impact plate, hit by a fragment at a velocity of 1653 m/s, can be seen in Figures 27 to 29. Hydraulic ram pressure caused bolt head pull through resulting in subsequent rupture of the impact plate. The impact hole is about 50 mm in size. The sides of the impact plate showed many large delaminations.
In a further test with the foam filled impact box 30 mm air buffer foil was bonded to the impact plate. The damage caused by a fragment at 1625 m/s is shown in Figures 30 to 32. The impact hole was about 13 mm and delaminations of first plies on the entrance side were about 80 mm long and 40 mm wide. The side of the impact plate showed some delaminations starting at the bolts.
Hydraulic ram pressure inside the impact box was largely reduced by the explosion suppression foam. Peak pressures measured ranged from about 11 MPa for the umprotected to 20 MPa for the air buffer protected impact plate. The propagation of the hydraulic ram pressure wave along the fragment flight path was reduced considerably.

6.3 Multiple fragment tests

Multiple fragment impact on a fuel tank section can result in extensive damage due to the interaction of the individual damage mechanism of each fragment and the superposition of hydraulic ram pressure. Additional structural damage can be caused by fragments which impact at a cavity and are not decelerated by the fuel. To evaluate the damage by multiple fragment hits a test programme was established.

Fuel tank section

A simulated fuel tank structure 1000 mm wide and 500 mm high was manufactured of 5 mm thick steel, Figure 33. The longeron joints were made of aluminium and were representative of a real fuel tank structure. A carbon/epoxy skin with cocured frames and longerons, Figure 34, and a carbon/epoxy sandwich skin with 14 mm Nomex core and cocured longerons were riveted to the steel tank structure. The skins were made of carbon/epoxy prepreg Fibredux 914C/T300 and had a thickness of 10 mm at the longerons and of 3.5 mm in the skin area for the cocured frame design, respectively of 1.6 mm for the outer and inner skin of the sandwich design.

Fragment projecting device

A fragment projecting device, Figure 35, was used for firing multiple fragments against the simulated fuel tank section. The fragment projector was made of a welded steel casing of interval dimensions 70 X 70 mm and 118 mm in length. The casing was filled with 750 grams high explosive, which was ignited by a booster. The front face of the fragment projector was of spherical shape and consisted of nine rows, each of nine fragments, adding up to a total of 81 fragments. The fragments were made of mild steel and had a mass of 3.5 grams.

Fragment impact parameters

The velocity of the fragments and the fragment hit density was determined by firing the fragment projector against a target plate 3.5 m away. Velocity was measured by means of two x-ray flashes at distances of 1100 mm and 2100 mm from the fragment projector.

Velocity ranged from 1600 m/s for the fragments in the middle to 1490 m/s for the outer ones. The fragment hit density was determined from the fragment impacts on the target plate and was about 25 fragments per square meter at a stand-off distance of 5.0 m.

Test setup

The fragment projector was fired at a distance of 5 m against the water filled fuel tank section. To determine the fragment hit density, a steel wall, 2 m X 2 m in size, was erected behind the impact section. Fragment impact was recorded by two Hycan cameras running at 8000 frames/sec. Twelve lithium niobate pressure gauges were installed in the fuel tank section, four in each side wall and four in the rear wall, to record hydraulic ram pressures. A sketch of the test setup is shown in Figure 36.

6.4 Results of multiple fragment impact tests

The damage to the carbon/epoxy skin with cocured frames caused by the impact of 11 fragments in the fluid is shown in Figure 37. Hydraulic ram pressure caused transverse rupture of the composite skin and frames and parts of skin were blown off. At the side walls the skin failed by bolt head pull through and rupture. At the longerons controlled fracture of the skin at the upper row of rivets occurred, the longeron itself retained its load carrying capability.

To absorb hydraulic ram pressures and to reduce the damage to the composite skin, air buffer foil was bonded to the skin between the frames. The damage resulting from the impact of 11 fragments into the liquid is shown in Figure 38. Hydraulic ram pressure caused traverse rupture of the skin and bolt head pull through and rupture at the side walls. Although fragment impact conditions and the distribution of hits were about the same, the damage to the protected skin was considerably smaller.

The impact of 10 fragments to a fuel tank section with sandwich skin, Figure 39, resulted in nearly complete destruction within the honeycomb core area. The skin panel shows multiple ruptures in traverse direction and large parts of the skin were blown off. At the side walls the skin failed at the interface of the honeycomb core and the solid laminate. The longerons remained undamaged.

7. Conclusion

Single fragment impact on carbon/epoxy plates results in a severe damage by hydraulic ram pressure. The damage size can be limited if shock-absorbing material is bonded to the back side of the impact plates. The use of fibrous explosion suppression foam prevents the propagation of hydraulic ram pressure and can help to protect the surrounding structure.

Multiple fragment impact on a simulated fuel tank section causes rupture and disintegration of the carbon/epoxy skin by the superposition of hydraulic ram pressure. The battle damage concept investigated allows for the fracture of the carbon/epoxy skin at the longerons to reduce hydraulic ram pressure to internal structure. The tests demonstrated, that fracture of the skin can be stopped at least at the rivets of the longerons and that longerons retained load carrying capability.

Acknowledgements

The authors gratefully acknowledge the German Ministery of Defence for the financial support to the programme and Dr. M. Held and Mr. Gehrsitz for their help in the definition of the test programme, and the test work at the MBB facilities at Schrobenhausen. The programme was conducted by Dr. W. Geier, R. Keraus and O. Bartsch.

References:

D. Atkinson, R. E. Ball, J. Sebolka, J. J. Morrow
Short Course in Aircraft Combat Survivability
Naval Postgraduate School
5.-8. March 1985 Oberammergau

O. Bartsch, G. Kagerbauer
Voruntersuchungen über das "Battle Damage"-Verhalten von Integraltanks aus CFK
MBB/FE214/S/TN/64 22.11.1983

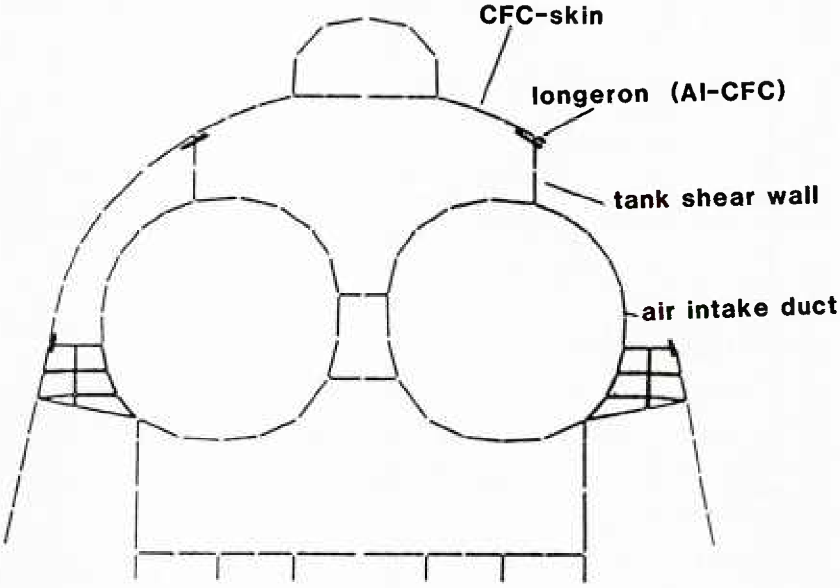
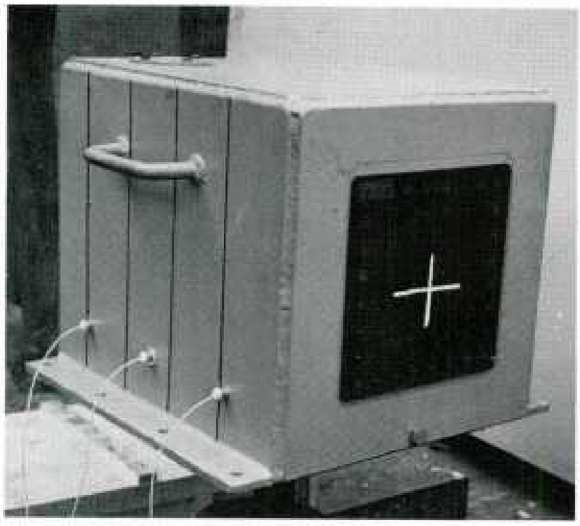


Figure 1: Battle damage concept for a fuselage integral tank



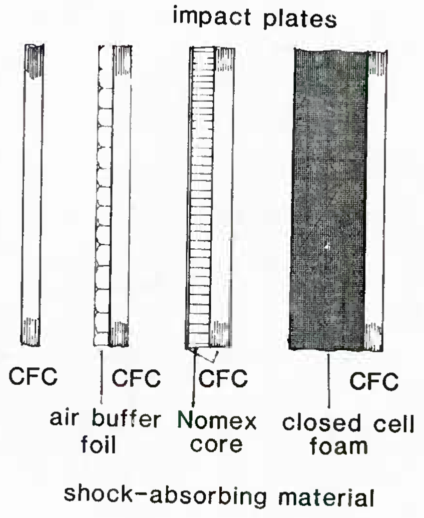


Figure 2: Impact box and impact plates with shock-absorbing material

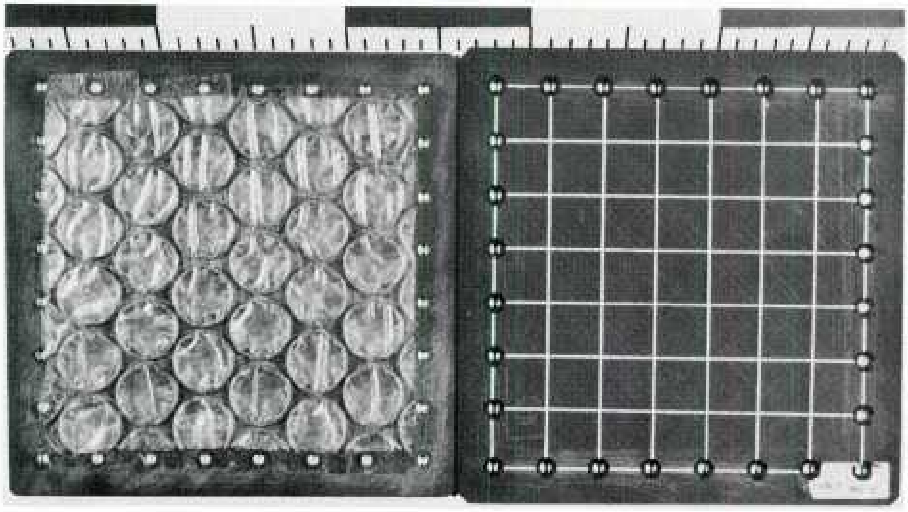


Figure 3: Impact plate with bonded air buffer foil

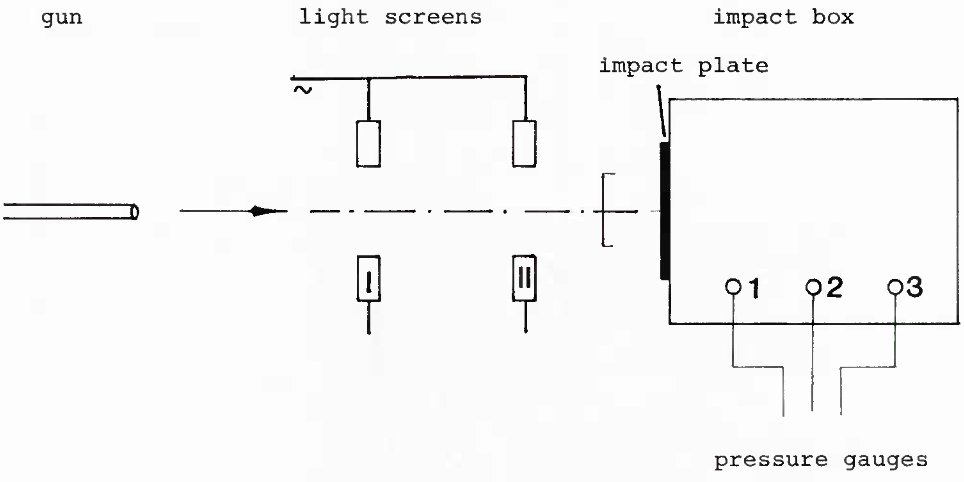


Figure 4: Impact test setup

Figure 5: Impact test setup

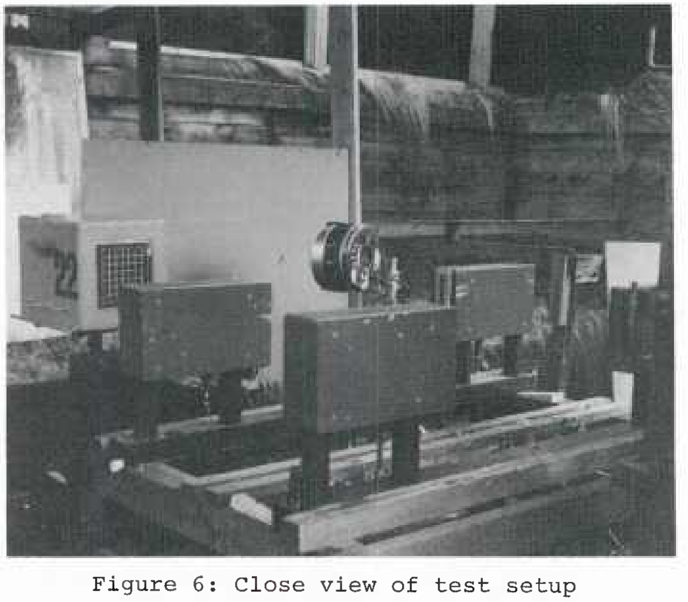


Figure 6: Close view of test setup

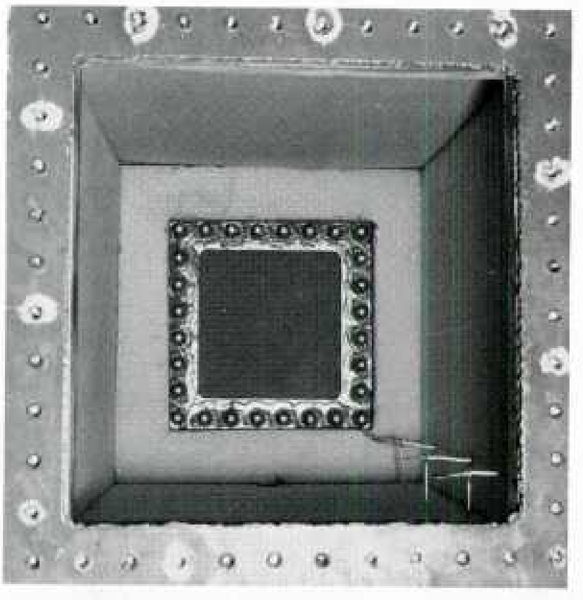


Figure 7: Installation of pressure gauges

Test-Nr.	fragment		shock-absorbing material
	mass (g)	velocity (m/s)	
15380	3.5	541	-
15381	3.5	1027	-
15382	3.5	1666	-
15387	3.5	1528	air buffer foil bonded to impact plate
15538	3.5	1647	18 mm closed cell foam bonded to impact plate
15537	3.5	1643	Nomex core sandwich bonded to impact plate
15388	3.5	1653	impact box completely filled with fibrous foam
15530	3.5	1625	impact box completely filled with fibrous foam, air buffer foil bonded to impact plate

Figure 8: Single fragment impact parameters

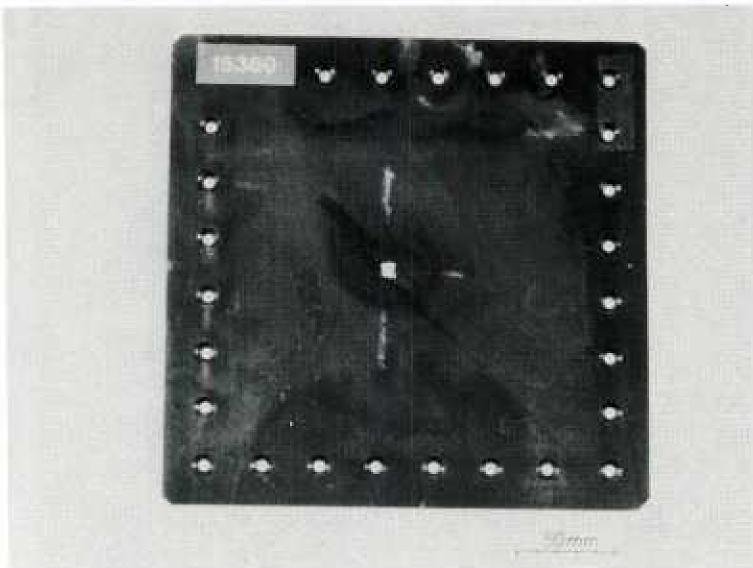


Figure 9: Ballistic impact damage at entrance side (15380)
m = 3.5g, v = 541 m/s

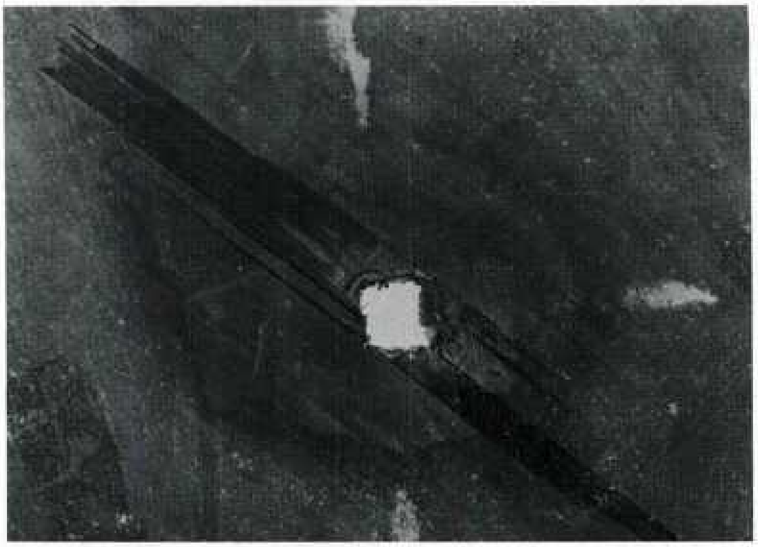


Figure 10: Entrance side (15380)

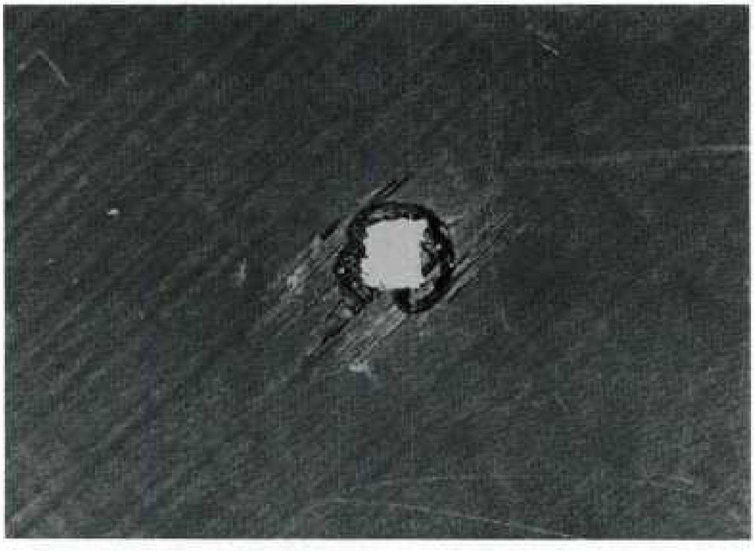


Figure 11: Exit side (15380)

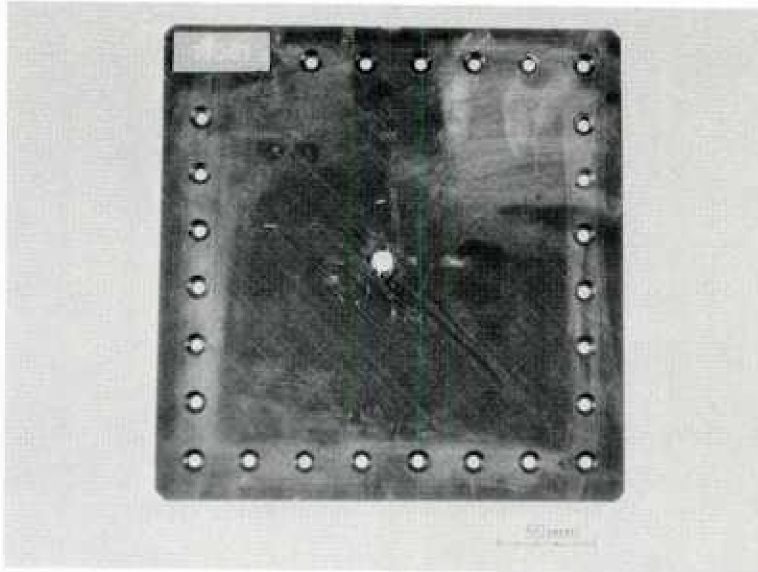


Figure 12: Ballistic impact damage at entrance side (15381)
m = 3.5g, v = 1027 m/s

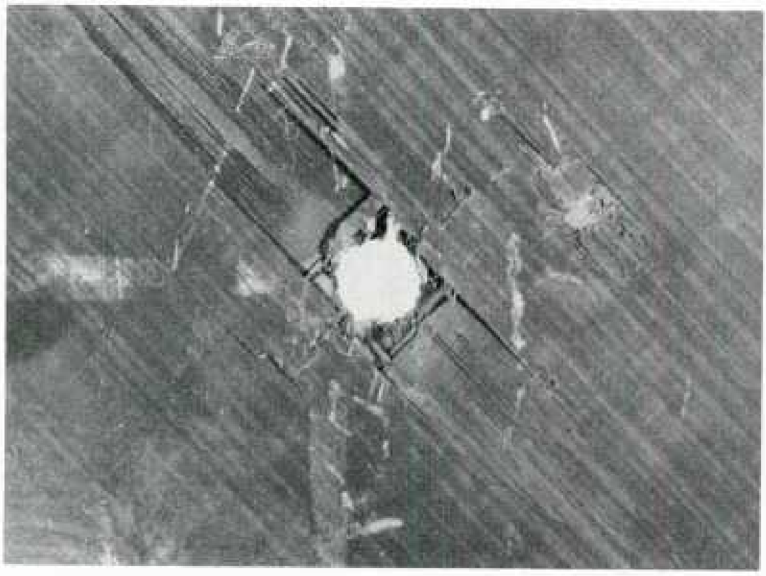


Figure 13: Entrance side (15381)

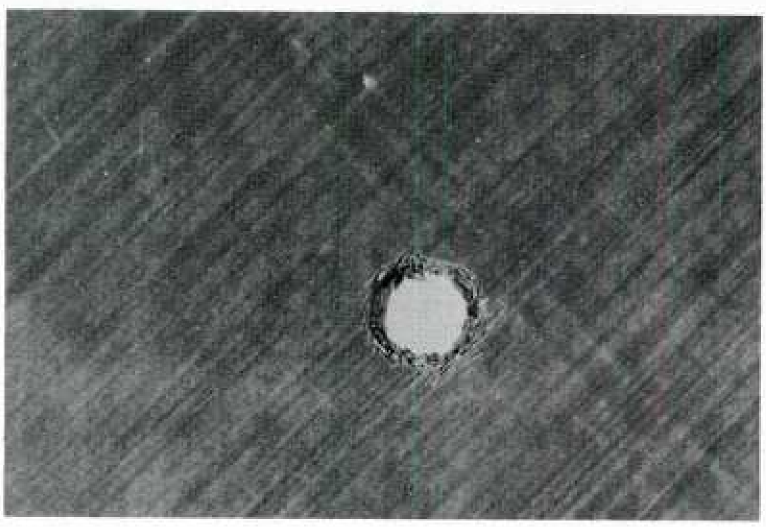


Figure 14: Exit side (15381)

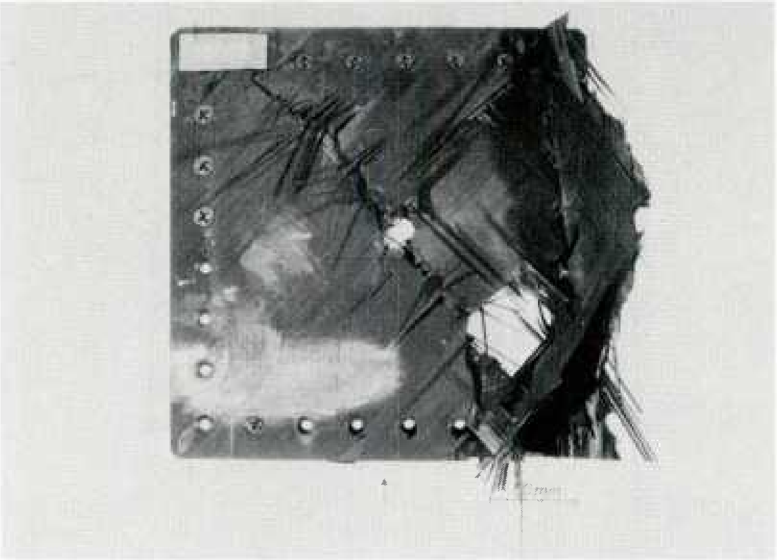


Figure 15: Ballistic impact damage at entrance side (15382)
m =3.5g, v = 1666 m/s

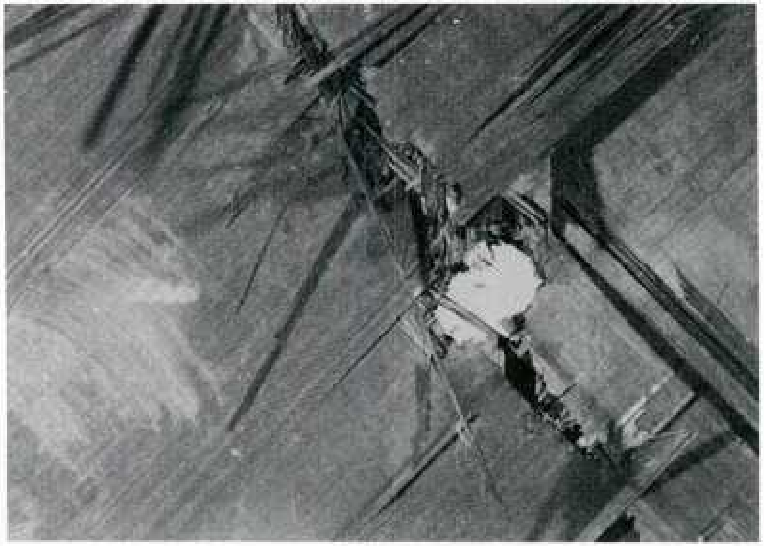


Figure 16: Entrance side (15382)

Figure 17: Exit side (15382)

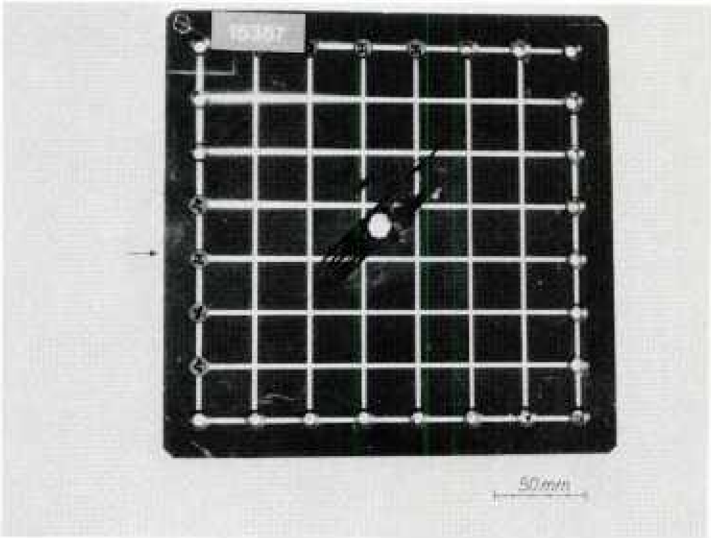


Figure 18: Ballistic impact damage at entrance side (15387)
m = 3.5g, v =1528 m/s, air buffer foil

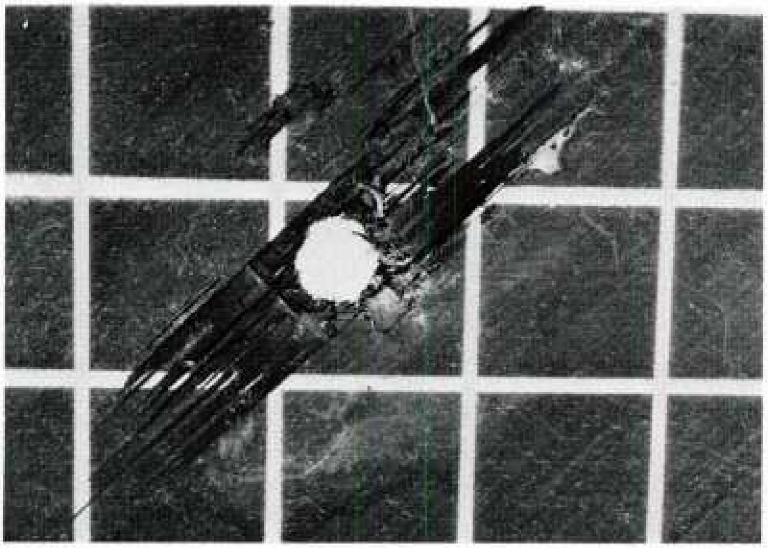


Figure 19: Entrance side (15387)

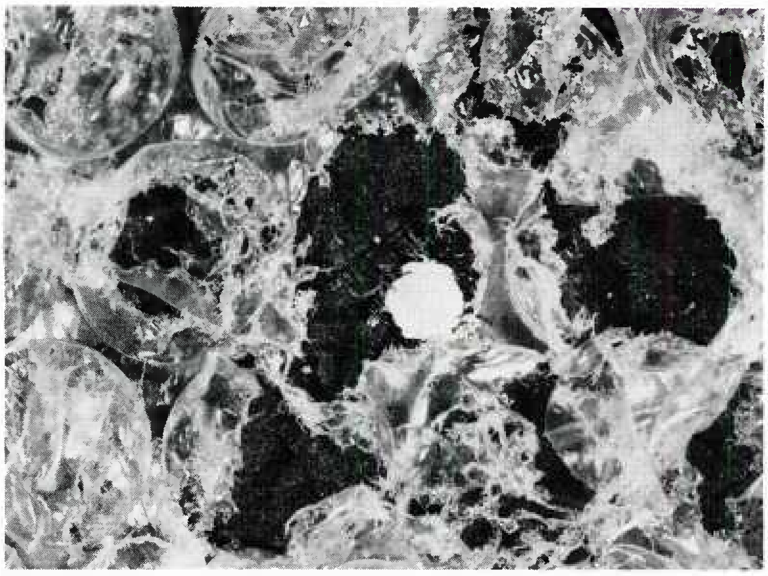


Figure 20: Exit side (15387)

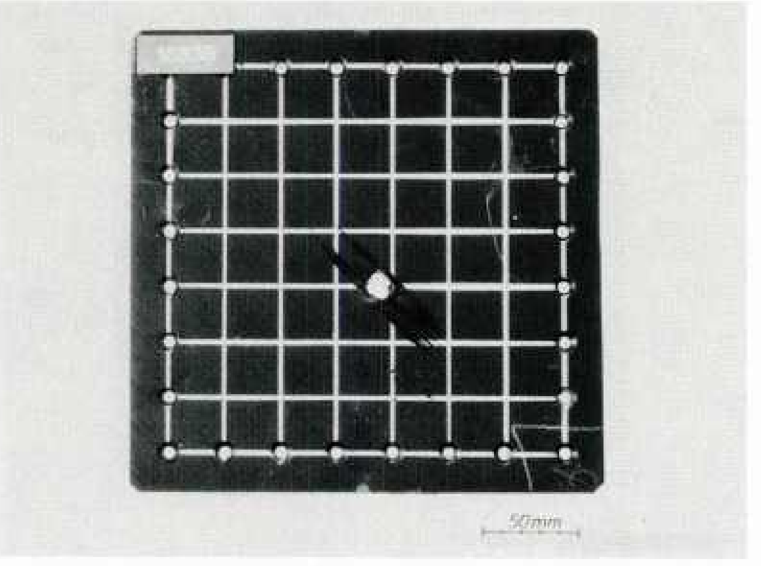


Figure 21: Ballistic impact damage at entrance side (15538)
m = 3.5g, v = 1643 m/s, bonded closed cell foam

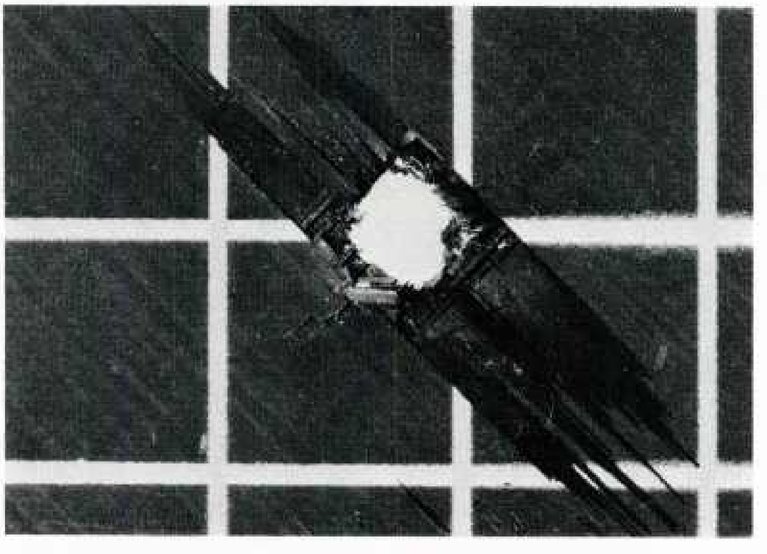


Figure 22: Entrance side (15538)

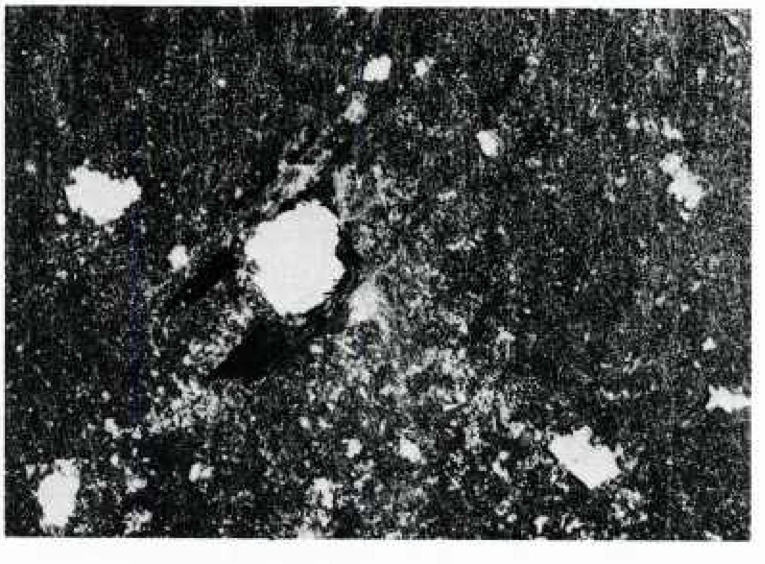


Figure 23: Exit side (15538)

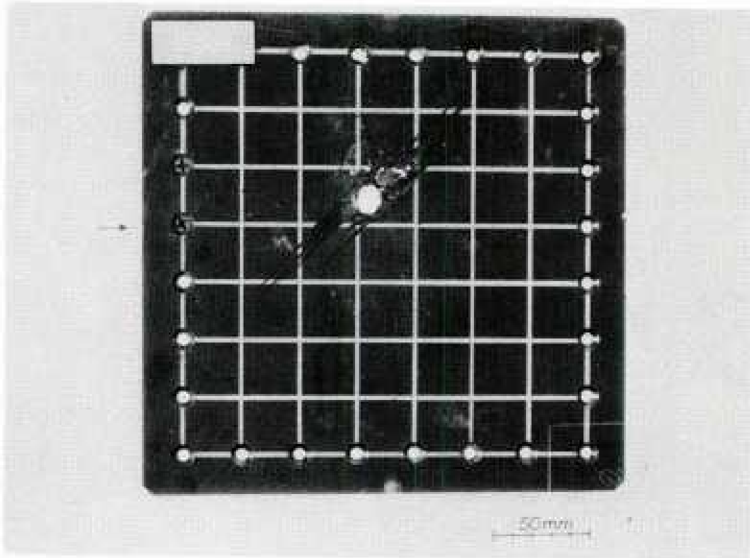


Figure 24: Ballistic impact damage at entrance side (15537)
m = 3.5g, v = 1643 m/s, bonded sandwich

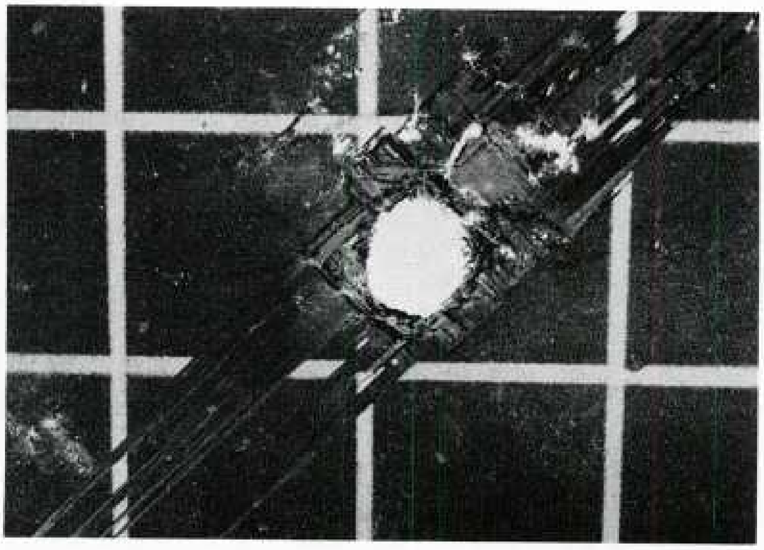


Figure 25: Entrance side (15537)

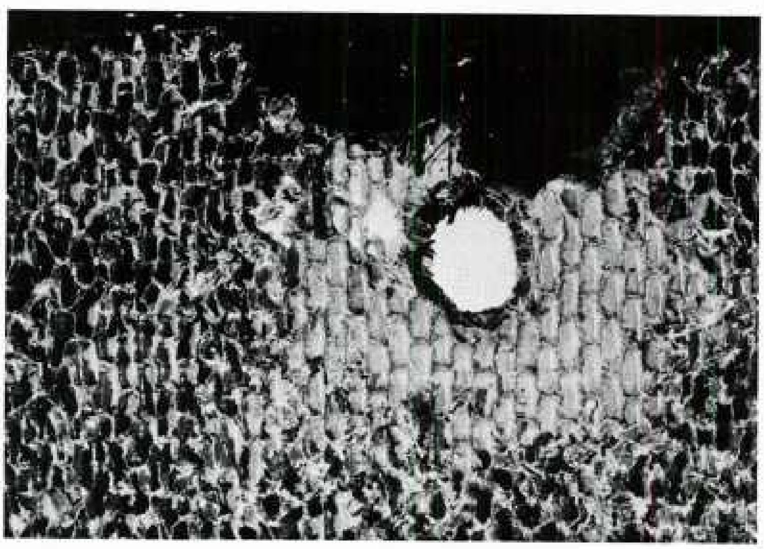


Figure 26: Exit side (15537)

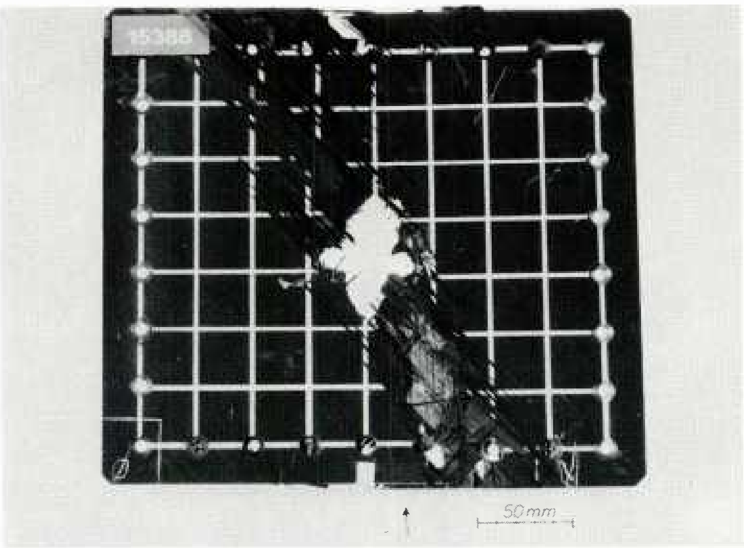


Figure 27: Ballistic impact damage at entrance side (15388)
m = 3.5g, v = 1653 m/s, box filled with fibrous foam

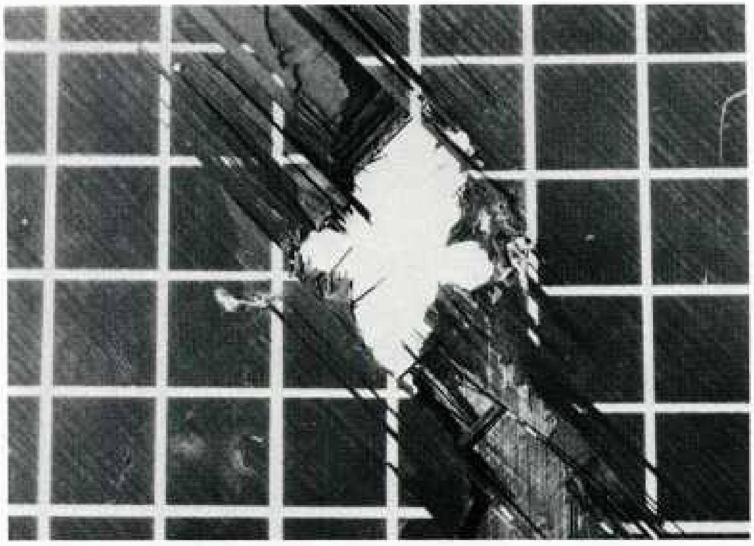


Figure 28: Entrance side (15388)

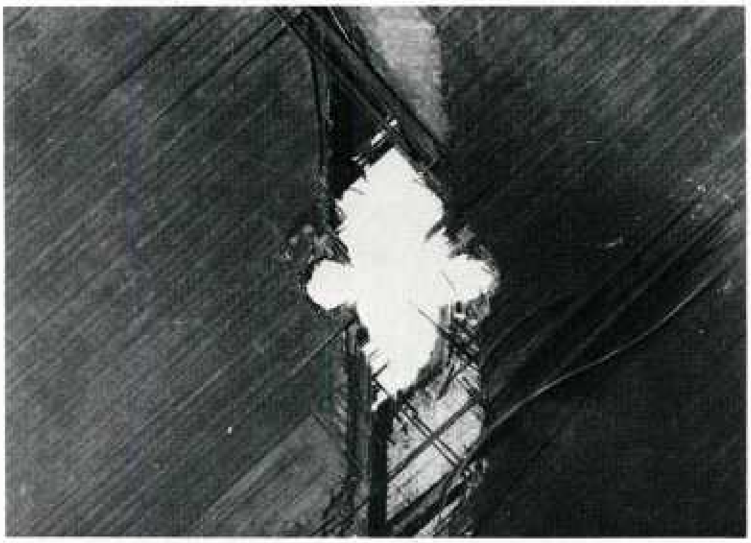


Figure 29: Exit side (15388)

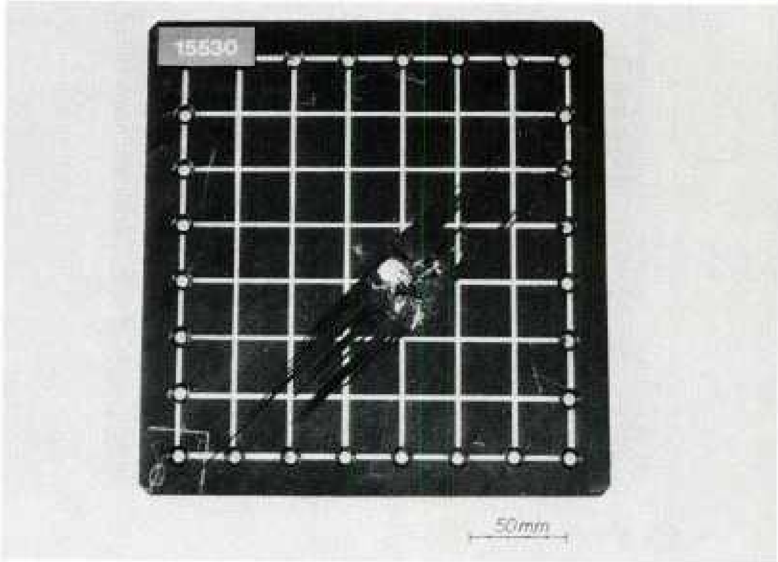


Figure 30: Ballistic impact damage at entrance side (15530)
m = 3.5g, v = 1625 m/s, box filled with fibrous foam,
air buffer foil bonded to impact plate

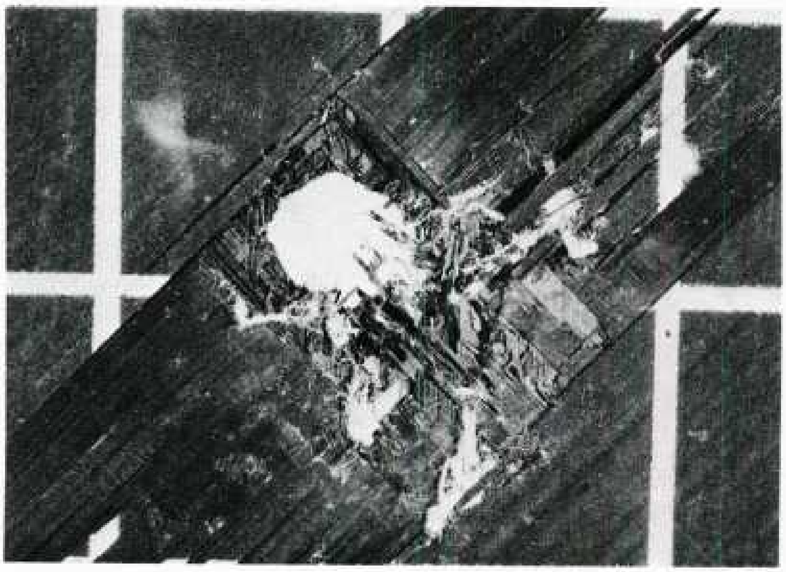


Figure 31: Entrance side (15530)

Figure 32: Exit side (15530)

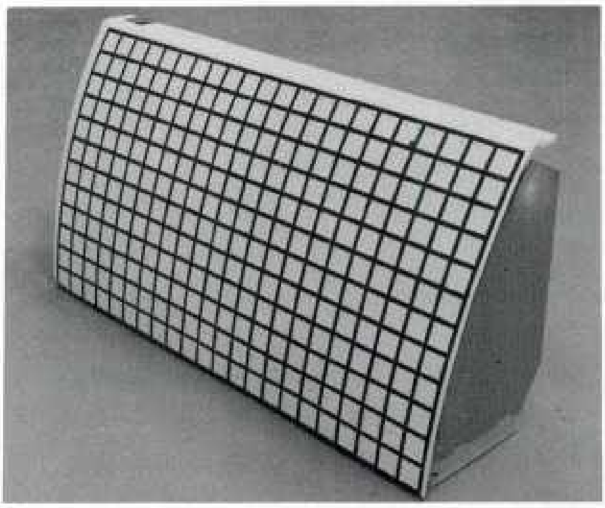


Figure 33: Fuel tank section

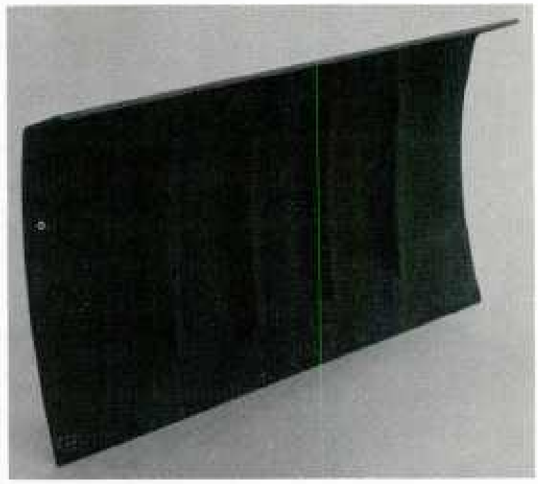


Figure 34: Carbon/epoxy skin with co-cured frames

Figure 35: Fragment projector

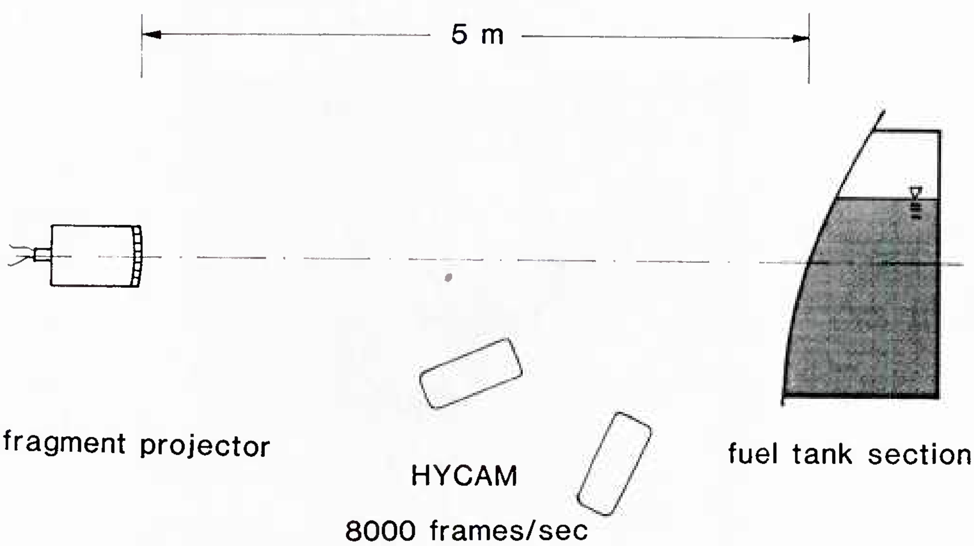


Figure 36: Multiple fragment impact test setup

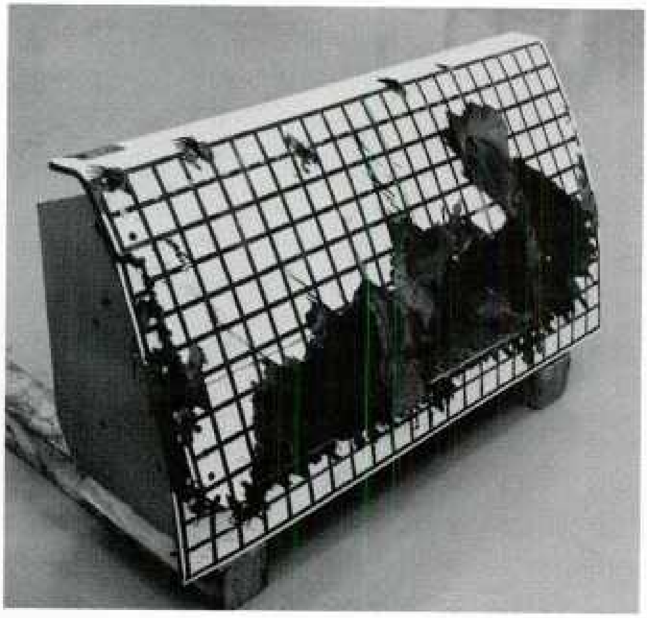


Figure 37: Ballistic impact damage to fuel tank carbon/epoxy skin with cocured frames and longerons

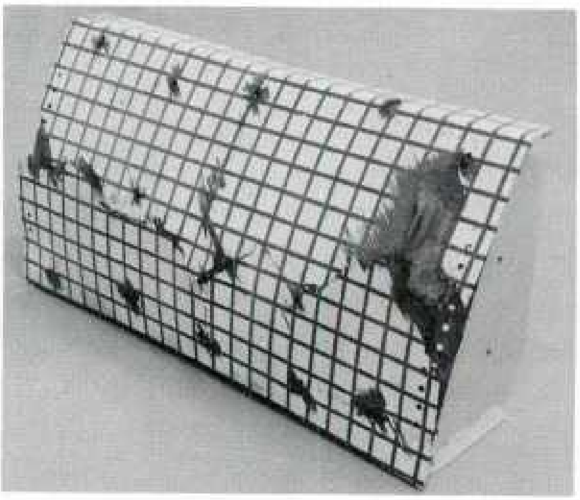


Figure 38: Ballistic impact damage to fuel tank carbon/epoxy skin with cocured frames and longerons, protected with air buffer foil

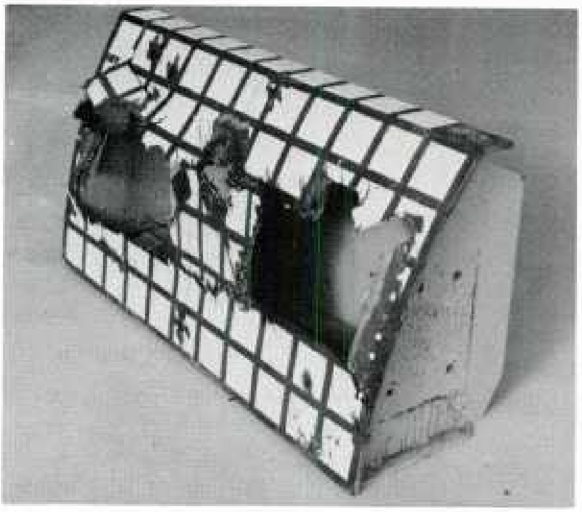


Figure 39: Ballistic impact damage to fuel tank carbon/epoxy sandwich skin

Impact Damage Effects and Computational Methods

by
A. Poth, F. Scharpf
Industrieanlagen-Betriebsgesellschaft mbH,
Ottobrunn, W. Germany

ABSTRACT

A special aspect in design technique of military aircraft is the investigation of the structural response to weapon loadings.

One of the most critical loading in this field is the fragment impact on tank structures with respect to the hydraulic ram effect.

For the analysis of structural response to combined impact and pressure wave loadings a numerical method is presented, modelling the fully threedimensional fluid structure interaction. Examples of application of Eulerian, Lagrangian and coupled Eulerian/Lagrangian formulations are shown, demonstrating the facilities of numerical simulation.

INTRODUCTION

For the solution of technical problems the application of computational methods is becoming more and more popular, especially in the field of structural analysis. Basis for the propagation of these methods was the development of powerful and efficient hard ware and soft ware tools. The stage of development of computational methods enables an efficient support and partially even substituting of experimental methods, depending on the technical complexity of the problem.

Even in the sophisticated area of impact and penetration events numerical simulation is possible today. Special aspects in application in this field are shown subsequently.

IMPACT DAMAGE EFFECTS

In terminal ballistics impact damage effects result from the interaction between a penetrator and a target structure within an extreme short duration. The essential phenomena of the physical event are the shock wave propagation, high rate and high pressure loading, large plastic flow and different failure mechanisms e.g. erosion, shear instability and cracking. The contact force acting between penetrator and target depends on inner forces and forces of inertia in the neighborhood of the impact and is generally unknown.

In many cases the primary damage like plastic flow and cratering due to the impact loading does not lead to the failure of the hit structure. But by superimposing with the design loads the catastrophic level may be reached resulting in a structural collapse. Therefore particular emphasis has to be laid on the damage tolerance of structural members.

COMPUTATIONAL METHODS

Codes suitable for the numerical simulation of impact events can be classified concerning to following criteria:

Basic formulation	:	Eulerian or Lagrangian
Solution method	:	Finite Difference or Finite Element
Time integration	:	Implicite or explicite

Most of the codes in this field use an explicite integration scheme. Eulerian formulations are generally advantageous for large material flow phenomena, most of them using a Finite Difference scheme. Lagrangian codes are preferable for problems, where an accurate material modelling is necessary. Most of the Lagrangian codes are based on a Finite Element concept /1/.

The key for a realistic simulation of the physical event is the availability of a natural model for the prefailure, failure and postfailure behaviour of the material at high rate and high pressure loading. Investigations of material behavior under such exheme conditions were strongly propelled by their necessity for the numerical simulation. Computational methods have proved to be a helpful instrument for the verification of material models, therefore an increasing number especially for metallic alloys is available today.

EXAMPLES OF APPLICATION

Examples in this presentation are calculated with codes of the DYSMAS-family (DYnamic System Mechanics Advanced Simulation), developed in Germany /2/. The program-family consists of the codes DYSMAS/L, a FE-Lagrangian code, DYSMAS/E, a FD-Eulerian code, and DYSMAS/ELC, the coupled version of the two stand-alone programs, all for both 2D and 3D applications.

Blast wave loading

A wide range of application of Eulerian codes is the calculation of the structural loading. An example of a blastwave impacting a shelter door which is shielded by a mound is shown in Fig. 1.

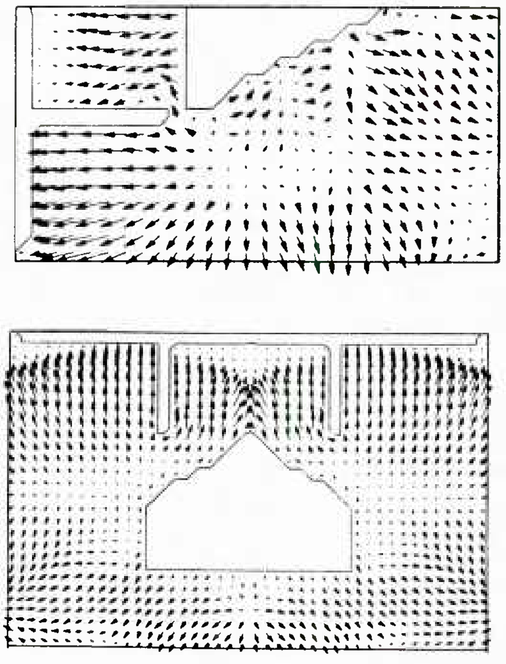


Fig. 1 : Numerical Simulation of Blast Wave Impacting a Shelter Construction
Above: Ground-Level Section (Top View)
Below: Mid-Plane Section (Side View)

The velocity distribution of the threedimensional problem is shown at the arrival time of the blastwave at the door. This problem can be calculated purely Eulerian (with a rigid structure as a boundary condition) if the motion of the structure has only little effect on the loading during the calculated time. In this case the structure is stiff and small movements of the structure are not causing significant changes of the air pressure wave. The time history of pressure at the surface of the structure is recorded and can be used later as the loading function for design.

An example of a shelter door loaded by air blast demonstrates the application of a Lagrangian code. The Finite Element discretization of the shelter door is shown in Fig. 2. The door is loaded by the detonation of a bomb. The pressure functions were calculated sperately with the Eulerian code.

The door opens due to underpressure caused by the reflected blast wave, illustrated by the displacement transient in Fig. 3.

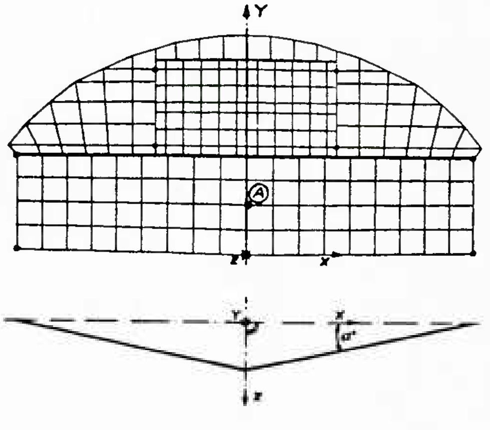


Fig. 2 : Shelter Door, Finite Element Discretization

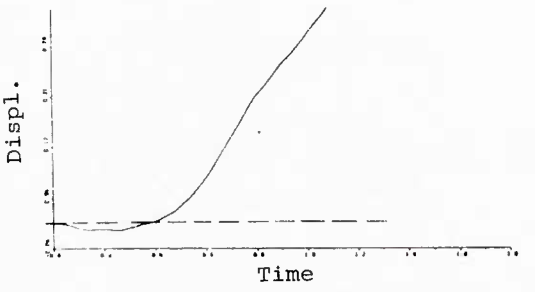


Fig 3 : Displacement Transient in z-Direction at the Lower Door Joint

Impact Loading

For the calculation of the accurate structural response to an impact loading the use of a Lagrangian code with a contact processor is advantageous.

Difficulties arise in cases of complete penetration, where the target mesh has to be cut or opened. To overcome the numerical problems caused by large distortion of failed elements, sometimes the only way is to set up this problem in Eulerian description or to use a coupled code with an Eulerian target and a Lagrangian penetrator.

At present there are models for the postfailure behavior of Lagrangian material by separating elements or meshlines from each other, as the slide line model, the model for arbitrary crack opening, or the erosion model. The latter model is demonstrated in the calculation of the penetration of a two-plate target in Fig. 4

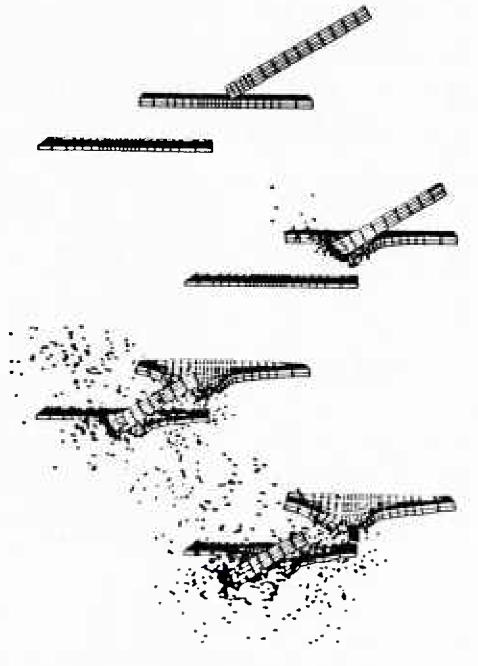


Fig. 4 : Penetration of a Two-Plate Target

In this model failed elements are erased dynamically. But the masses of the elements still remain in the system as single masses controlled by the contact processor and exchanging kinetic energy with surfaces henceforth.

Combined Impact and Pressure Wave Loading

Often the loading process acting upon a structure is not only caused by an external energy source but also influenced by the interactive response of the structure itself. In these cases it is not possible to run the Eulerian code for calculation of the response in succession.

A wide field of application for coupled calculations are underwater explosions against ships. Fig. 5 shows a result of a numerical simulation of a torpedo shot against a frigate at a real time of about 60 msec.

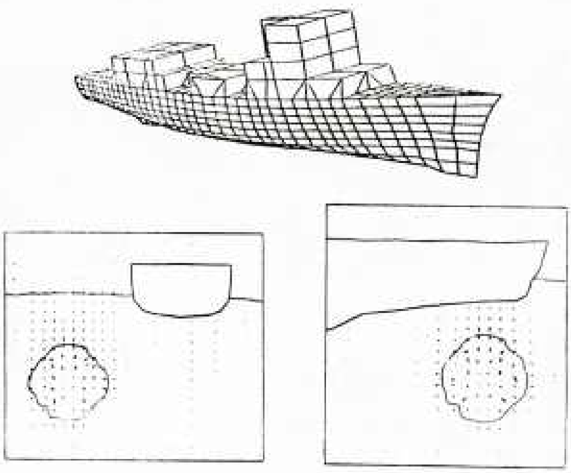


Fig. 5 : Numerical Simulation of an Underwater Detonation against a Vessel
Undeformed Structure
Two Plane Sections Through the Gasbubble

A sudden motion of a structure against water causes high pressure due to the nearmost incompressibility of water. A sudden motion of this structure in the other direction causes immediate cavitation in the water with a pressure collapse. In the case of a torpedo shot the ship structure locally moves very fast within the initial loading time. So loading and response is an interactive process, which means that a coupling processor has to exchange information between fluid and structure within each time step. The Eulerian code needs the information about the actual position of the structure as a geometric boundary condition. The Lagrangian code requires forces depending on the actual pressure distribution at the submerged parts of the structural interface.

If the motion of the structure is small a coupling model can be used, where the structure is only allowed to move within one row or column of the Eulerian grid. Such a model can be used to solve e.g. hydraulic ram problems with small structural movements. If, however, one has to calculate the penetration of a fragment through the wall of an aircraft tank, a coupling processor has to be chosen allowing arbitrary motion of the structure like in the example above.

CONCLUSIONS

It was shown that even in the very complex field of structural response due to impact and pressure wave loading numerical solution technique is a worthwhile support to experimental investigation. More over the benefit of numerical simulation is not only to get an answer to a particular problem. Due to the complete information about the physical event in its dependency of space and time it is an irreplaceable instrument to gain a better understanding of the physical nature of impact damage effects.

REFERENCES

/1/ Zukas J.A., Impact Dynamics, John Wiley & Sons, New York (1982)
/2/ The Program Family DYSMAS, B-TF-V197,IABG, Munich (1984)

BALLISTIC SURVIVABILITY CONSIDERATIONS FOR AIRCRAFT STRUCTURES

by

Thomas E.Hess
Aircraft and Crews Systems Technology Directorate
Naval Air Development Center
Warminster, Pennsylvania 18974-5000
United States of America

INTRODUCTION

This paper presents an overview of some structures development programs in which ballistic survivability was a design consideration. Some of these programs treated ballistic damage as a hole of a particular size, with no ballistic testing being performed. In the others, actual ballistic conditions, including hydraulic ram, were used and ballistic tests were performed. Most of the programs discussed here are fuselage programs, including postbuckling (tension field), but one wing program is also discussed. Some of these programs are still underway, but in the final stages of completion.

PROGRAMS USING SIMULATED BALLISTIC DAMAGE

All three programs in this group are fuselage programs. The center and aft fuselage are typical of patrol type aircraft structures, and the bismaleimide fuselage is typical of tactical aircraft structure. All three are integrally stiffened, cocured construction.

The center and aft fuselage considered ballistic damage to be a 4-cm hole. The former was made from graphite/epoxy and used crack arrester strips as the primary method for containing damage and, thereby, providing survivability. The aft fuselage was made from a combination of materials, the stiffener caps being graphite/epoxy and the rest of the structure being Kevlar®/epoxy. Survivability was achieved here by the choice of materials and the fact that the loads are relatively low. The bismaleimide fuselage structure's intended use is for temperature regimes beyond that for which graphite/epoxy can be used, namely 350°F to 400°F. Here also crack arrester strips were used, but in this case the damage size was 20 cm.

We need not dwell too much on these programs since the situation of simulated ballistic damage is not as interesting as that of actual ballistic conditions.

However, these programs did demonstrate that fuselage structure can be designed in such a way that damage is contained within a local area and limit loads can be sustained with such damage.

Figure 1 shows the design features of the center fuselage as described above. Crack arrester strips are placed in the skin as shown in figure 2. Figure 3 shows a test subcomponent under design ultimate load during static test. This was a postbuckled design, initial buckling planned for about 1/3 of limit load. The buckles in the test specimen are clearly visible, as are the crack arrester strips. Following successful static test to design ultimate load and two lifetimes of fatigue loading, damage was imposed by cutting a 4-cm hole and slits in the structure. Load was reapplied until the damage propagated. The crack arrester strips successfully arrested the crack propagation, as shown in figure 4. This damage was repaired and another hole was cut, through a stiffener, shown in figure 5, Limit load was sustained in this case also.

PROGRAMS USING ACTUAL BALLISTIC DAMAGE

The programs in this category are two fuselage programs, a wing program and a program which investigated the behaviour of postbuckled fuselage structure under ballistic impact conditions.

The first fuselage program in this group goes back several years, but was the first one in which actual ballistic conditions were considered. The design was a hybrid honeycomb sandwich. The faces contained graphite and glass in an epoxy matrix material, and the core was Nomex® honeycomb. This hybridization together with crack arrester strips provided survivability. A 2.5-cm hole, produced by a solid fragment, was the threat. This was a dry bay and, therefore, hydraulic ram was not an issue. The ability of this design to arrest damage propagating from such a hole is shown in figure 6. An added characteristic of the hybrid face is that an early warning of crack propagation is provided by a lightening in color of the face material at the tip of the about-to-advance crack. A target vehicle fuselage section was built and installed as shown in figure 7. Extensive testing was performed which verified the survivability of this design to not only the threat mentioned above but also to damage induced in the form of large cutouts in the skin.

Figure 8 shows the features of an integral fuel tank design which contains two cells and wing carry-through bulkheads. This is a stiffened graphite/epoxy structure which contains crack arrester strips and stitching at all the stiffeners. A subcomponent, figure 9, was fabricated for testing, which has yet to be performed. This subcomponent is approximately 1.2 m long, 0.8 m wide and 0.6 m high. One representative wing bulkhead is included. The objective here was to limit the fuel ingestion into the engine inlet to 10 gallons per minute following a 23-mm HEI encounter. Figure 10 shows the results of development ballistic tests performed in this program. The curved panel which was tested failed catastrophically as a result of the explosion of the 23-mm HEI within the fuel volume. This panel was the entrance face and represents the outer skin of the aircraft. Despite this disastrous failure, it was determined that loss of one bay would not preclude safe return of the aircraft to its base. On the other hand, the exit panel, which represents the internal tank-inlet interface sustained only minor damage, as seen in figure 11. In another test, not shown here, a rubber coating was put on this panel and no penetration occurred. Even with the damage shown in figure 11, the 10 gallon per minute requirement was met. It should be noted that this tank was also designed for crashworthiness.

Figures 12 and 13 show the results of 23-mm HEI testing of a composite wing box structure. In this graphite/epoxy design, stitching, crack arrester strips and buffer strips at fastener holes were used to achieve survivability. The skins were designed to carry only torsional loads while bending is taken by the spars. The stitching in the skin forms a blow-out panel which was effective in relieving the hydraulic ram pressures, as seen in the figures.

Finally, due to the increasing use of lightweight postbuckled structure in fuselage construction, a program was undertaken to investigate the resistance of such structure to ballistic impact. The test specimens were graphite/epoxy and some were graphite/bismaleimide. Figures 14 to 16 show typical damage encountered in the tests. A summary of results and conclusions are shown in figure 17. There was enough residual strength in all cases for safe return of the aircraft.

SUMMARY

The work which has been done to date leads to the following conclusions:

(1) Hybrid materials are resistant to damage propagation and provide some visual warning of impending propagation.

(2) Crack arrester strips are effective in containing damage.

(3) Full-scale structures are more tolerant than expected from element tests.

(4) Most structures are tolerant of holes up to 20 cm.

(5) Hydraulic ram and blast pressures are more difficult to deal with and internal explosion appears to be the most serious.

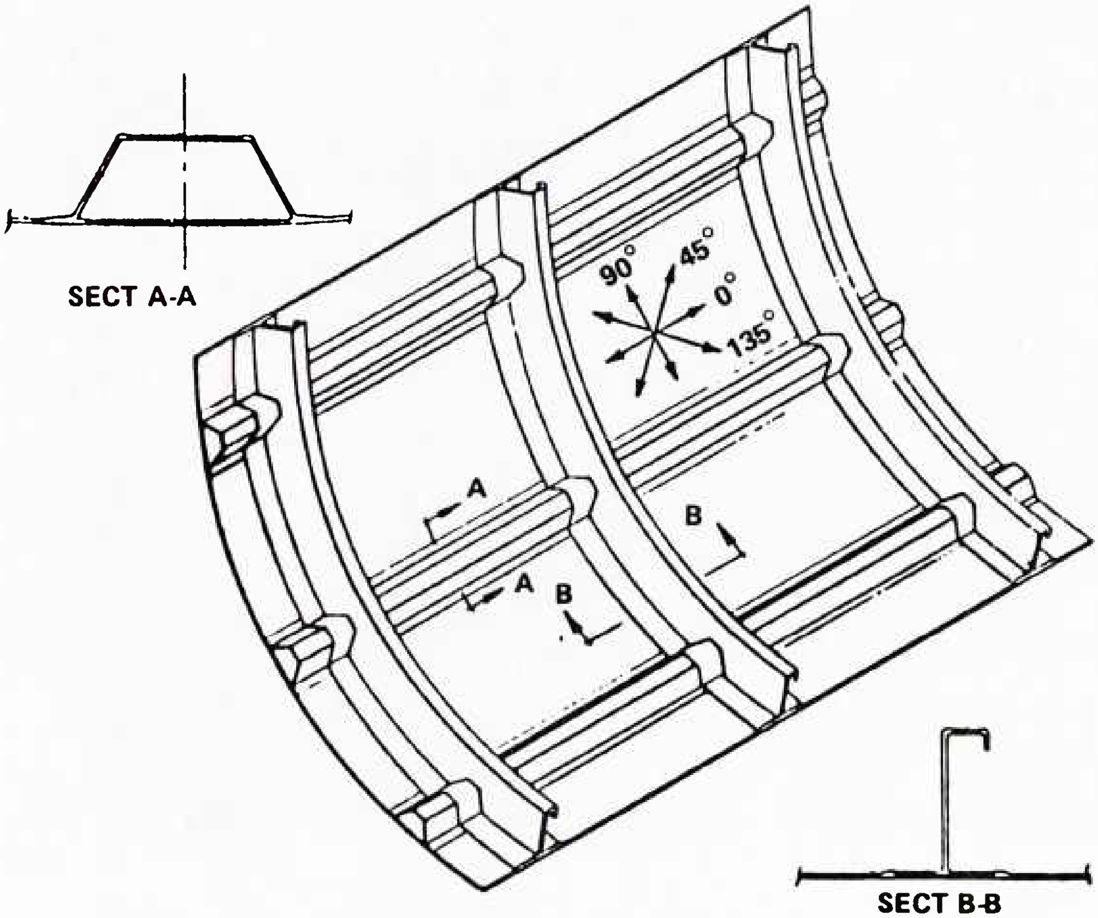


Figure 1. Structural Design Features For Center Fuselage.

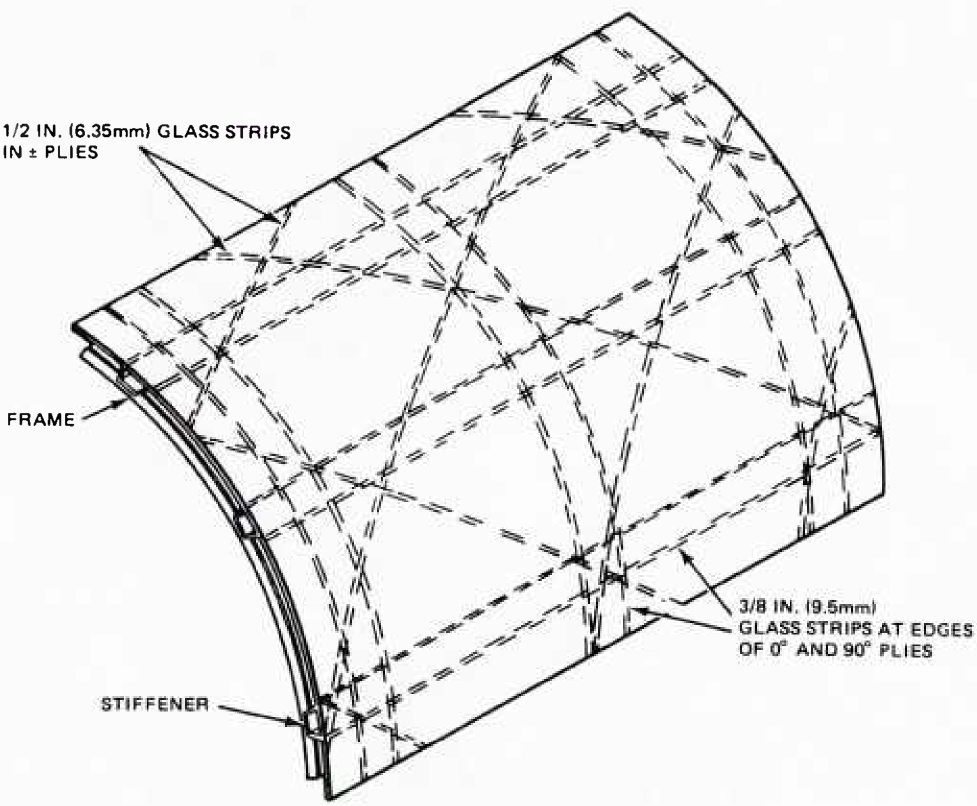


Figure 2. Placement Of S-Glass Crack Arrestment Strips.

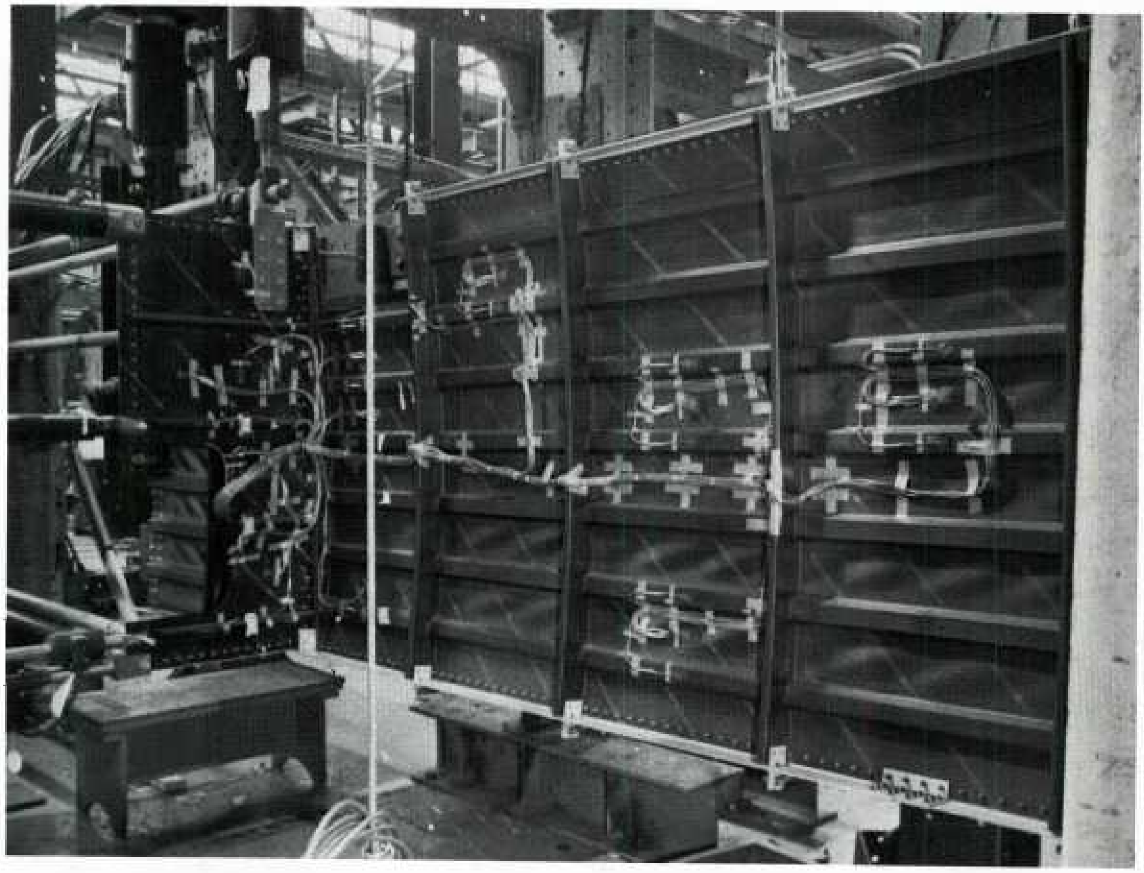


Figure 3. Center Fuselage Subcompoment Under A Static Test (DUL).

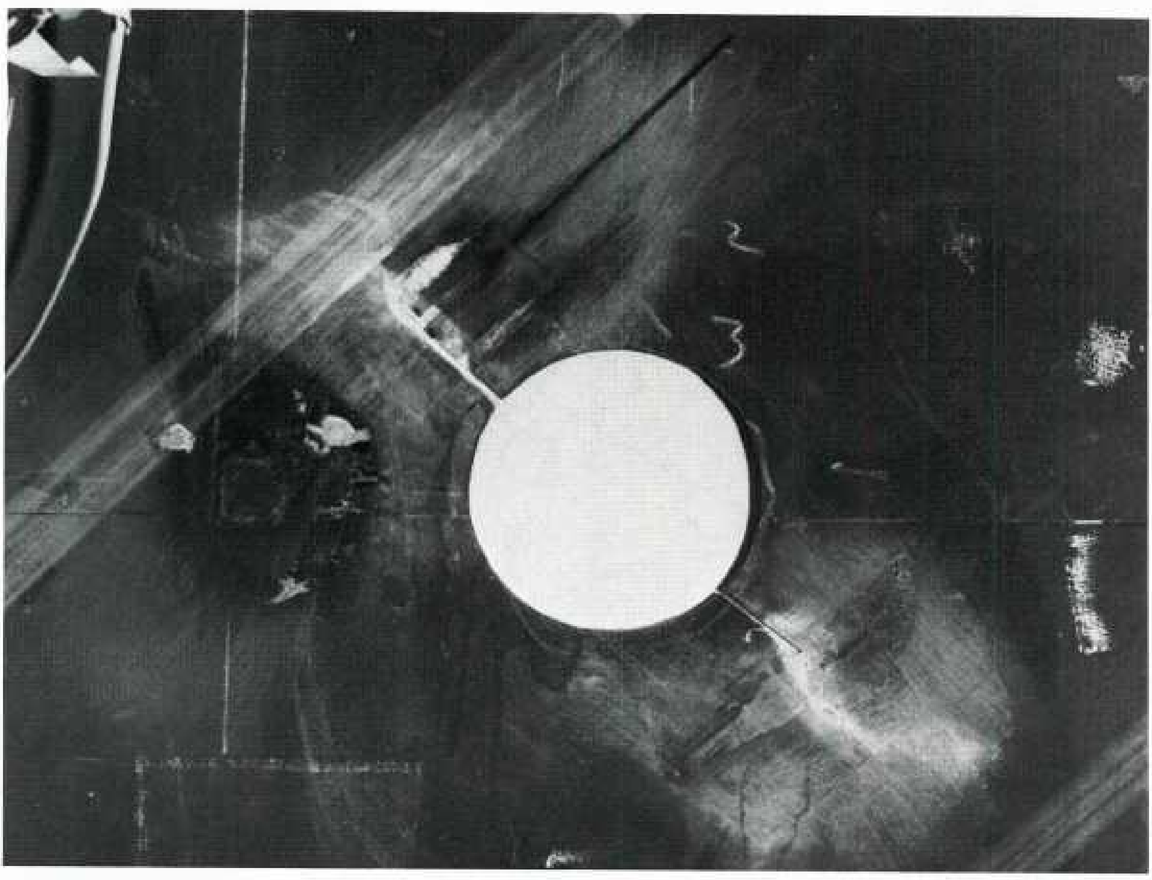


Figure 4. Arrested Crack In Center Fuselage.

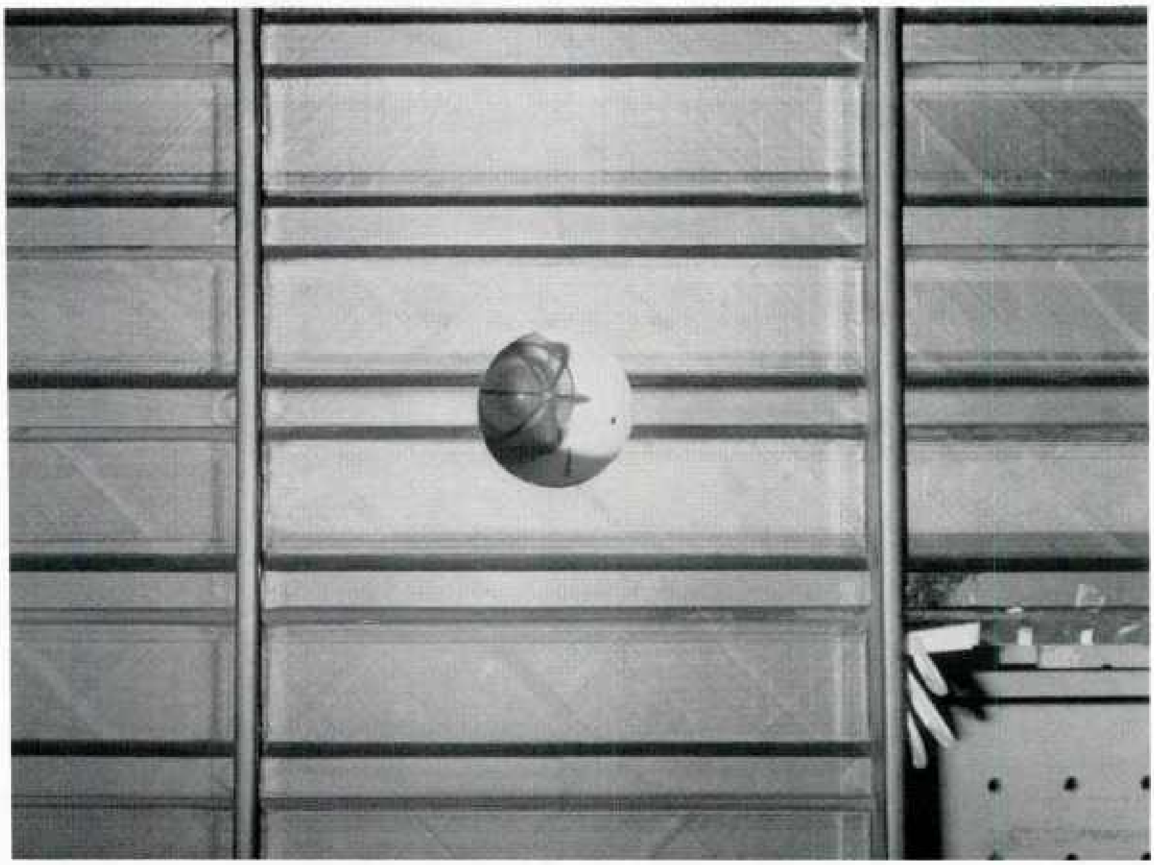


Figure 5. Simulated Damage In Stiffened Structure.

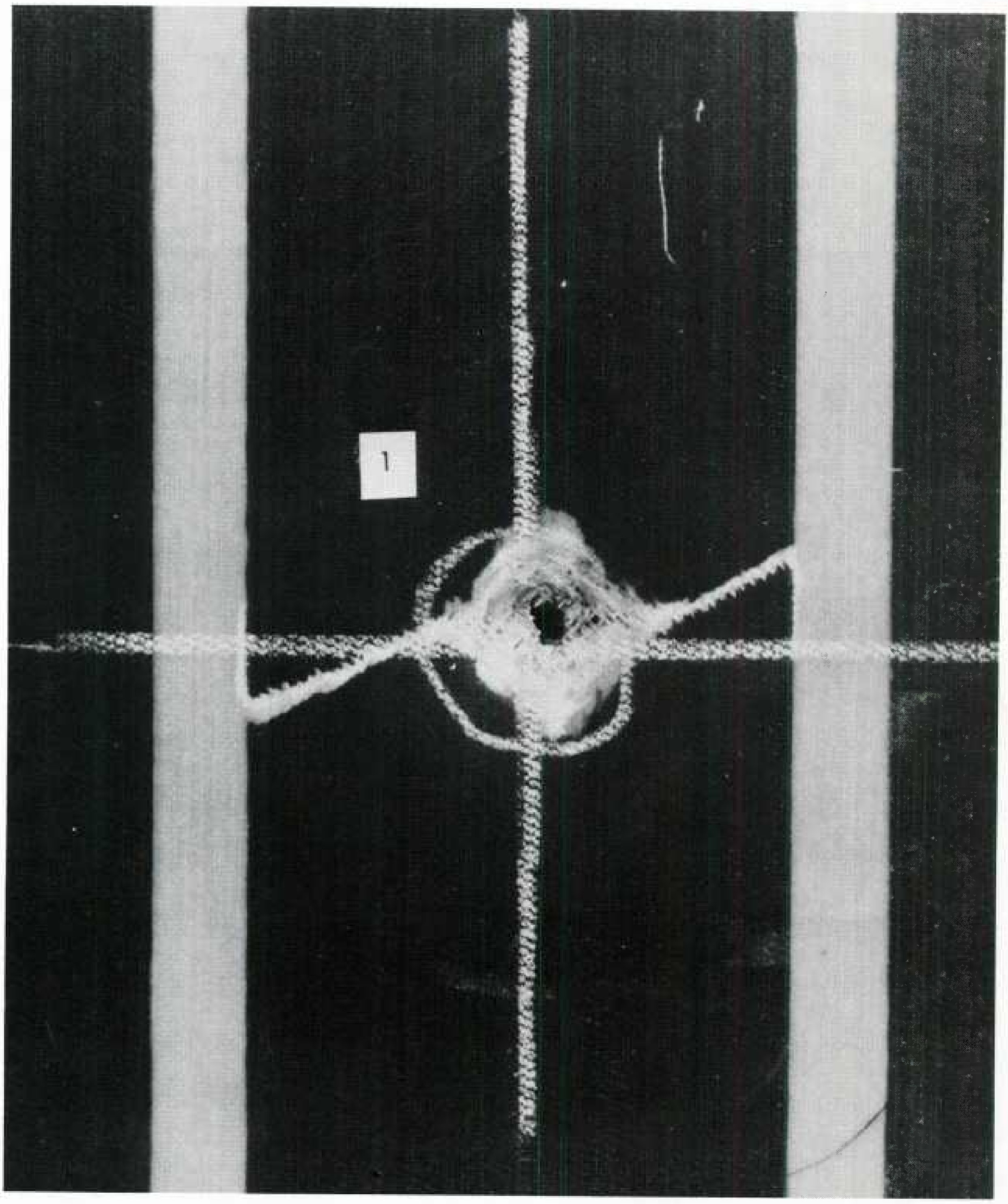


Figure 6. Projectile Induced Damage In Hybrid Fuselage.

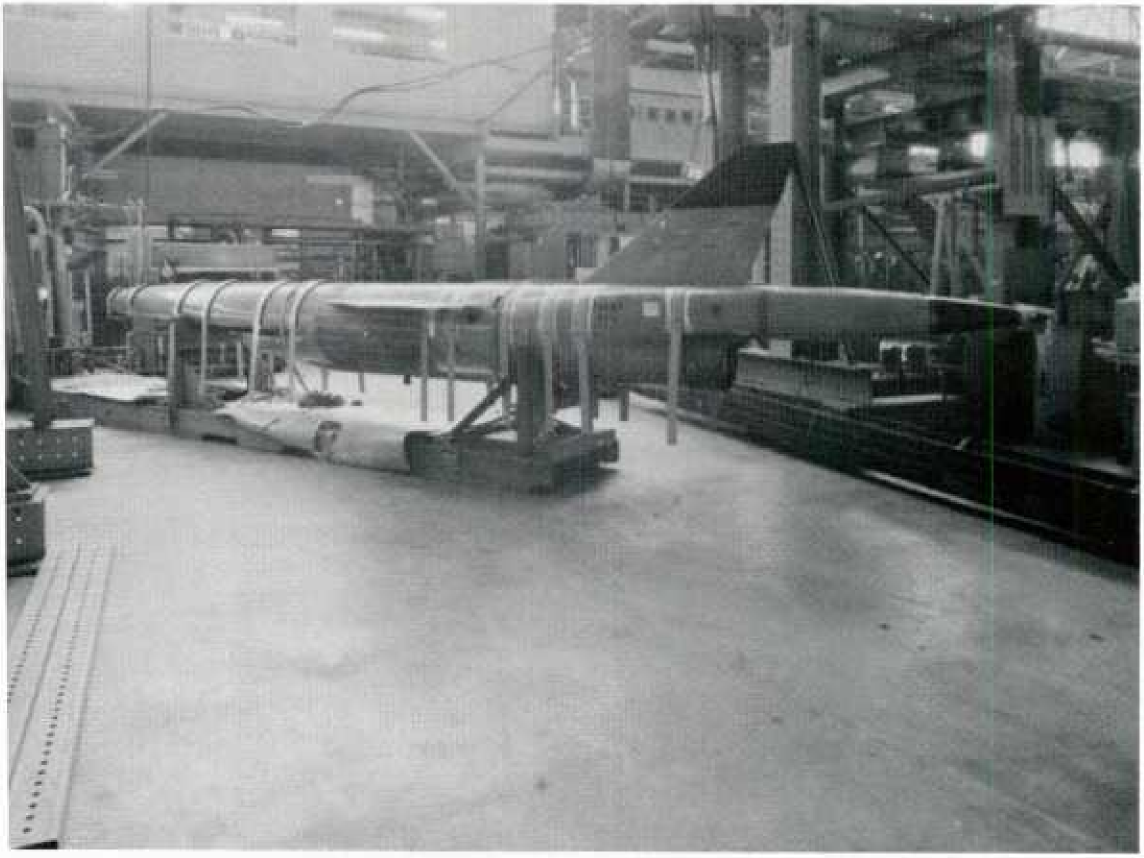


Figure 7. Hybrid Composite Fuselage Section With Crack Arrester Strips.

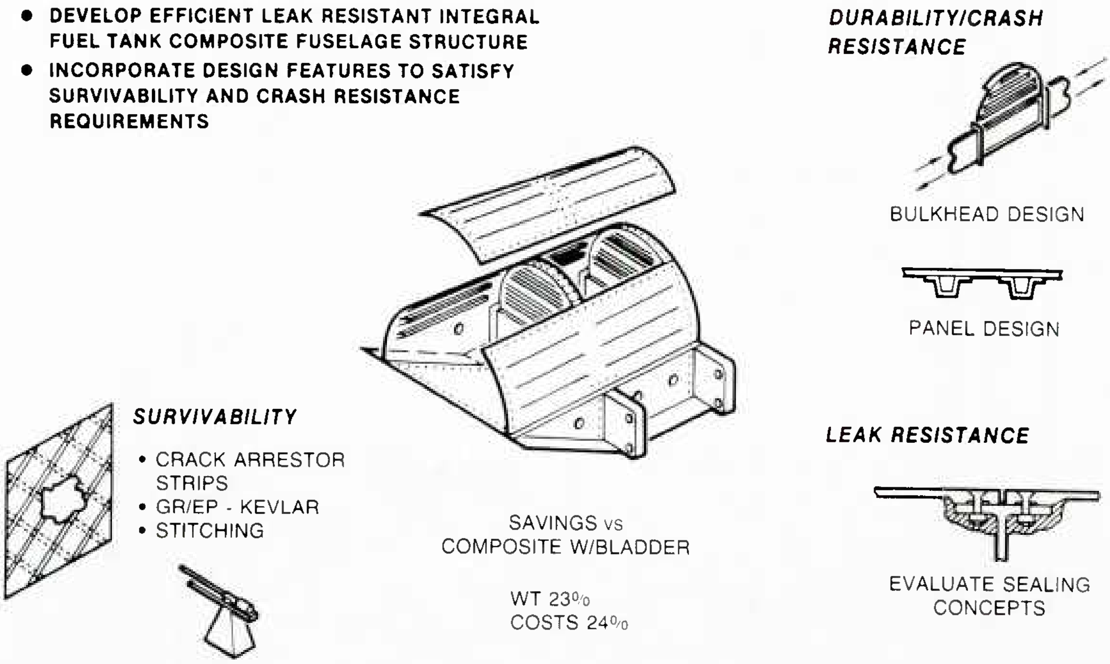


Figure 8. Composite Integral Fuel Tank.

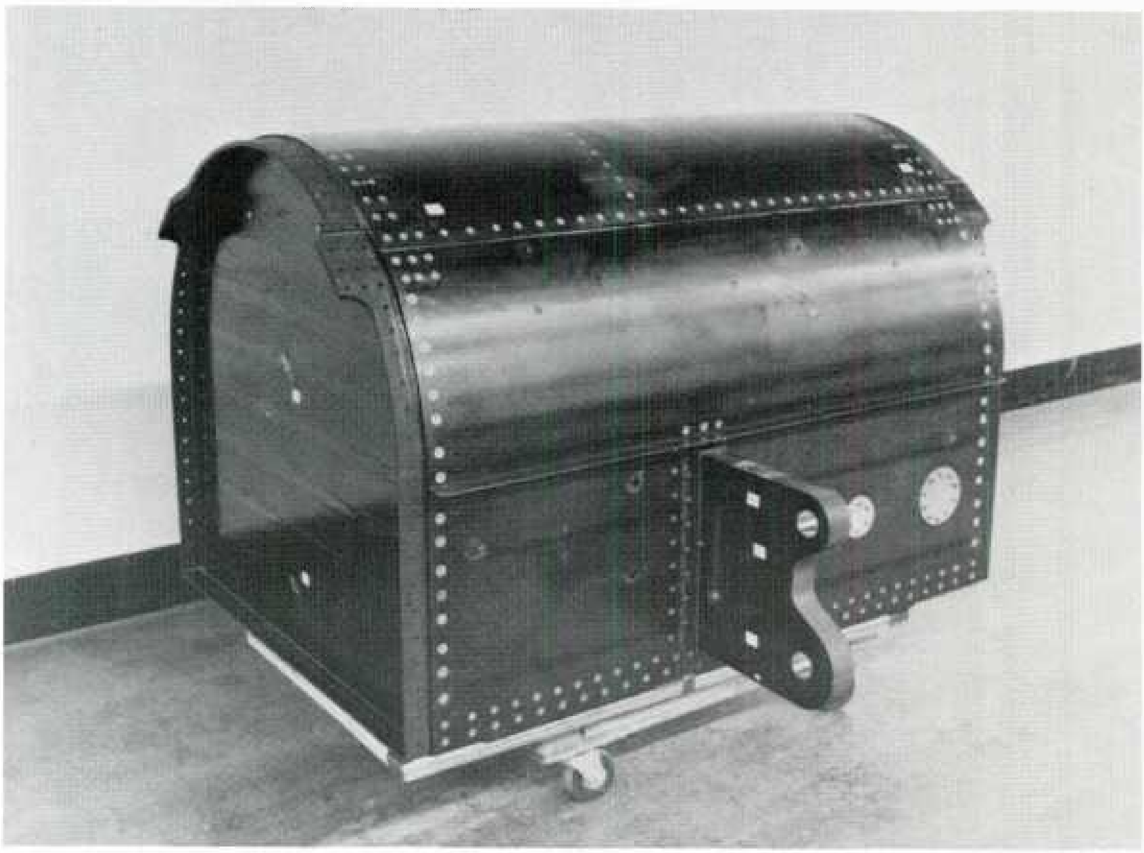


Figure 9. Integral Fuel Tank Composite Fuselage Structure.

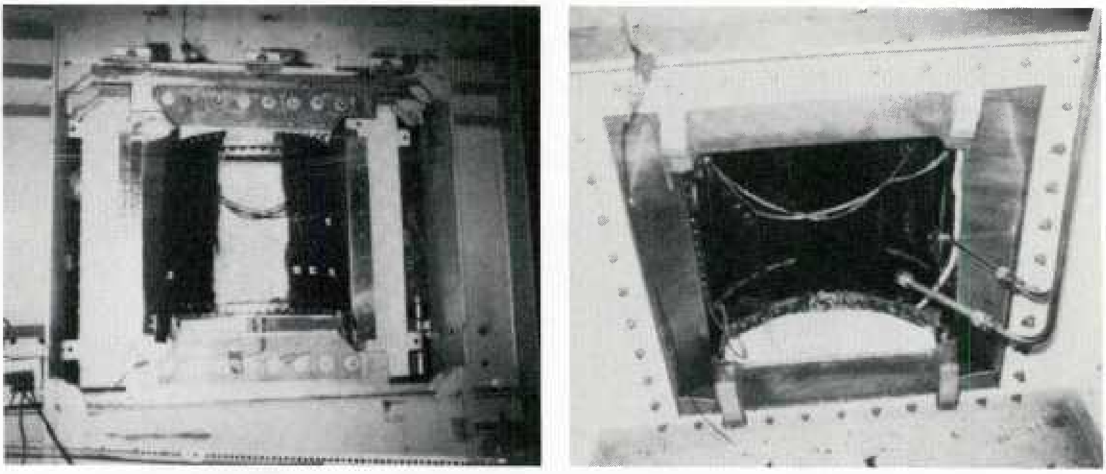


Figure 10. Failed Graphite/Epoxy Curved Entry Panel.

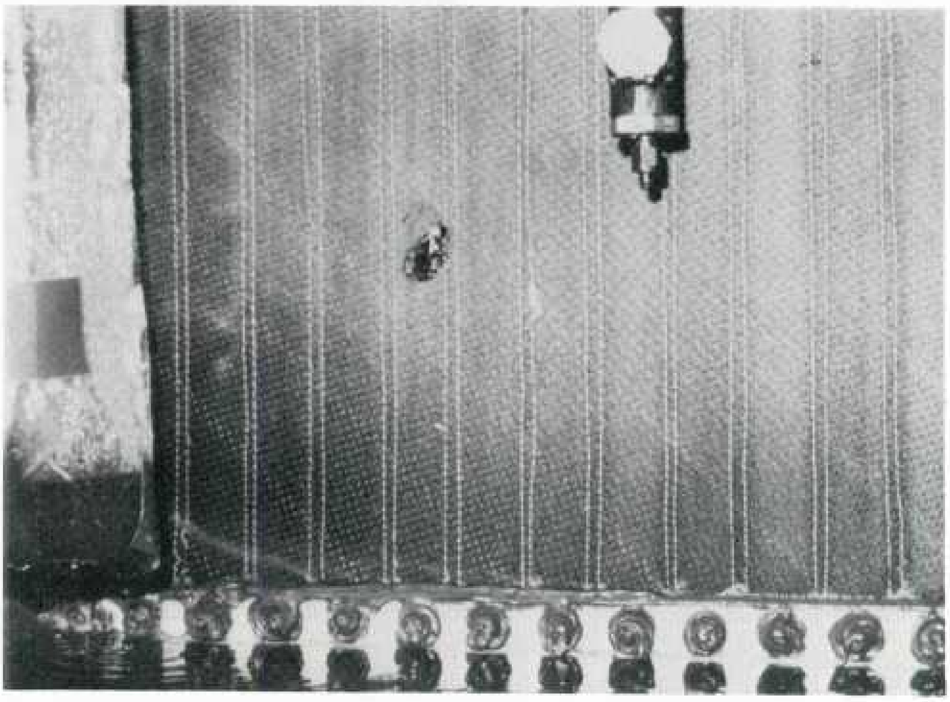


Figure 11. 23 mm HEI Projectile Tip Penetration.

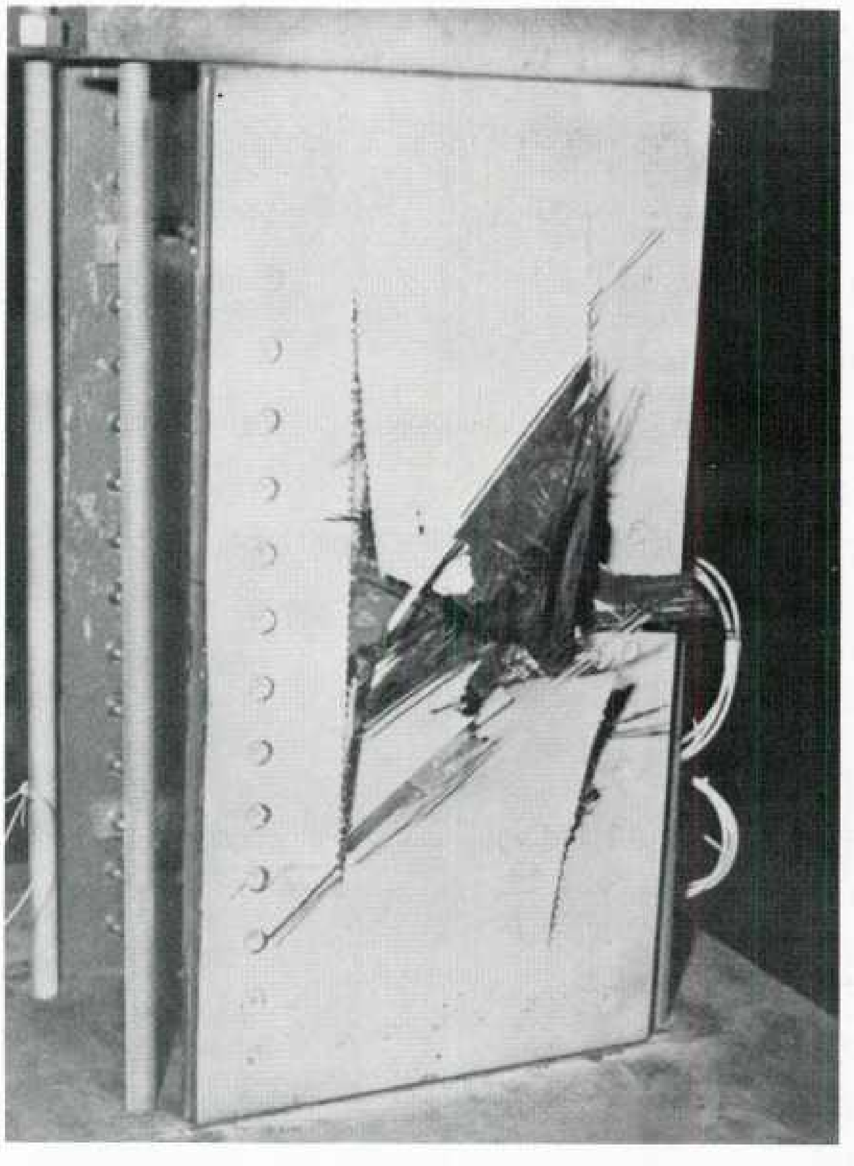


Figure 12. Hydraulic Ram Test Box-Projectile Entrance Surface.

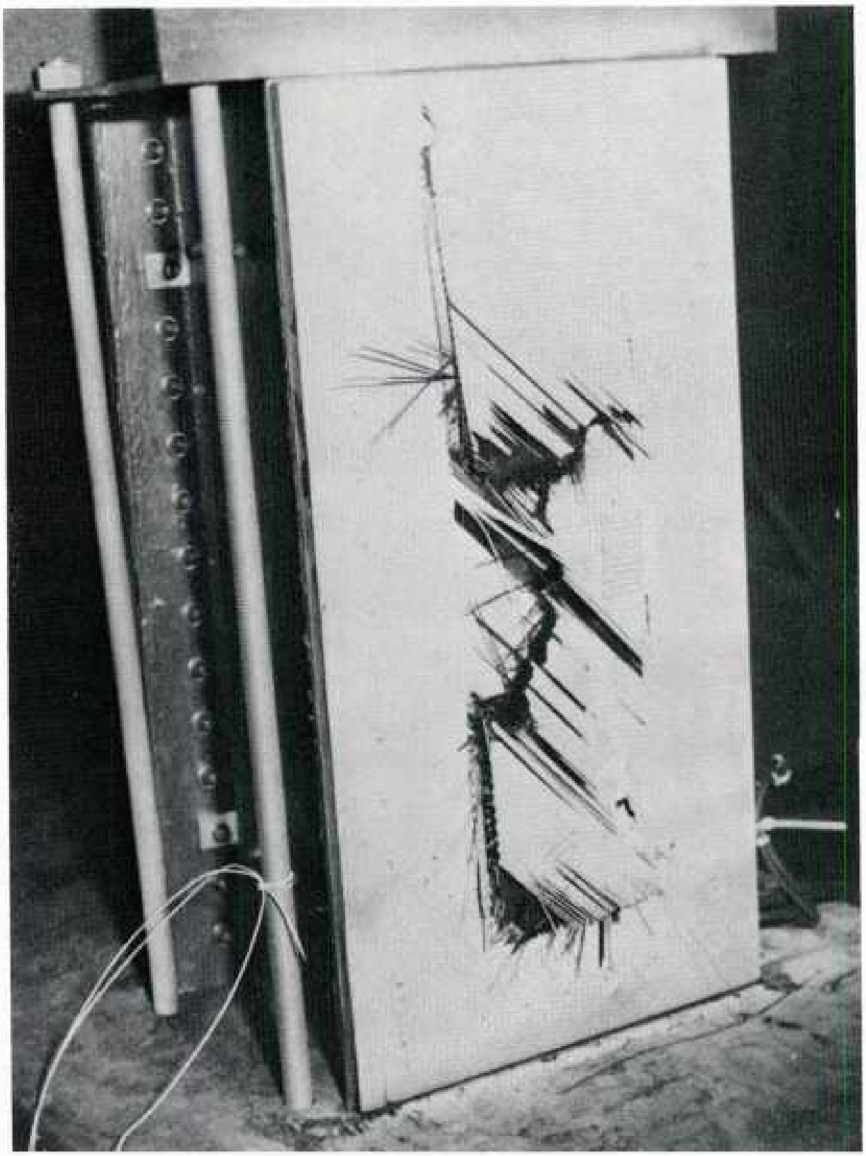


Figure 13. Hydraulic Ram Test Box-Projectile Exit Surface.

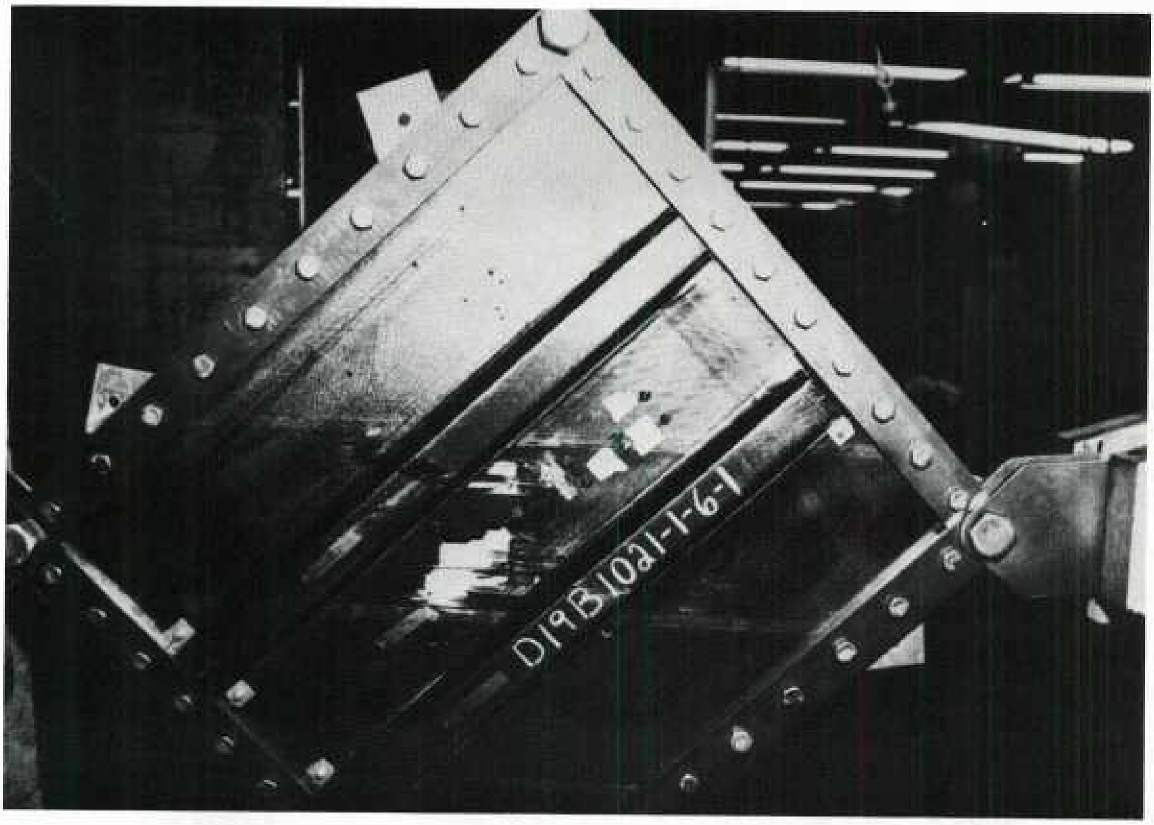


Figure 14. Hydraulic Ram Damage-Exit Side.

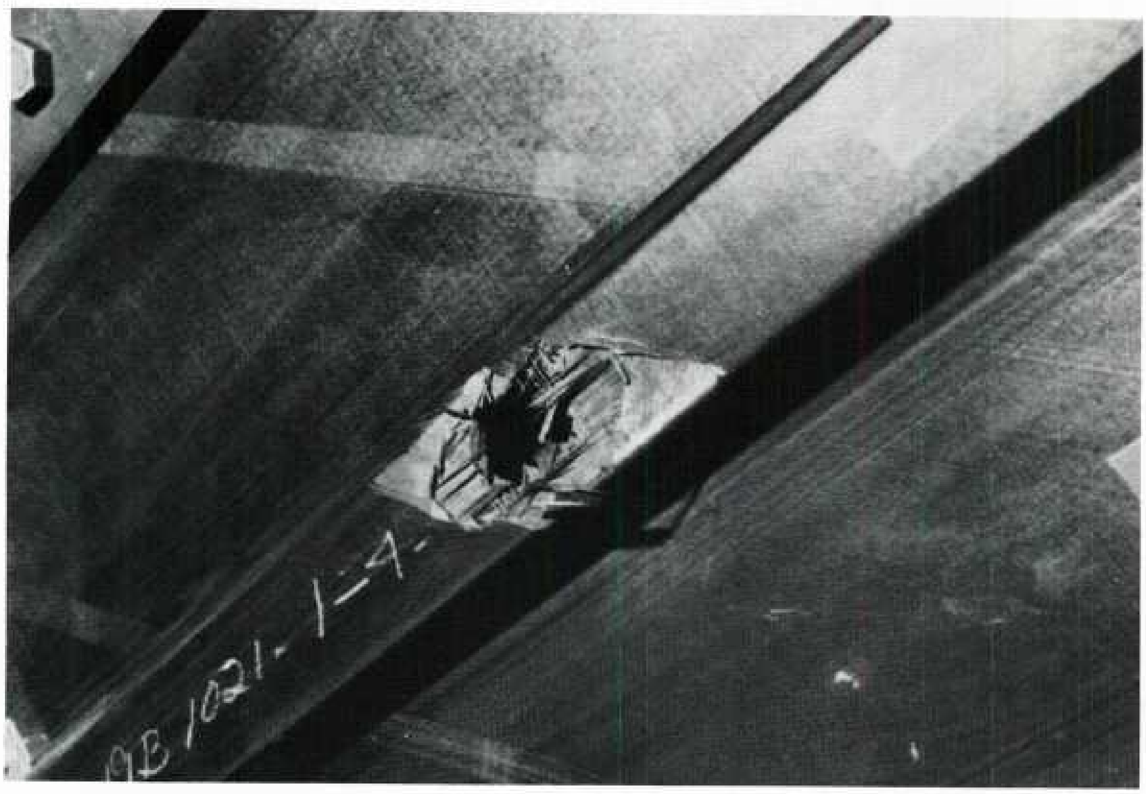


Figure 15. Typical Spallation Damage In Secondary Structures.

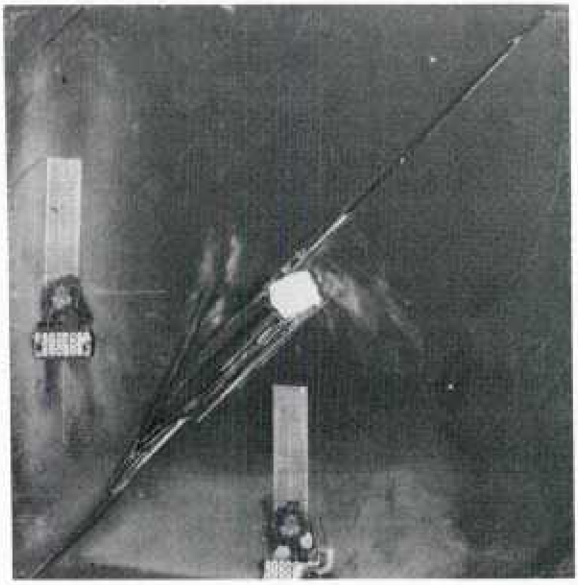
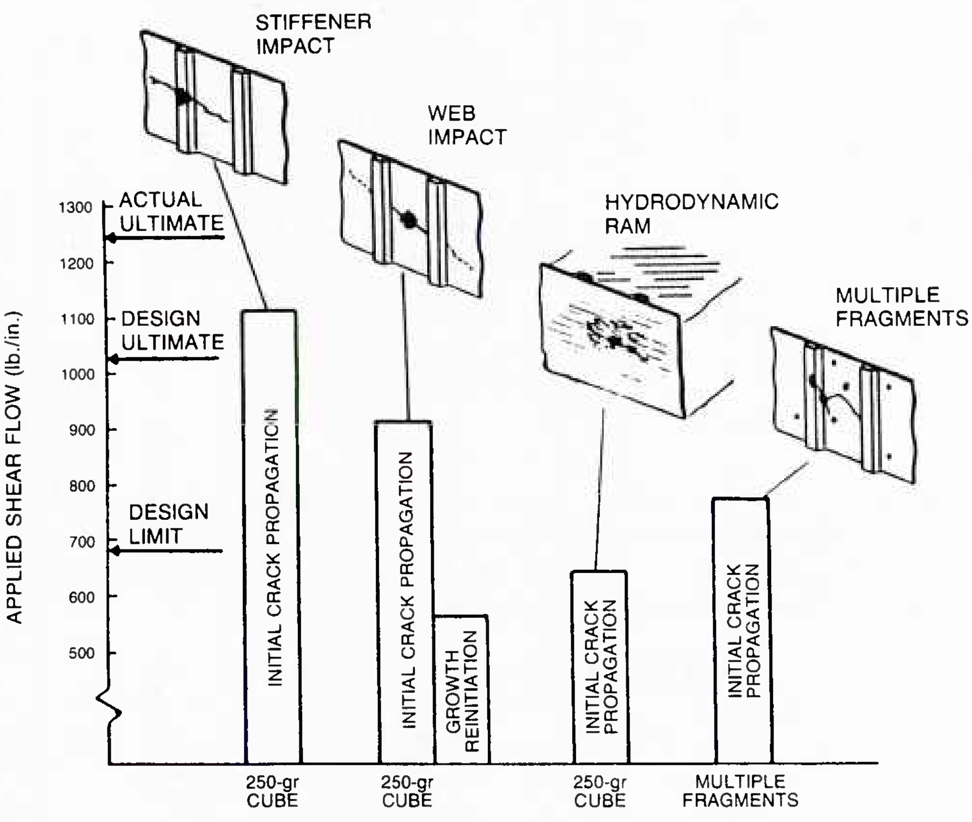


Figure 16. Failed 12.5 x 12.5 In Shear Panel With Impact Damage From 1/2 In. Cube.



Summary of Residual Strength Test Results (Average)

- **Initial Buckling Not Affected By Damage 2 in. And Below**
- **Degree of Buckling at Impact Did Not Influence Damage Size**
- **Extent of Damage & Crack Propagation Can Be Predicted**

Figure 17. Conclusions From Postbuckling Structure Ballistic Tests.

AGARD Report No. 729	AGARD-R-729
Advisory Group for Aerospace Research and Development, NATO IMPACT DAMAGE TO COMPOSITE STRUCTURES Published February 1986 40 pages The Structures and Materials Panel has instituted a Sub-Committee to study the Survivability of Battle-Damaged Composite Structures. This publication includes three papers heard by the Sub-Committee; they survey various aspects of the topic including theoretical analysis and experimentally simulated ballistic damage of test specimens. This Report was sponsored by the Structures and Materials Panel of AGARD. ISBN 92-835-1517-X	Composite materials Composite structures Structural analysis Mechanical properties Impact strength Damage

AGARD Report No. 729	AGARD-R-729
Advisory Group for Aerospace Research and Development, NATO IMPACT DAMAGE TO COMPOSITE STRUCTURES Published February 1986 40 pages The Structures and Materials Panel has instituted a Sub-Committee to study the Survivability of Battle-Damaged Composite Structures. This publication includes three papers heard by the Sub-Committee; they survey various aspects of the topic including theoretical analysis and experimentally simulated ballistic damage of test specimens. This Report was sponsored by the Structures and Materials Panel of AGARD. ISBN 92-835-1517-X	Composite materials Composite structures Structural analysis Mechanical properties Impact strength Damage

AGARD Report No. 729	AGARD-R-729
Advisory Group for Aerospace Research and Development, NATO IMPACT DAMAGE TO COMPOSITE STRUCTURES Published February 1986 40 pages The Structures and Materials Panel has instituted a Sub-Committee to study the Survivability of Battle-Damaged Composite Structures. This publication includes three papers heard by the Sub-Committee; they survey various aspects of the topic including theoretical analysis and experimentally simulated ballistic damage of test specimens. This Report was sponsored by the Structures and Materials Panel of AGARD. ISBN 92-835-1517-X	Composite materials Composite structures Structural analysis Mechanical properties Impact strength Damage

AGARD Report No. 729	AGARD-R-729
Advisory Group for Aerospace Research and Development, NATO IMPACT DAMAGE TO COMPOSITE STRUCTURES Published February 1986 40 pages The Structures and Materials Panel has instituted a Sub-Committee to study the Survivability of Battle-Damaged Composite Structures. This publication includes three papers heard by the Sub-Committee; they survey various aspects of the topic including theoretical analysis and experimentally simulated ballistic damage of test specimens. This Report was sponsored by the Structures and Materials Panel of AGARD. ISBN 92-835-1517-X	Composite materials Composite structures Structural analysis Mechanical properties Impact strength Damage

U224159

AGARD

NATO OTAN

7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE

FRANCE

Telephone (1) 47.45.08.10 · Telex 610176

DISTRIBUTION OF UNCLASSIFIED AGARD PUBLICATIONS

AGARD does NOT hold stocks of AGARD publications at the above address for general distribution. Initial distribution of AGARD publications is made to AGARD Member Nations through the following National Distribution Centres.Further copies are sometimes available from these Centres, but if not may be purchased in Microfiche or Photocopy form from the Purchase Agencies listed below.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD — VSL
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Defence Scientific Information Services
Dept of National Defence
Ottawa, Ontario K1A 0K2

DENMARK
Danish Defence Research Board
Ved Idraetsparken 4
2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92320 Châtillon

GERMANY
Fachinformationszentrum Energie,
Physik, Mathematik GmbH
Kernforschungszentrum
D-7514 Eggenstein-Leopoldshafen

GREECE
Hellenic Air Force General Staff
Research and Development Directorate
Holargos, Athens

ICELAND
Director of Aviation
c/o Flugrad
Reyjavik

ITALY
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
3 Piazzale Adenauer
00144 Roma/EUR

LUXEMBOURG
See Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 126
2600 AC Delft

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Portuguese National Coordinator to AGARD
Gabinete de Estudos e Programas
CLAFA
Base de Alfragide
Alfragide
2700 Amadora

TURKEY
Department of Research and Development (ARGE)
Ministry of National Defence, Ankara

UNITED KINGDOM
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

UNITED STATES
National Aeronautics and Space Administration (NASA)
Langley Research Center
M/S 180
Hampton, Virginia 23665

THE UNITED STATES NATIONAL DISTRIBUTION CENTRE (NASA) DOES NOT HOLD STOCKS OF AGARD PUBLICATIONS, AND APPLICATIONS FOR COPIES SHOULD BE MADE DIRECT TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS) AT THE ADDRESS BELOW.

PURCHASE AGENCIES

Microfiche or Photocopy
National Technical
Information Service (NTIS)
5285 Port Royal Road
Springfield
Virginia 22161, USA

Microfiche
ESA/Information Retrieval Service
European Space Agency
10, rue Mario Nikis
75015 Paris, France

Microfiche or Photocopy
British Library Lending
Division
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
England

Requests for microfiche or photocopies of AGARD documents should include the AGARD serial number, title, author or editor, and publication date. Requests to NTIS should include the NASA accession report number. Full bibliographical references and abstracts of AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
published by NASA Scientific and Technical
Information Branch
NASA Headquarters (NIT-40)
Washington D.C. 20546, USA

Government Reports Announcements (GRA)
published by the National Technical
Information Services, Springfield
Virginia 22161, USA

SPS

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

ISBN 92-835-1517-X