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Review of Aircraft Crash Structural Response Research

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August 1982

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16. Abstract

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Some recent theoretical and experimental studies of the behavior of composite-material structures subjected to severe static, dynamic, and/or impact conditions are noted. Such topics as crashworthiness testing of composite fuselage structures, the impact resistance of graphite and hybrid configurations, and the effects of elastomeric additives on the mechanical properties of epoxy resin and composite systems are reviewed.

The principal theoretical methods for predicting the nonlinear transient structural responses of severely loaded structures are reviewed. Available lumped-mass and finite-element computer programs tailored to aircraft crash response analysis are noted.

A review is made of some current and planned research to investigate experimentally the mechanical failure, postfailure, and energy-absorbing behavior of a sequence of composite-material structural elements and structural assemblages subjected to static loads or to simulated crash-impact loads.

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FOREWORD

This research was carried out by the Aeroelastic and Structures Research Laboratory, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Mass. 02139 under Supplement No. P00010 of AFWAL Contract F33615-77-C-5155. The technical monitors were David Nesterok and R. Garcia of the FAA Technical Center, Atlantic City Airport, New Jersey. The advice, guidance, and cooperation of these individuals are acknowledged most gratefully.

For helpful advice and information, the authors are indebted to M. Card, H. Carden, R. Hayduk, J. Housner, H. McComb, J.H. Starnes, and R. Thomson of the Structures Division, NASA-Langley; to B. Dexter and G. Farley working at the Process/Applications Branch, Materials Division of NASA-Langley; to R. Burrows, G.T. Galow, and T. Mazza of AVRADCOM, Ft. Eustis, Va.; and to J.D. Cronkhite of Bell Helicopter Textron. All of these individuals were helpful in providing information on past, current, and planned research on aircraft structural response under static and/or crash conditions, simulated or actual.

The authors much appreciate the permission granted to reproduce in full herein four well-written and informative summary papers on past, current, and/or future crash-response research. Reproduced in Subsection 2.1 is the paper "Investigation of Crash Impact Characteristics of Composite Airframe Structures" [20] by J.D. Cronkhite et al by permission of the American Helicopter Society. The papers by Thomson and Goetz [11] and Thomson and Caiafa [2] are reproduced in Subsections 2.2 and 2.3, respectively, by permission of the authors. Also reproduced in Subsection 2.3 is the paper by Wittlin [21] by permission of the author and the Lockheed-California Company.

CONTENTS

LIST OF ILLUSTRATIONS

SUMMARY

A review of aircraft crash structural response research has been carried out by studying the literature, discussions with researchers working in that area, and visits to facilities/personnel involved in conducting and/or monitoring aircraft crash structural response investigations. Aircraft structures consisting of conventional built-up metallic construction and those consisting of advanced composite materials were of interest. The latter type of materials and construction is of particular interest since their use is expanding rapidly, and crashworthiness of such structures is of increasing importance.

Some recent theoretical and experimental studies of the behavior of composite-material structures subjected to severe static, dynamic, and/or impact conditions are noted. Such topics as crashworthiness testing of composite fuselage structures, the impact resistance of graphite and hybrid configurations, and the effects of elastomeric additives on the mechanical properties of epoxy resin and composite systems are reviewed.

The principal theoretical methods for predicting the nonlinear transient structural responses of severely loaded structures are reviewed. Available lumped-mass and finite-element computer programs tailored to aircraft crash response analysis are noted.

A review is made of some current and planned research to investigate experimentally the mechanical failure, postfailure, and energy-absorbing behavior of a sequence of composite-material structural elements and structural assemblages subjected to static loads or to simulated crash-impact loads. These structures consist of beams, frames, fuselage keelson, tubes, etc. with either discrete stiffening or sandwich stiffening, utilizing graphite-epoxy, Kevlar-epoxy, and/or other fibrous composite combinations. Plans for drop-impact tests of full-scale composite-material fuselage sections with skin, frame, subfloor, seat and seat-restraint systems are noted. An associated program of structural response predictions and comparisons with measurements is expected to validate and upgrade those prediction capabilities. These research efforts are intended to expand the data base for improving the crashworthy design of composite-material aircraft structures and to improve dynamic structural response predictions and analytical/design tools.

Some recommendations for further work are offered.

SECTION 1

INTRODUCTION

1.1 Study Objectives

Innovative design and the use of a variety of structural and supplementary materials have been undergoing continuous development for decades in order to enhance the survivability of occupants of various types of civilian and military vehicles when subjected to severe loads encountered in crash, impact, blast, and other dangerous conditions. Many governmental agencies and industrial organizations have sponsored and/or conducted studies designed to improve the state of knowledge concerning the transient response and damage suffered by both the vehicle structure and the occupants under these severe loading conditions. This, in turn, has led to the development and use of crashworthy design procedures and/or requirements for certain classes of vehicles: aircraft, automotive, rail, etc. Some of the material utilization and design concepts developed are applicable to a variety of vehicles, but many others are tailored to the specific type of vehicle involved. The basic physics of crash and impact phenomena in the (low) impact velocity regime of interest in these situations are common to all of these various vehicles.

With the accelerating use of advanced composite materials in military, commercial, and general aviation aircraft as well as in the automotive industry, there is an increasing need to develop a better understanding of the behavior of composite-material structures under crash and impact conditions which are representative of aircraft (and automotive) crash situations.

While much work has been done both experimentally and theoretically on the severe transient structural responses of conventional built-up metallic aircraft structures (which absorb a considerable amount of energy as they deform and fold), much less information and experience have accrued on the behavior of advanced composite aircraft structures under these postulated severe environmental conditions. Hence, it is timely to review and assess this overall problem to summarize the state of knowledge (both theoretical and experimental) for these two generic types of aircraft structures, with the principal objective being to identify the key unresolved problems which must be addressed to improve our understanding of the crash dynamics of aircraft structures which utilize a significant amount of composite material in structural regions which can undergo severe structural responses.

Recently the Federal Aviation Administration Technical Center prepared a comprehensive report and plan of research on aircraft crashworthiness applicable to both built-up metallic and composite-material aircraft [1]*. Included in that research plan were essentially four categories of crash-

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* Numbers in square brackets [] denote references given in the reference list at the end of the text of this report.

Army Research and Technology Laboratories sent us some documents from their extensive past work on aircraft crashworthiness.

At MIT we conducted a NASIC library search for documents on crash research and crashworthiness for aircraft and automobiles, crash simulation, crash models, and composite materials. Abstracts of some 710 publications were printed out and checked to identify useful documents. Among those documents considered to be pertinent and useful in the present review, about one-half had already been seen and studied. We sought to obtain the remainder for study.

In studying the various documents retrieved, additional interesting references were noted. As many of these as feasible were sought and/or obtained for study.

In addition, telephone discussions were held with various individuals working on crashworhiness (NASA-Langley, AVRADCOM, Bell Helicopter Textron,...).

1.2.2 Facility Visits

Advice, guidance, and crashworthiness information from FAA Technical Center personnel were sought and obtained during two visits to the FAA Technical Center -- on Sept. 4, 1981 and again on April 16, 1982. Discussions were held principally with R. Garcia, D. Nesterok, and C. Nuckolls.

On Jan. 27, 1982 we visited the Structural Mechanics Branch of the NASA Langley Research Center to become more familiar with the very extensive crashworthiness work already conducted so ably at that facility and of planned future crashworthiness related work. Various structures and impact test facilities at NASA-Langley were visited. NASA-Langley personnel gave us a stack of pertinent documents for study, and generously shared their experience and views on crash response matters pertaining to both built-up metallic aircraft structures and composite-material structures. Effective design concepts for cabin floors/substructure as well as seats/restraints were discussed and illustrated with example hardware. The paucity of crash response experimental data for many structural components and/or assemblies composed of composite material was noted. Many unanswered questions remain. NASA-Langley personnel involved in parts of these discussions included:

M. Card
H. Carden
R. Hayduk
J. Housner
H. McComb
J.H. Starnes
R. Thomson

During these discussions, it was noted that various design features found to be effective in enhancing crash survivability have been identified in the NASA-Langley studies, and certain aircraft operators or manufacturers have adapted these features to improve crash survivability of specific general aviation aircraft which employ "conventional construction."

On Jan. 28, 1982, we met with R. Burrows, G.T. Galow, and T. Mazza at the U.S. Army Research and Technology Laboratories (AVRADCOM), Ft. Eustis, Virginia. The extensive work already carried out by AVRADCOM and its principal contractors was reviewed. Crew or occupant survivability in helicopter crashes has been a primary concern. Crash alleviation features included in the landing gear system, the fuselage subfloor, and stroking seats have under "survivable" conditions -- the other cited topics are beyond the scope of the present study.

To assist in identifying the principal structural response and failure behavior under crash conditions, full-scale crash tests [5,6] were conducted by the FAA on a DC-7 and a Lockheed L-1649 aircraft in 1964 at the Flight Safety Foundation facility in Phoenix, Arizona. Later in the 1972-1980 time period, various types of full-scale light aircraft, a CH-47 helicopter, and aircraft fuselage sections were crash tested at the Impact Dynamics Research Facility of the NASA Langley Research Center [7,8,9,10]. Acceleration, strain, and photographic instrumentation (interior and exterior) as well as post-morten studies provided transient response, failure, and post-failure data; data from instrumented dummies provided "transmitted acceleration-time" information. In some cases the vehicles were caused to impact upon concrete surfaces at appropriate combinations of impact incidence angle and impact velocity. In other cases, impact against a packed dirt surface to simulate conditions in a plowed field was employed. These tests permitted observing,under many realistic but controlled conditions, representative types of transient and failure response, but various secondary effects such as aircraft overturning, cartwheeling, or tree and obstacle impact were not covered in these studies [11].

Since the late 1950's [3], the U.S. Army has been carrying out an effective and comprehensive study of crash behavior of Army aircraft, accident data, and concepts to improve crashworthiness. Highly important crashworthiness developments were made, and this work resulted in the Crash Survival Design Guide [12] which subsequently has been revised and updated [13-17]. Those guidelines are used by aircraft designers to meet criteria spelled out in MIL-STD-1290(AV) for Light Fixed-and-Rotary-Wing Aircraft Crashworthiness [18]. This has resulted in a very substantial improvement in aircraft crashworthiness performance and occupant survival in the field. This development program included an extensive Army Flight Safety and Helicopter Crash Testing Program [19] and a program of laboratory tests.

Similarly, under the auspices of the National Highway Traffic Safety Administration various organizations have conducted a wide variety of crash tests on many different types of vehicles and structures. Extensive photographic and other instrumentation provided data to identify the principal types and sequences of structural failure and crush-up present in each of many vehicle/structural systems. This led to innovative designs for load-limiting and appropriate energy management histories to enhance occupant survival. All of this work has been supplemented by laboratory tests of structural components and assemblages under static and (sometimes) dynamic conditions. Many of the automotive manufacturers have conducted similar very extensive research the results of which are reported in part in the open literature.

The aircraft and automotive crash/impact experiments have involved structures which can be characterized conveniently in two categories: (1) built-up metallic structures (assemblages) and (2) composite-material (non-metallic) structural components and/or assemblages; of course, combinations of these two types of structures are common in many of today's vehicles. Built-up metallic structures "fail" typically in some mode of buckling and then can undergo a considerable amount of deformation and strain

SECTION 2

STATUS OF AIRCRAFT CRASH RESPONSE RESEARCH

Authoritative and comprehensive but concise reports on the status of aircraft crash and crash-response research have appeared in the past few years. This work pertains to helicopters, general aviation aircraft, and transport aircraft. The earlier phases of those studies dealt with vehicles of conventional built-up metallic construction, but in the past decade emphasis has focused upon aircraft structures and structural concepts employing advanced composite materials which promise greater structural efficiency and durability with lower costs. Also sought for composite-material aircraft is "a degree of crashworthiness at least equal to its replaced built-up metal counterpart".

Crash-response characteristics of airframe structures of both metallic and advanced composite construction with emphasis on helicopter applications have been described in an excellent comprehensive paper by Cronkhite, Haas, Winter, Cairo, and Singley [20]; this was followed by a more detailed report by Cronkhite, Haas, Berry, and Winter [3]. Extensive laboratory and field experiments, analysis method developments, and design concept studies are reported; this pioneering work was supported by the U.S. Army Research and Technology Laboratories (and its predecessors).

Studies by NASA and the FAA on the crash response behavior of general aviation aircraft have been summarized in a clear comprehensive fashion by Thomson and Goetz [11] and by Thomson and Caiafa [2]. Laboratory tests, full-scale crash tests, and analysis method developments are reviewed.

Thomson and Caiafa [2] also discuss past and current studies of transport aircraft crash behavior as well as planned future research in this area, including transport aircraft structures composed of advanced composite material. Many aspects of transport aircraft crash response and crash effects are reviewed. Here also laboratory tests of structural elements and assemblages, under both static and crash-impact dynamic conditions as well as a full-scale field crash test of a fully-instrumented B-720 transport aircraft, are being employed to develop a fuller understanding of aircraft crash response and to lead to improved aircraft crashworthiness and occupant survival.

Wittlin [21] has summarized an extensive series of past crash-response studies and transient response analysis developments pertaining to helicopters and light fixed-wing aircraft. He also has summarized current studies being conducted for the FAA and NASA on transport crash response problems by Lockheed, Boeing, and Douglas; this comprises an early phase of a comprehensive transport crash response research effort planned by the FAA and NASA. These studies strive to identify categories of potentially-survivable crash conditions and the principal structural and systems aspects which influence occupant response and survival. Wittlin demonstrates the role and effectiveness of a lumped-parameter simulation model for analyzing the crash responses of helicopters, light aircraft, and transport aircraft.

Since the state of knowledge on aircraft crash response as described in Refs. 2, 3, 11, 20, and 21 is essentially as it exists today, and those

2.1 Helicopters

The kind permission of the American Helicopter Society for the reproduction of the following paper presented originally at the 34th Annual National Forum of the American Helicopter Society, Washington, D.C. in 1978 and subsequently in the October 1981 issue of the Journal of the American Helicopter Society is acknowledged most gratefully.

Investigation of the Crash Impact Characteristics of Composite Airframe Structures

J. D. Cronkhite, T. J. Haas
Bell Helicopter Textron

R. Winter, R. R. Cairo
Grumman Aerospace Corporation

G. T. Singley, III, USAAVRADCOM

PRESENTED AT THE 34th ANNUAL NATIONAL FORUM
OF THE
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WASHINGTON, D.C.
MAY 1978

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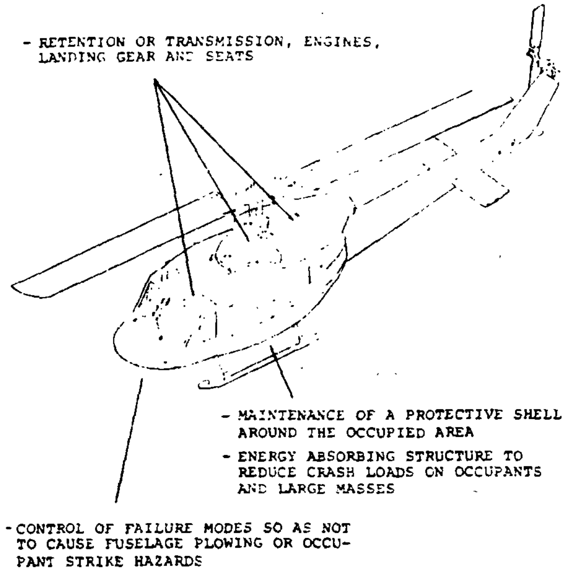


Figure 1. Helicopter fuselage crashworthiness design considerations.

into a design, such as the UTTAS, has been on the order of 8 - 10 years. Therefore, this investigation represents the initial effort toward designing a crashworthy composite airframe structure in the mid 1980's.

The objectives of this investigation are the following:

1. Survey the literature and determine the existing data base on the crash impact behavior of composite materials.
2. Review current analytical methods used for the design of crashworthy airframe structures and assess their suitability for analysis of composite structures.
3. Review current crashworthiness design criteria for military and commercial utility helicopter airframe structures to determine its application to a composite airframe structure.

Behavior of Composite Materials

Literature Survey

The first step in this part of the investigation was to survey existing literature on the behavior of composite materials in a crash environment. The data bases used in the survey were:

1. The National Technical Information Service (NTIS)
2. The Defense Documentation Center (DDC)
3. The Engineering Index (Compendex)
4. "ORBIT (SDC)
5. "DIALOG" (Lockheed)

A flow diagram of the literature search methodology used to retrieve information from data bases and other sources is shown in Figure 2. To access a data base, NTIS for example, blocks of keywords are formed and input to the system so that all information pertinent to the particular topic in question can be retrieved. Keyword blocks are then combined to further focus the search on the subject being surveyed. The number of references found under keyword blocks and various combinations of keywords is presented in Figure 3. Combinations of keywords and a summary of the literature found under each combination are discussed in the following paragraphs.

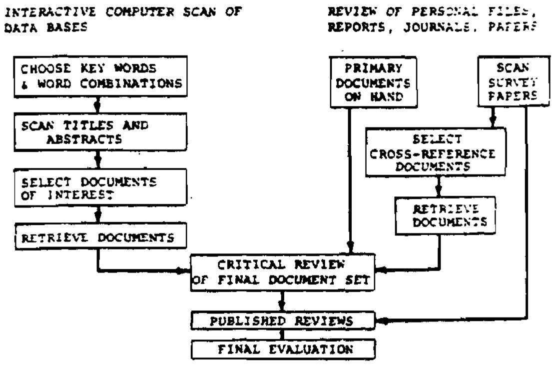


Figure 2. Literature survey methodology.

The conclusion of the Budd Company was that the fiberglass reinforced plastic sandwich structure was superior to the solid laminate structures tested by others for energy absorption. They also concluded that a composite structure could be formulated which would be satisfactory in a crash environment if designed properly.

Several general aviation type aircraft have used composite construction, but referenceable documents on the accident and crash experience with these aircraft could not be found in the literature or through the FAA.

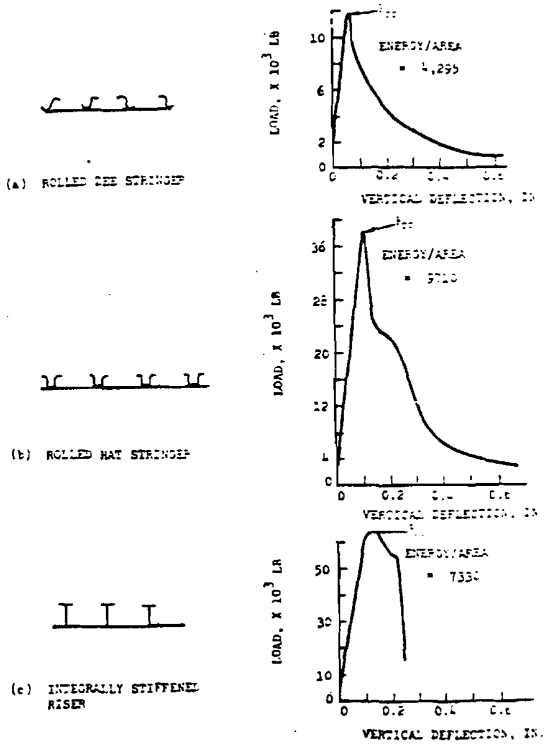
At least two helicopter composite fuselage design studies have been conducted in which crashworthiness was addressed. These were the preliminary design studies of medium utility transport (MUT) helicopters conducted for the Army by Boeing-Vertol and Sikorsky (References 10 and 11). Although crashworthiness was addressed, the primary emphasis was placed on optimizing basic design concepts, cost, weight and producibility.

Energy Absorption/Composite Materials With the exception of the automobile tests, the use of composite materials as energy absorbers or attenuators has been limited to low velocity impact applications such as bumpers (References 12, 13 and 14). There has been work on improving the energy absorption characteristics of composite materials at the micro or local structural level, but no correlation has been drawn between this research and its application in a crash environment.

Impact/Composite Materials There has been a great deal of research in the area of impact strength of composite materials but this research has been mainly directed toward local impacts produced by tool drops, foreign objects, missiles and particles. Although damage due to a local impact can compromise the compressive failure mode of a structure, the techniques used in determining this damage are not applicable to a crash impact involving gross structural deformations.

Compression Failure Mode/Composite Materials During a crash, the compression failure modes of the structure influence the energy absorption and crash impact behavior of the design. The work that has been done on metal structures has sought to predict and improve the post-buckling characteristics of the airframe structure, thereby increasing the energy absorbed during a crash (Reference 15).

The results of some tests conducted by General Dynamics-Convair to measure the load deflection characteristics of various aluminum plate-stringer panel configurations are shown in Figure 5. Note that the load deflection behavior of the integrally stiffened panel is poor in comparison to the rolled stringer sections because the failure mode was an explosive fracture. Also note that the load at initial failure was higher; this translates to higher inertia forces transmitted to the occupants and to the large mass items during a crash impact.



P_{cc} = CRIT. CRIP. LOAD

Figure 5. Load-deflection curves for various aluminum sheet/stringer panels.

In contrast to the work done on metallic structures, the research on the compression failure modes of composite materials has been concerned with predicting the static allowable load of a structural element. Some test results of typical research on compression failure modes are shown in Figure 6. The researchers were primarily interested in the post-buckling characteristics of these specimens and increasing the static allowable load and not the total load-deflection or energy absorbing characteristics of the structures.

As part of this study, an investigation was made to determine the usefulness of currently available plastic, large deformation structural crash simulations; especially those which can be applied to airframe structures of composite materials. This investigation was aided substantially by previous surveys of the crash simulation literature, particularly those done by Saczalski (Reference 16), McIvor, et al (Reference 17) and Kamat (Reference 18).

Use can be made of a mathematical crash simulation during the design process as shown in Figure 7. The key elements in this process are a set of design criteria and a valid crash simulation method. Inputs of structural behavior, which take the form of stress-strain curves or component crush test data, are used to predict the structure's dynamic response. The crashworthiness of the design can then be evaluated against the criteria to determine if it is satisfactory or if a redeisgn is necessary. During this process, some simulations require the assumption of internal crush modes while others are used to predict them. It should be noted that experimental crash simulations can also be used, but because of cost factors, are probably best used for validating the final design as determined by the analytical methods.

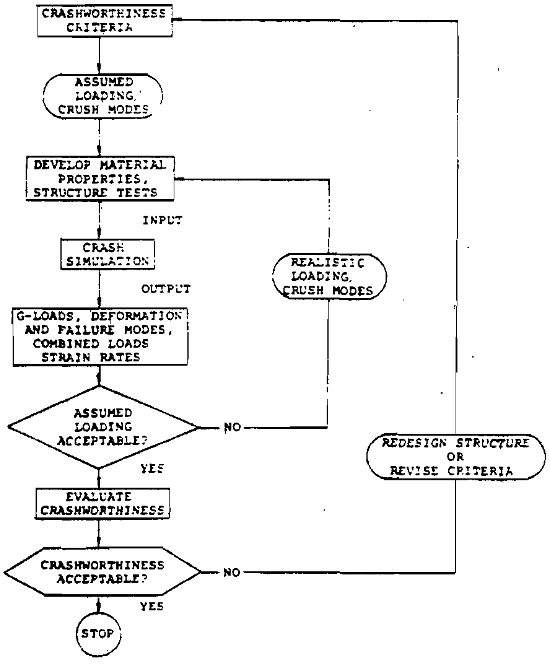


Figure 7. Computer crash simulation in vehicle design process.

The main characteristics used for evaluating the functionality of the mathematical crash simulations were:

- Capability Level
- Structural Model
- Mathematical Type
- Convenience Features

Other features which were of secondary importance in this investigation were: the mass model, the terrain and barrier model, the external loads, and the numerical solution procedure.

For this study three broad categories of capability level were established, along with potential uses during design. They are as follows:

Simple Capability These simulations can be used to evaluate gross responses and design trends. They feature:

1. Large structural assemblies modeled as single crush elements
2. Up to 10 masses, 50 degrees-of-freedom (unknowns in motion equations)
3. One or two dimensional geometry and motions

Intermediate Capability These simulations can be used for studies of structural design parameters and energy dissipation in subassemblies. They feature:

1. Structural subassemblies modeled separately, no sheet/skin panel model
2. Up to 100 masses, 500 degrees of freedom
3. Two or three dimensional geometry and motions

Detailed Capability These simulations can be used for predicting failure or collapse modes, and redesigning individual components. They feature:

1. Individual structural components modeled separately, including sheet/skin panels
2. More than 100 masses, 500 degrees of freedom
3. Three dimensional geometry and motions

ITEM	HYBRID	FINITE ELEMENT
PLASTIC COLLAPSE & CRUSH	ALL	ALL
WITH COMBINED LOADS	NONE	ALL EXCEPT SHIEH'S
MATERIAL FAILURE	ALL	NONE
WITH COMBINED LOADS	NONE	NONE
SKIN & BULKHEAD	ALL (POORLY)	WRECKER, WHAM, ACTION, DYCAST
ANISOTROPIC LAMINATES	ALL	DYCAST
CORED SANDWICHES	ALL	NONE
BEAM CROSS-SECTION DEFORM. (CRIPPLING)	ALL	NONE
JOINT DEFORM. & FAILURE	ALL	NONE
STRAIN RATE STIFFENING	KAMAL, HERRIDGE	WRECKER
WITH LOCAL VARIATIONS	NONE	WRECKER

Table I. Computer Crash Simulations Assessment.

bined loads, because the crash data inputs are derived from tests with a single load. All of the finite element codes, with the exception of Shieh's, can account for multiple load components. The crush test can furnish the hybrid computer codes with data to analyze orthotropic laminates and core-sandwich panels, while only "DYCAST", of the finite element codes, can analyze an orthotropic material, and none of the evaluated finite element codes can currently analyze a core sandwich. "WRECKER" is the only one of these codes which will account for strain rate effects in a logical way by determining the local strain rate and adjusting the stiffnesses. All the hybrids can account for joint failure and crippling, because these effects are part of the crush test data.

The major conclusions of this investigation on computer crash simulations for advanced material applications are:

1. That there is not a single existing code that is satisfactory
2. That hybrid codes are theoretically incomplete.
3. That finite element codes currently lack sufficient advanced material capability.

The recommendation for current crash simulations on advanced materials is to use "KRASH" with applicable crush test data for the preliminary parametric studies and gross evaluations. For a detail design, "DYCAST" can be used for analyzing orthotropic laminates. However, this code is still under development and has not yet been experimentally verified. It is not currently possible to perform an extensive detailed design evaluation of a structure with sandwich core construction. This type of construction seems to hold promise for increased energy dissipation with advanced composites.

Research in Progress

During the survey of the current data base of information on the crash impact behavior of composite structures, some pertinent research in-progress was found that has not yet been documented or made available to the public. The three areas of research in-progress that will be discussed are:

1. The NASA Langley study of airframe crashworthy design concepts for general aviation aircraft.
2. The Bell Helicopter testing of energy absorbing cylinders.
3. The Army testing of stiffened cylinders and helicopter fuselage structure sections.

Airframe Crashworthy Design Concepts

A joint FAA and NASA research program is in progress at Langley Research Center to develop valid, practical structural design criteria and improve crashworthiness design technology. The total program is shown in Figure 9. NASA, under the direction of R. Thomson, Crash Safety Program Group Leader, is conducting full-scale crash tests of light fixed wing aircraft, developing analytical techniques and evaluating crashworthy design concepts for seats and airframe structures.

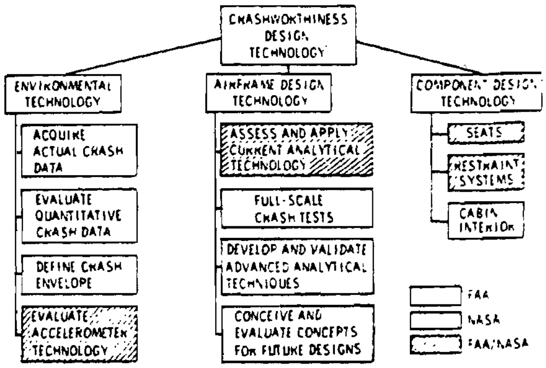


Figure 9. Joint FAA/NASA aviation crashworthiness program.

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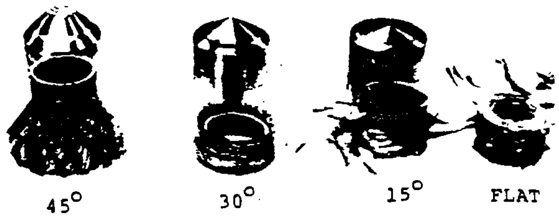
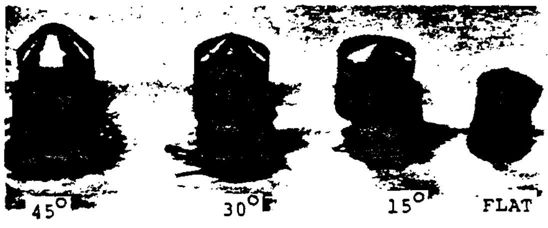


KEVLAR



FIBERGLASS

Figure 12. Static crush tests of composite tubes for various anvil angles.

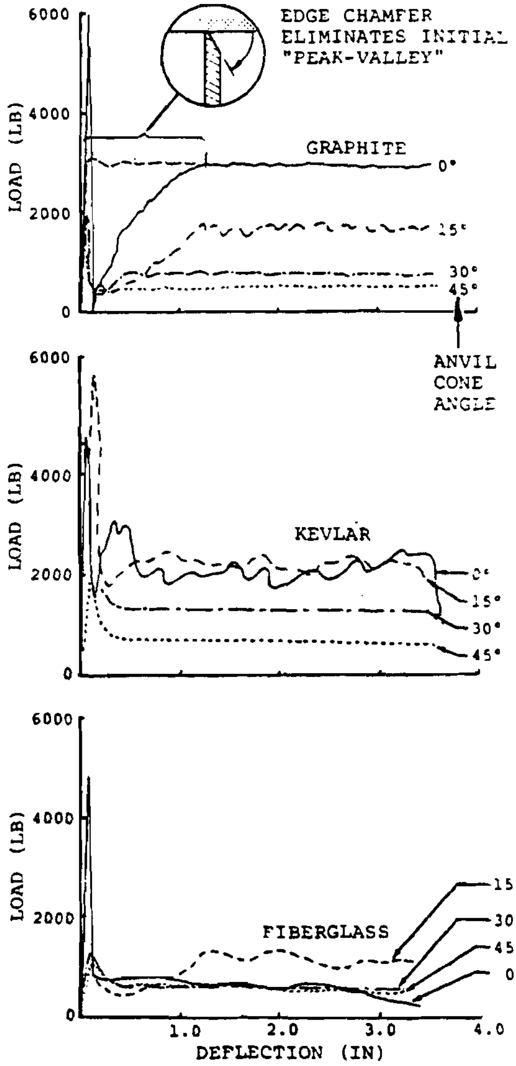


Figure 13. Load-deflection curves for energy absorbing composite tubes.

Composite Tube Energy Absorbers

When discussing composite fuselage structures, it generally is assumed that some other material is needed for energy absorption, but there does not appear to be any specific information available to support this assumption. Bell therefore conducted a study to investigate the energy absorption characteristics of some simple composite material deformation concepts. Composite tubes were designed with equivalent static strengths and filament wound at ±45° angles from three materials: graphite/epoxy, Kevlar/epoxy, and fiberglass/epoxy. These tubes are shown in Figure 12 after being crushed on coned anvils.

The specimens were statically and dynamically tested and exhibited good energy absorption characteristics with progressive failure and a flat, rectangular shaped load-deflection curve as shown in Figure 13.

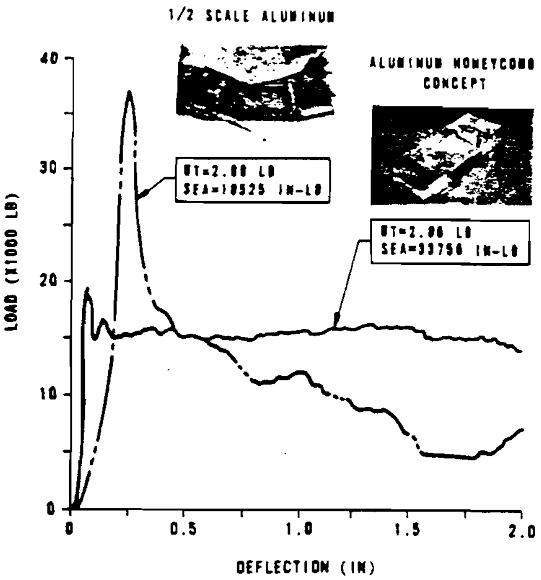


Figure 15. Load-deflection curves for half-scale structure sections.

Crashworthiness Design Criteria

There are many considerations in the design of a crashworthy airframe structure. For this investigation, only those that relate to the crash impact characteristics of airframe structures constructed of composite materials will be discussed. These crashworthy design considerations are as follows:

1. Maintaining an airframe protective shell for occupant protection
2. Providing tiedown strength to react the applied inertia forces to large mass items
3. Designing for breakaway airframe structure to reduce the total mass
4. Reducing occupant strike hazards within the cabin area
5. Absorbing energy by fuselage crushing
6. Reducing post-crash hazards
7. Designing for failure modes

Discussions of crashworthy design considerations can be found in the Army's Crash Survival Design Guide (Reference 1) and many other sources, for example, References 15, 37, 38, and 39.

DESIGN CONSIDERATIONS	ARMY MIL-STD-1290, TR 71-22	NAVY AP-56	AIR FORCE MIL-A-8865 [illegible]	FAA FAR [illegible]
AIRFRAME PROTECTIVE SHELL	●	●		●
BREAKAWAY AIRFRAME STRUCTURE	●			
OCCUPANT STRIKE HAZARDS	●			
ENERGY ABSORPTION	●			
POST CRASH HAZARDS	●			
FAILURE MODES	●			
INERTIA FORCES TIEDOWN STRUCTURE	●	●	●	●

Figure 16. Airframe structure crashworthiness criteria and current design criteria.

These design considerations have been addressed in civilian and military regulations, standards and specification wherein they have been formulated into criteria. A summary of available criteria and the crashworthy design considerations addressed by each is presented in Figure 16.

By far the most comprehensive crashworthiness requirements document is MIL-STD-1290 (Reference 2). MIL-STD-1290 establishes minimum crashworthiness design criteria which, when implemented in the initial stages of aircraft systems design, will provide aircraft possessing improved crash safety characteristics. This standard was based on the design guidelines of the Crash Survival Design Guide. Because these criteria represent a needed capability, crash impact survivability, modification of this criteria in any manner that would reduce the level of crash protection to be provided was not considered. Although some of the material properties of composites run counter to the material properties preferred for crashworthy structures (e.g., low ductility, fracture, and splintering), nothing learned in this investigation indicates that the crashworthiness of MIL-STD-1290 cannot be met with structures constructed from composite materials. On the contrary, the aforementioned Budd Co. automotive effort with fiberglass/polyurethane foam sandwich panels and tubes indicates that crashworthy composite structures are possible through innovative design. Certainly satisfying the crashworthiness guidelines shown in Figure 1 with composite structures is challenging; however, available R&D results indicate that the challenge is not so much one of simply meeting the criteria, rather it is how to do so without significantly compromising the

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2.2 General Aviation Aircraft

The permission of the authors for the reproduction of the following paper by Thomson and Goetz originally presented at the AIAA/ASME/ASCE/AHS 20th Structures, Structural Dynamics, and Materials Conference April 4-6, 1979 and subsequently in the August 1980 issue of the Journal of Aircraft is acknowledged gratefully.

AIAA 79-0780R

NASA/FAA General Aviation Crash Dynamics Program—A Status Report

R.G. Thomson and R.C. Goetz

Reprinted from

Journal of Aircraft

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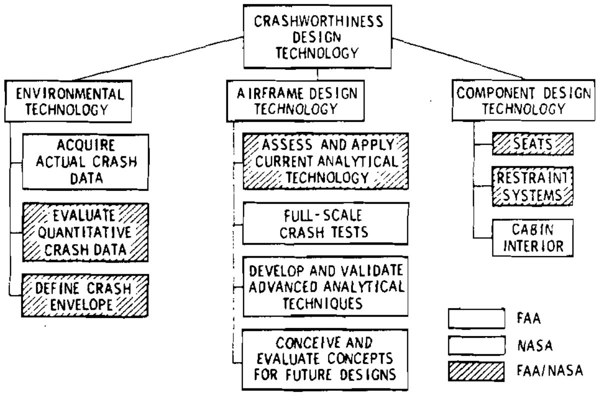


Fig. 1 Agency responsibilities in joint FAA/NASA general aviation crashworthiness program.

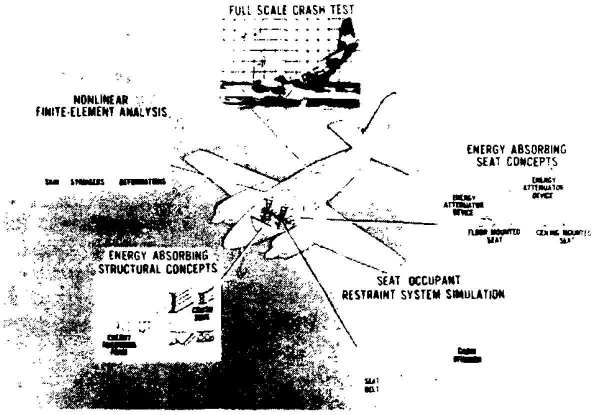


Fig. 2 Research areas in Langley general aviation crash dynamics program.

The aircraft is released after rocket ignition, and the rockets continue to burn during most of the downward acceleration trajectory but are dormant at impact. The velocity augmentation method provides flight path velocities of 26.8-44.7 m/s (60-100 mph) depending upon the number and burn time of the rockets used.

Instrumentation

Data acquisition from full-scale crash tests is accomplished with extensive photographic coverage, both interior and exterior to the aircraft using low-, medium-, and high-speed cameras and with onboard strain gages and accelerometers. The strain gage type accelerometers (range of 250 and 750 g at 0-2000 Hz) are the primary data generating instruments, and are positioned in the fuselage to measure accelerations both in the normal and longitudinal directions to the aircraft axis. Instrumented anthropomorphic dummies (National Highway Traffic Safety Administration Hybrid II) are on board all full-scale aircraft tests conducted at Langley. The location and framing rate of the cameras are discussed in Ref. 1. The restraint system arrangement and type of restraint used vary from test to test.

Tests Conducted

A chronological summary of the full-scale crash tests conducted at the Impact Dynamics Research Facility is represented in Fig. 4. The shaded symbols are crash tests that have been conducted, the open symbols are planned crash tests. Different symbols represent different types of aircraft under different impact conditions; for example, ○ represents a twin-engine specimen impacting at 26.8 m/s (60 mph) while △ represents the same twin-engine specimen, using the velocity augmentation method, impacting at 40.2 m/s (90 mph). Various types of aircraft have been successfully crash tested at Langley from 1974 through 1978 including CH-47 helicopters, high and low wing single-engine aircraft, and aircraft fuselage sections. Data from these tests are presented in Refs. 2-6. The aircraft fuselage section tests are vertical drop tests conducted to simulate full-scale aircraft cabin sink rates experienced by twin-engine aircraft tested earlier. The response of the aircraft section, two passenger seats, and two dummies are being simulated analytically (see section on Nonlinear Analysis). Some single-engine crash tests were conducted using a dirt impact surface but most were conducted on a concrete surface. The dirt embankment was 12.2 m (40 ft) wide, 24.4 m (80 ft) long, and 1.2 m (4 ft) in depth. The dirt was packed to the consistency of a ploughed field with a CBR of approximately 4. The variation of full-scale crash test parameters is not complete and does not consider such effects as aircraft overturning, and cartwheeling, fire, or tree and obstacle impact.

Controlled Crash Test and Las Vegas Accident

On Aug. 30, 1978, a twin-engine Navajo Chieftain, carrying a pilot and nine passengers crash landed in the desert

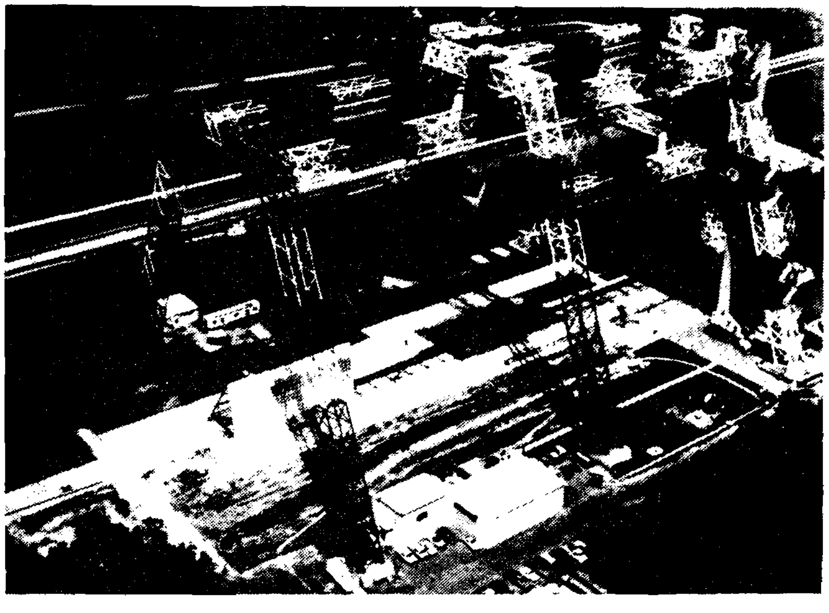


Fig. 3 Langley Impact Dynamics Research Facility.

collapse response of such structures under implusive loadings. Two specific computer programs are being developed, one focused on modeling concepts applicable to large plastic deformations of realistic aircraft structural components, and the other a versatile seat/occupant program to simulate occupant response. These two programs are discussed in the following sections.

Plastic and Large Deflection Analysis of Nonlinear Structures (PLANS)

Description

For several years Langley has been developing a sophisticated structural analysis computer program which includes geometric and material nonlinearities.[8,9] PLANS is a finite element program for the static and dynamic nonlinear analysis of aircraft structures. The PLANS computer program is capable of treating problems which contain bending and membrane stresses, thick and thin axisymmetric bodies, and general three-dimensional bodies. PLANS, rather than being a single comprehensive computer program, represents a collection of special-purpose computer programs or modules, each associated with a distinct physical problem. Using this concept, each module is an independent finite element computer program with its associated element library. All the programs in PLANS employ the "initial strain" concept within an incremental procedure to account for the effect of plasticity and include the capability for cyclic plastic analysis. The solution procedure for treating material nonlinearities (plasticity) alone reduces the nonlinear material analysis to the incremental analysis of an elastic body of identical shape and boundary conditions, but with an additional set of applied "pseudo loads." The advantage of this solution technique is that it does not require modification of the element stiffness matrix at each incremental load step. Combined material and geometric nonlinearities are included in several of the modules and are treated by using the "updated" or convected coordinate approach. The convected coordinate approach, however, requires the reformation of the stiffness matrix during the incremental solution process. After an increment of load has been applied, increments of displacement are calculated and the geometry is updated. In addition to calculating the element stresses, strains, etc., the element stiffness matrices and mechanical load vector are updated because of the geometry changes and the presence of initial stresses. A further essential ingredient of PLANS is the treatment of dynamic nonlinear behavior using the DYCAST module. DYCAST incorporates various time integration procedures, both explicit and implicit, as well as the inertia effects of the structure.

Comparison with Experiment

PLANS is currently being evaluated by comparison with experimental results on simplified structures. In the order of increasing complexity these structures are: an axial compression of a circular cylinder; a tubular structure composed of 12 elements with symmetric cross sections joined at common rigid joints; an angular frame composed of asymmetric angles and bulkheads with nodal eccentricities at the rigid joints; and the same angular frame covered with sheet material. Static and dynamic analyses of these structures loaded into the large deflection plastic collapse regime have been conducted with PLANS and compared with experimental data in Ref. 10 and reported on in Ref. 11. Presently an analytical simulation of a vertical drop test of an aircraft section is being compared with experimental full-scale crash data. Preliminary computer deformation patterns are shown in Fig. 8 using an implicit Newmark-Beta integration algorithm. The use of implicit time integration methods, for this particular nonlinear problem, resulted in more practical time steps than was previously obtained using an explicit Adams Predictor-Corrector algorithm. The results of this study are reported in Ref. 12.

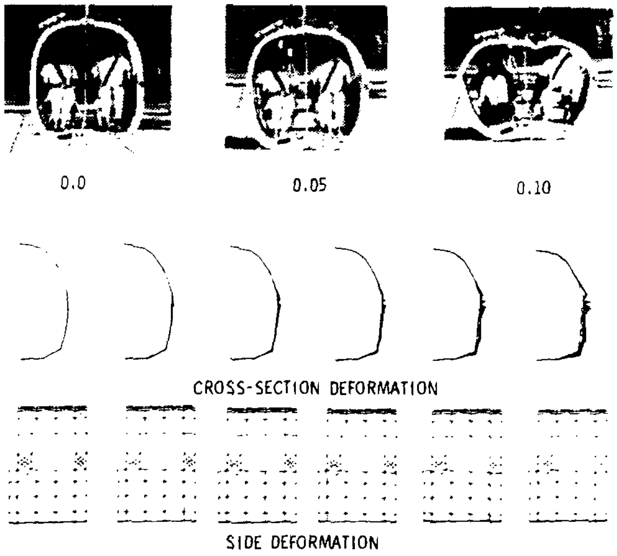


Fig. 8 Computer deformation patterns of an aircraft section impacting rigid surface with vertical velocity of 9.1 m/s (30 ft/s).

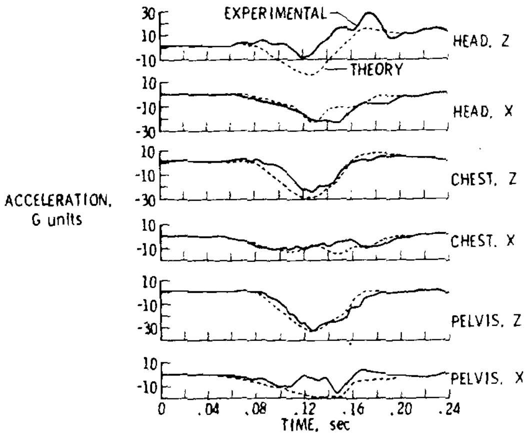


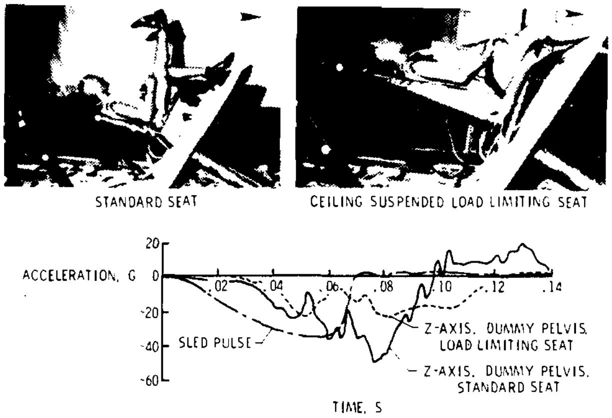
Fig. 9 Experimental and computer dummy accelerations for the −30 deg, 27 m/s full-scale crash test.

Modified Seat Occupant Model for Light Aircraft (MSOMLA)

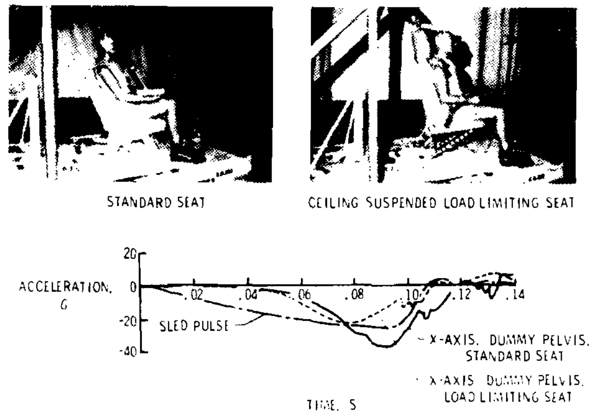
Description

Considerable effort is being expended in developing a good mathematical simulation of occupant, seat, and restraint system behavior in a crash situation. MSOMLA was developed from a computer program SOMLA funded by the FAA as a tool for use in seat design.[13] SOMLA is a three-dimensional seat, occupant, and restraint program with a finite element seat and an occupant modeled with 12 rigid segments joined together by rotational springs and dampers at the joints. The response of the occupant is described by Lagrange's equations of motion with 29 independent generalized coordinates. The seat model consists of beam and membrane finite elements.

SOMLA was used previously to model a standard seat and dummy occupant in a NASA light aircraft section vertical drop test. During this simulation, problems were experienced with the seat model whenever the yield stress of an element was exceeded. Several attempts to correlate various finite element solutions of the standard seat with OPLANE-MG, DYCAST, and SOMLA, using only beam and membrane elements, to experimental data from static vertical seat loading tests were only partially successful. Consequently, to expedite the analysis of the seat/occupant, the finite element seat in SOMLA was removed and replaced with a spring-



(a) "VERTICAL" (-30° PITCH, 10° ROLL)



(b) "LONGITUDINAL" (30° YAW)

Fig. 12 Pelvis accelerations for dummy in standard and ceiling-mounted (load limiting) seat subjected to "vertical" and "longitudinal" sled pulses.

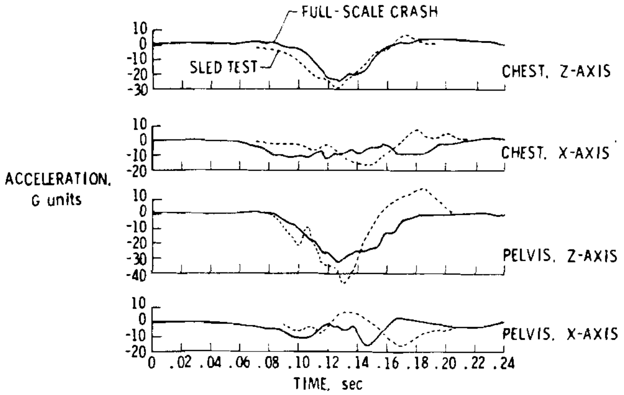


Fig. 13 Dummy accelerations from sled test and from a full-scale crash test under similar impact conditions.

50th percentile dummy instrumented with accelerometers loaded the seats and restraint system on impact. The restraint system for these seats consisted of continuous, one-piece, lap belt and double shoulder harness arrangement.

Time histories of dummy pelvis accelerations recorded during two different impact loadings are presented in Fig. 12 with the dummy installed in a standard seat and in a ceiling-mounted, load limiting seat. The vertical impulse of Fig. 12a positioned the seats (and dummy) to impact at a pitch angle (angle between dummy spine and direction of sled travel) of −30 deg and a roll angle of 10 deg. In the "longitudinal" pulse (Fig. 12b) the seats were yawed 30 deg to the direction of sled travel. The sled pulses are also included in the figure and represent the axial impulse imparted to the inclined dummies. The x- and z-axis of the dummy are local axes perpendicular and parallel to its spine, respectively. The figure shows that for both impact conditions the load limiting seat in general provided a sizable reduction in pelvis acceleration over those recorded during similar impacts using the standard seat.

The impact condition associated with a dummy passenger in one of the full-scale NASA crash tests were quite similar to those defined by the sled test of Fig. 12a, particularly in terms of velocity change, thereby permitting a gross comparison of their relative accelerations. Figure 13 shows that comparison. Although the dummy acceleration traced from the two tests are similar in both magnitude and shape, some phase shift is evident. This agreement suggests that sled testing provides a good approximation of dummy/seat response in full-scale aircraft crashes.

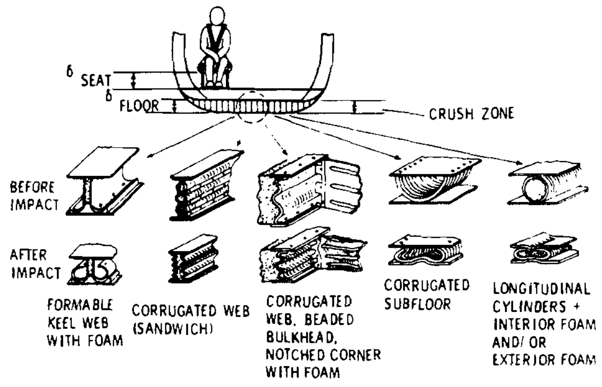


Fig. 14 Load limiting subfloor concepts.

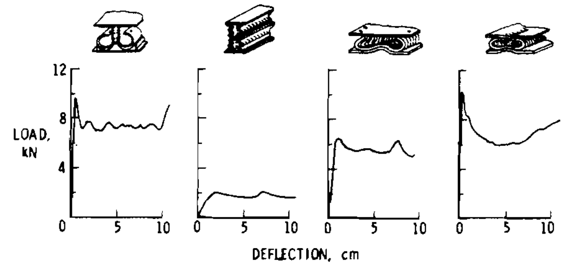


Fig. 15 Load deflection curves for load limiting subfloor concepts.

Subfloor Structure

The subfloor structure of most medium size general aviation aircraft offers about 15-20 cm (6-8 in.) of available stroking distance, which suggests the capability to introduce a velocity change of approximately 8.2 m/s (27 ft/s) (see Fig. 10). Aside from that necessary for routing hydraulic and electrical conducts some volume is available within the subfloor for energy dissipation through controlled collapse. A number of energy absorbing subfloor concepts have been advanced and Fig. 14 presents sketches of five prominent candidates. The first three concepts, moving from left to right, would replace existing subfloor structure and allow for: 1) the metal working of floor beam webs filled with energy dissipating foam; 2) the collapsing of precorrugated floor beam webs filled with foam; or 3) the collapsing of precorrugated foam-filled webs interlaced with a notched lateral bulkhead. The remaining two concepts eliminate the floor beam entirely and replace it with a precorrugated canoe (the corrugations running circumferentially around the cross-section) with energy dissipating foam exterior to the canoe; and foam-filled Kevlar cylinders supporting the floor loads.

2.3 Transport Aircraft

In addition to some discussion of helicopters and general aviation aircraft, the following two papers contain excellent reviews of transport crash response research. These two papers are reproduced in full in the following by the kind permission of the authors.

AIAA-81-0803

Designing for Aircraft Structural Crashworthiness

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Langley Research Center,
Hampton, VA; and C. Caiafa,
Federal Aviation Administration,
Atlantic City, NJ

AIAA/SAE/ASCE/ATRIF/TRB
1981 International
Air Transportation Conference

50th Anniversary
1981

May 26-28, 1981/Atlantic City, New Jersey

and crew are jeopardized.

The two primary factors contributing to fatalities in transport accidents are trauma resulting from impact forces and fire. The total financial loss for commercial jets between 1952 and 1977 due to accidents is estimated at $1.4 billion.[15] These estimates include 98 hull losses at $600 million, hull damage at $280 million, and 2800 liability cases (fatals only) at $520 million.

The initial effort in this program is focused on a definition of a meaningful research program based in part on a careful study of all transport accident data from 1958-1979. These data have revealed that approximately 80 percent of fatal commercial transport accident occur on or near airports during either approach, landing, or take-off operations. The aircraft during these operations is typically below normal cruise speed and it would appear that potential for survivability could be enhanced through applied crashworthiness technology in the design of the airplane.

General Aviation Crash Dynamics Program

In 1972, the FAA, NASA, and industry embarked on a cooperative effort to develop technology for improved crashworthiness and occupant survivability in general aviation aircraft. The effort included analytical and experimental verification of structural airframe and seat configuration modifications to limit the loads transmitted through the airframe and seat subsystem to the occupant. The methods and concepts developed in the general aviation crash dynamics program will be examined and evaluated to determine their applicability to the transport crash dynamics program. The current research efforts in the general aviation program are expected to make possible future aircraft design concepts having enhanced survivability under specified crash conditions with little or no increase in weight and acceptable cost. A research program intended to accomplish this objective is defined by five technical areas indicated in figure 2. A summary of the pertinent technical accomplishments performed in four of these technical areas - full-scale crash simulation, airframe structural concepts, dynamic analysis methods, and seat/restraint system concepts - are discussed in the following sections (under general aviation crash dynamics). The five technical areas indicated in figure 2 are also applicable to transport crash dynamics including the data base technical area. Under the transport crash dynamics program accident data pertinent to crash dynamics are being examined as a data base to identify fruitful areas of crashworthiness research and to define transport crash scenarios.

Full-Scale Crash Simulation

Full-scale free-flight crash tests were conducted in the Impact Dynamics Research Facility, Langley Research Center in which deceleration histories and structural deformation modes were measured in twenty-four fixed wing and two helicopter crash tests.[16-22] A comparison was also made between accident field data for a twin-engine airplane and controlled full-scale twin-engine airplane crash test.[23] These test data indicated that the impact loads ("G" forces) measured in the cabin area in the vicinity of the seats and in the dummy pelvic region were, in most cases, above human tolerance levels even though the livable volume and integrity of the cabin area had been maintained.[24] The need for more uniform and controlled "crushing" of the subfloor and vertical stroking load attenuating mechanisms for seats became apparent from these full-scale crash simulations.

Airframe Structural Concepts

The cabin floor of a twin-engine aircraft involved in a fatal accident is shown in figure 3.[23] The floor undulations were the result of crushing and overturning moments exerted by the seated occupants as the front legs of the seats applied compressive loads to the floor while, at the same time, the rear legs experienced a tensile loading. The intersections of the longitudinal beams and the lateral bulkheads in the floor provided "hard points" or columns which are very efficient load paths from the under belly of the airplane to the seat rails.

The airframe structural design philosophy developed under the general aviation program is illustrated in figure 4. The concept is simply to provide an integral stiff upper floor (approximately 5 cm (2 in.)) to maintain structural integrity between the floor and seat and to prevent seat rotation (either transverse or longitudinal) but not allow the floor panels and floor beams to separate. The lower subfloor is designed to provide a uniform crush zone and various structural subfloor concepts have been developed in which the floor beams and lateral bulkheads were modified.[25] One such concept which features corrugated floor beams with notched corners at the intersections of the beams with the lateral bulkheads, is shown in figure 5, along with an unmodified airplane section. These airplane sections are approximately 120 cm (47 in.) long by 107 cm (42 in.) in width and represent the first passenger row location behind the pilot and the copilot.

Static crush test results are shown in figure 5 for the two subfloor sections. The unmodified subfloor section exhibits much higher (15 kip) crush loads than the modified subfloor (10 kip) and experienced loss of structural integrity between the floor panels and floor beams by buckling of the floor beams (sudden decrease in load) and tearing of the floor panels. The same amount of work (area under the load deflection curve) is involved in the two static crushes but the work is much better controlled in the modified section. Dynamic tests were also conducted on the modified and unmodified sections and a dynamic analysis was performed for comparison with the experimental data. The static crush data of the corrugated beam with notched corners was used as input to the analytical model in the form of nonlinear spring elements representing the corrugated beams. The dynamic test was a vertical drop test onto a concerte surface with an impact velocity of 7.3 m/s (24 fps). The results are presented in figure 6 and show the lower floor accelerations provided by the modified subfloors. The agreement between theory and experimental data (pelvis mass acceleration) for the modified corrugated beam subfloor is excellent.

crashworthy design were realized within the aviation community and in particular by the U. S. Army. With this realization, design philosophy evolved based on accident data, whereby safety features which would reduce injuries/fatalities in a crash were incorporated early in the aircraft design stages. Having a similar objective, three identical transport accident study contracts were awarded to Boeing Commerical Aircraft Company, Lockheed-California Company and Douglas Aircraft Company, (Long Beach). The specific tasks in these three contracts are summarized as follows:

(a) To review and evaluate transport aircraft accident data, define a range of survivable crash conditions or crash scenarios that may form a basis for developing improved crashworthiness design technology.

(b) To identify structural features and subsystems that influence injuries/fatalities in the crash scenarios defined in (a).

(c) Define areas of research and approaches for improving transport crashworthiness.

(d) Identify test techniques, analytical methods, etc. needed to assess and evaluate the crash response of transport aircraft.

The data base for this study began with a review of the 993 transport accidents which had occurred between the years 1958-1979 and the establishment of a selection process. First disregarded were those accidents in which the structural airframe played no significant role, such as in flight turbulence accidents or maintenance personnel accidents on the ground. Next to be disregarded were the more severe, nonsurvivable midair collision accidents, from the accident data base. In an objective, but somewhat unavoidably subjective manner, a combined total of 241 "survivable" accidents remained to form the data base. The criteria that was generally applied in the selection process included the following conditions: (1) at least 15% of the cabin volume was maintained, (2) the trauma forces were estimated to be within human tolerance levels, and (3) at least one survivor was identified. In a few isolated cases the one survivor condition was waivered when it was felt that trauma forces were within human tolerance levels but a fire hazard existed. The distribution of accident data is illustrated in figure 10. The three transport manufacturers generally examined different accidents, but some accidents were examined by all three manufacturers as indicated in the figure by the cross-hatched area, some by two of the three as indicated by the hatched areas, and other accidents solely by one manufacturer (primarily the accidents involving his aircraft).

Some preliminary survivable accident scenarios are evolving from the studies and are being used in defining classes of accidents. The scenarios consist of four different accident conditions:

(I) A hard landing involving high sink speed with gear collapse, wheels-up airplane attitude, and some swerve. The ranges of forward speed and sink speed are 65 to 82 m/s (126 to 160 knots) and 3 to 10 m/s, respectively. The airplane attitude is symmetrical with $\leq$ 15° pitch, on the runway or within 200 m of the runway.

(II) A collision with an obstacle on the ground (ditch, light poles, vehicles, etc.) with gear down, level airplane attitude, and swerve. The ranges of forward speed and sink speed are 31 to 51 m/s (60 to 100 knots) and $\leq$ 1.5 m/s, respectively. The airplane is in a symmetrical, level, attitude on the runway or within 500 m of the runway.

(III) A severe impact on runway with gear down, high angle of attack and ranges of forward speed and sink speed of 57 to 103 m/s (110 to 200 knots) and 1.5 to 10 m/s, respectively. Airplane attitude; pitch 0°-5°, roll ±5°- ±45°, yaw 0°-10°, on runway.

(IV) A severe ground/water impact off runway with gear up or down, high angle of attack collision, and ranges of forward speed and sink speed of 51 to 103 m/s (100 to 200 knots) and 1.5 to 10 m/s, respectively. Airplane attitude; pitch 0°-45°, roll ±5°- ±45°, yaw 0°-10°, off runway.

The range of impact conditions for these scenarios are tentative and are only given as an illustrative example in this paper. Until such time that all data are finalized, these scenarios and parameter ranges are subject to change.

Fuel Containment

One of the identifiable structural features and subsystems that influence injuries/fatalities in transport accidents is the wing structure fuel tank system. Fuel spillage from a damaged wing structure is one of the primary causes of catastrophic fires and passenger fatalities. The accident studies, previously addressed, clearly identify mechanisms in which wing structure damage could result in fuel spillage; namely, for example, main gear penetration into the fuel tank area, wing-mounted engine pylon failure, or simply failure of the wing structure itself.

Fuel containment is also a research area in which advanced analytical techniques will play a role in analyzing the response of the wing tank to localize crash loadings and studying the main gear and engine pylon failure mechanisms. The nonlinear analytical techniques developed under the general aviation crash dynamics program will be applied to these unique nonlinear transport failure mechanisms. Consideration of advanced composite structural materials and their effect on structural behavior and failure mechanisms must be included in future transport airplane design. The necessary modeling capability for nonlinear dynamic composite structural analysis needs to be developed and verified, first on an element level, and then on more representative aircraft structural component level Full-scale dynamic testing of instrumented inboard wing tank and fuselage sections subjected to impact (with obstacles) under controlled deceleration and attitude conditions are also anticipated. These full-scale dynamic tests may

Concluding Remarks

The FAA, NASA, and industry have initiated a transport crash dynamics program to develop technology to define and demonstrate new structural concepts that will enhance passenger and crew survivability by minimizing crash force trauma and the potential fire hazard caused by fuel spillage. This technology will facilitate the integration of crashworthy structural design concepts into transport design methods and will consider airframe, seat, floor, fuel tanks and landing gear behavior. In addition, the potential of anti-misting kerosene additives to reduce the fire hazard are to be determined as well as the additives compatibility with aircraft engines.

The dynamic nonlinear behavior of structural components will be determined analytically and verified by full-scale and scaled dynamic tests. The nonlinear analytical techniques developed under the general aviation crash dynamics program will provide a foundation for application to metal transport structure. Consideration of advanced composite structural materials and their affect on structural behavior and failure mechanisms will be studied and design tools developed to aid in future transport airplane design.

In the development of transport crash scenarios, a thorough evaluation of accident data will be made to provide a fundamental understanding of occupant injury mechanisms and aircraft structural response. The effort will be a continuing one, with both industry and government participation and should provide a data base from which design philosophy can evolve. Close cooperation with other governmental agencies is being maintained to provide data on human tolerance limits concerning the magnitude and duration of deceleration levels, toxicity levels, and heat exposure.

To date, the U. S. Army experiences indicate that crashworthy design technology has been a most productive art not only in reducing injuries/fatalities but in achieving these benefits economically. Through continued research and development efforts of government and industry significant gains can be achieved in reducing transport crash hazards by crashworthy design technology.

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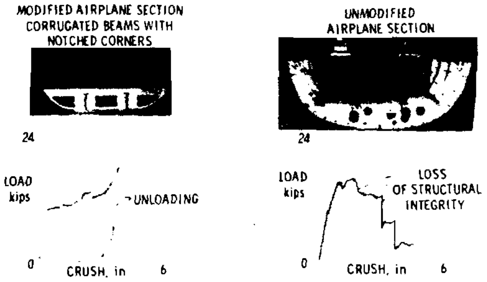

Fig. 5 Static tests of load-limiting subfloor structures.

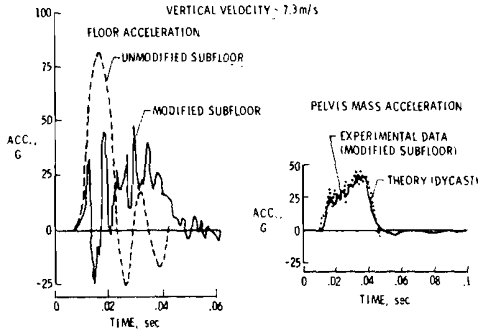

Fig. 6 Dynamic tests and analysis of load-limiting subfloor structures.

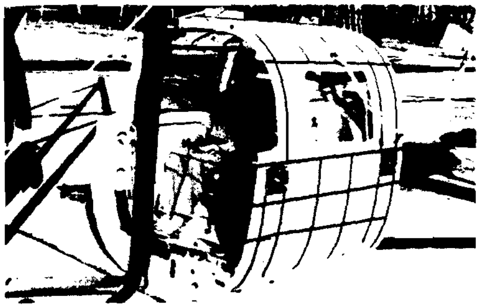

Fig. 7 Fuselage section drop - test specimen.

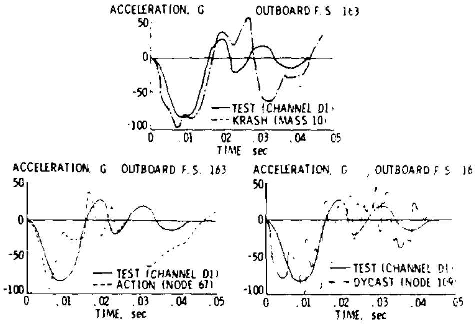

Fig. 8 Comparison of fuselage floor outboard vertical accelerations.

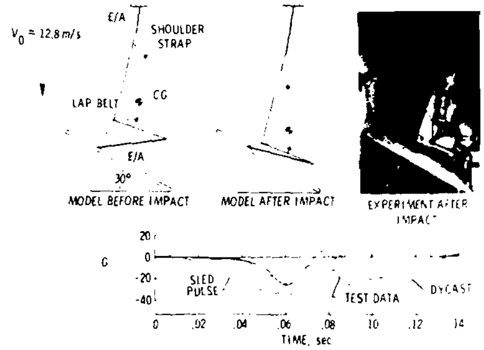

Fig. 9 Analytical & experimental pelvis acceleration in load-limiting seat.

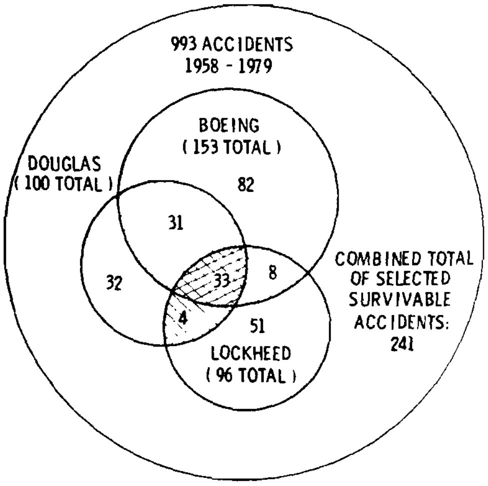

Fig. 10 Selection of transport accidents for study.

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82-0694

ANALYSIS OF AIRCRAFT DYNAMIC BEHAVIOR IN A CRASH ENVIRONMENT

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Abstract

Differences in the crash environments and design aspects which influence occupant survivability in military and commercial aircraft are discussed. Available analytical techniques for assessing structural behavior during a crash are described. The application of a hybrid technique in assessing aircraft structural behavior and trends in crash environments is provided. Representative mathematical simulations of aircraft crash tests and correlation with light fixed-wing and rotary-wing aircraft test results are shown. The results of a recent FAA/NASA sponsored research program involving the review of transport accidents from 1964–79 and the formulation of potential crash scenarios to be considered with future analysis and test verification are presented. Current and future analytical model studies to ascertain the crash dynamics of large transports are also discussed.

INTRODUCTION

In the 1955–1965 era, a popular approach to a determination of aircraft structural crash design capability was to perform full-scale crash tests. Tests of this nature are extremely expensive, particularly as the test article increases in size, such as current wide-body jets have. In addition to cost, the test conditions are not repetitive, the results are highly dependent on the impact conditions, and airplane configuration, as well as measurement selection; consequently, essentially only one test parameter data set per test is available. Unfortunately during this time period, there was limited correlation with analysis and extrapolation of the test data. However, the 1970s witnessed significant advances in computer modeling of nonlinear crash dynamic behavior, both at the substructure and airframe level. In particular, hybrid (combining analytical and empirical data) and finite element techniques have had the opportunity to be correlated with test data generated for the purpose of verifying and improving the analytical methods. This paper describes differences in the crash environment associated with various categories of aircraft, discusses experimental verification of hybrid analysis with light fixed-wing and rotary-wing aircraft, and describes efforts to develop analytical techniques for transport aircraft.

Crash Environment

The definition of the crash environment is essential before any aircraft crash dynamics capability can be determined. Unfortunately, no single crash environment is applicable to all aircraft. Size, speed, configuration, and operational aspects associated with aircraft influence the crash environment. No universal definition of a crash environment is therefore possible. Descriptions of a survivable crash can include velocity envelopes, crash pulses, crash load factors, and crash scenarios. Comparison of the survivable crash environment and responses of the structures indicates significant differences between small and large aircraft. The survivable large transport accident usually occurs around airports at flight path velocities below 150 knots and vertical descent rates at less than 20 ft/sec. These conditions are normally associated with such landing and take-off operations as landing short, overruns, and skidding off the runway. Smaller aircraft, such as helicopters and general aviation airplanes, have lower longitudinal velocities but higher vertical rates of descents during a crash condition; they can include stall/spin and emergency landings on unprepared terrain. The percentage of occupiable space in large transports greatly exceeds that of smaller aircraft. Furthermore, occupants of small aircraft are much closer to the airframe/terrain impact point due to obvious airframe construction differences. The crash pulses experienced by transport occupants varies along the length of the fuselage moreso than do the pulses for the smaller aircraft.

The crash environment for military helicopters, as defined by 95th percentile survivable crash pulses in different directions, was established for U.S. Army helicopters on the basis of 373 accidents that occurred between the time period July 1960 and June 1965[1]. In a recent update of the U.S. Army Crash Survival Design Guide[2] the recommended design environment was presented as the design pulse. Although the crash environments are identical to the historical 95th percentile survivable crash pulse, the U.S. Army recognizes that improved crashworthiness increases the severity of the survivable crash, thereby producing a never-ending increase in the level of crashworthiness at the expense of aircraft performance. The U.S. Army defines a survival envelope[2] as "the range of impact conditions – including magnitude and direction of pulses and the duration of forces occurring in an aircraft accident – wherein the occupiable area of the aircraft remains substantially intact, both during and following the impact, and the forces transmitted to the occupants do not exceed the limits of human tolerance when current state-of-the-art restraint systems are used." The U.S. Army design pulses are applicable to all aircraft in a given category regardless of weight and operational requirements. Figure 1[2] shows a three-dimensional envelope of combined longitudinal, lateral and vertical velocity (ft/sec) changes for helicopters.

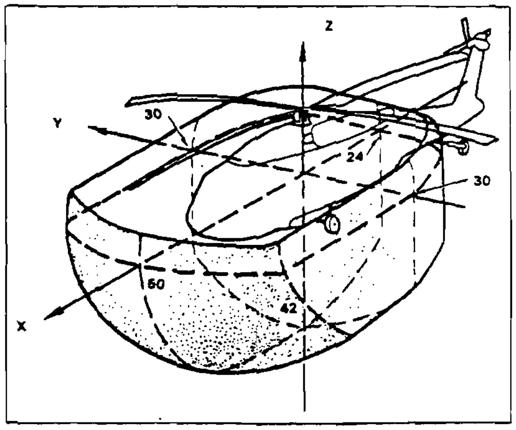

Fig. 1 Three-dimensional display of design velocity change envelope for helicopters.

Light fixed-wing (general aviation) aircraft weighing ≤ 12,500 pounds operate at speeds up to 280 knots, carry 1 to 17 people, have one or two engines, and have a low- or high-wing configuration. Aircraft of this type can be involved in stalls, ground collisions, and collisions with obstacles. Accidents[3] have occurred on terrains that are flat (≈ 40%), rolling (≈ 22%), mountainous (≈ 11%), hilly (≈ 8%), or dense with trees (≈ 9%) and at airports

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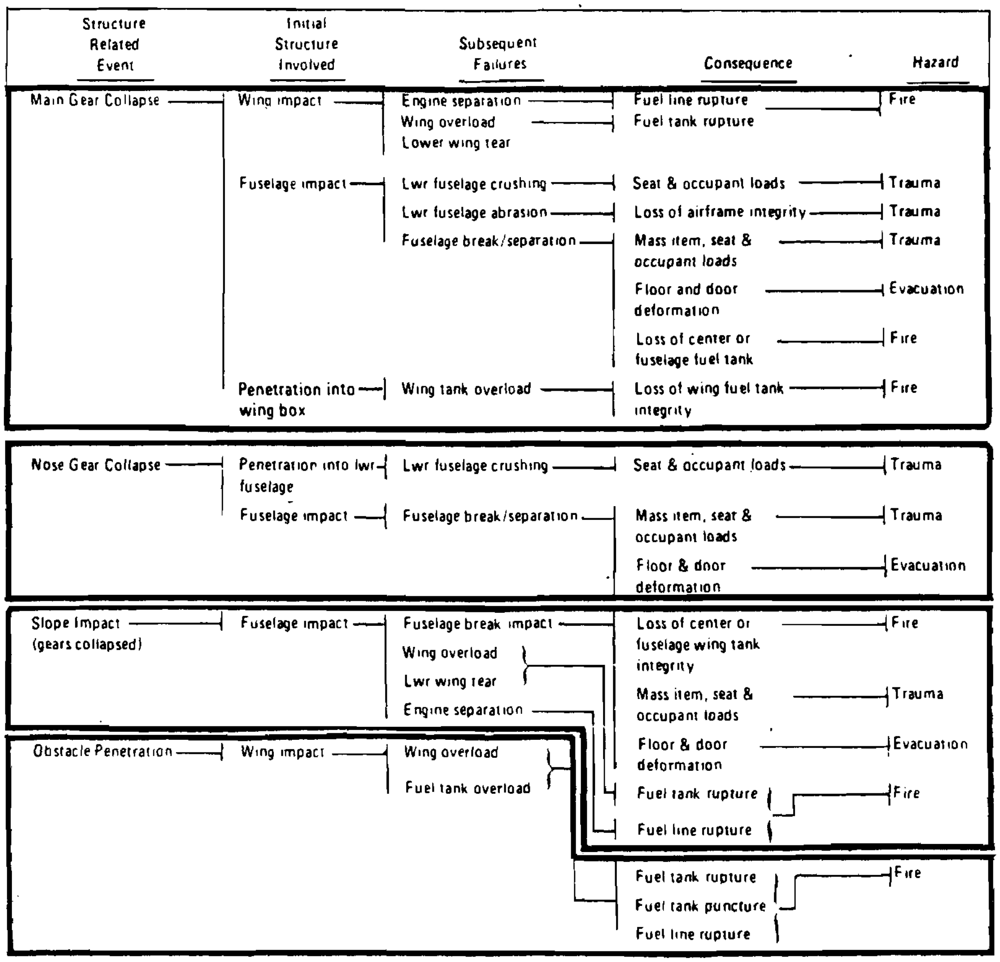

Fig. 4 Flow diagram, candidate crash scenario.

configuration for a combined vertical (23 ft/sec) and lateral (18.5 ft/sec) full scale crash test of a utility type helicopter. Figure 8[12] shows the post-impact configuration for four full-scale crash tests of a single-engine high-wing general aviation aircraft type. In both crash test programs high-speed film, accelerometer recorded data and deflection measurements were used to correlate test and analysis results. The test conditions for the fixed-wing aircraft are provided in Table 4. The aircraft configurations noted in Figures 7 and 8 were used to help verify program KRASH as an analytical tool for crash dynamics.

Table 2 Summary of transport airplane fixed-wing crash test conditions.

AIRPLANE	APPROXIMATE WEIGHT, Kg	(lbs)	VELOCITY m/sec	(ft/sec)	SLOPE (DEGREES)
C-82	19026	(42,000)*	40.8	(133.8)	16
LODESTAR	9739	(21,500)*	39	(127.9)	12
			48.8	(160.2)	16
C-46	18120	(40,000)	41.4	(136.7)	14
			43.5	(142.6)	27
L1649	72027	(159,000)	52.4	(172.0)	8
			33.5	(110.0)	20
DC-7	55266	(122,000)*	67.2	(220.6)	8
			49.3	(161.7)	20

*MAX TAKEOFF WEIGHTS, TEST WEIGHT NOT STATED

Table 3 Comparison of peak decelerations and durations.

AIRPLANE	LONGITUDINAL DECELERATION g	APPROXIMATE DURATION SEC
FIGHTER, FH-1	40	≤.02
PACKET-TYPE CARGO, C-82	15	.02
UNPRESSURIZED TRANSPORT, LODESTAR	16	.05 - .08
PRESSURIZED TRANSPORT, C-46	9	.200

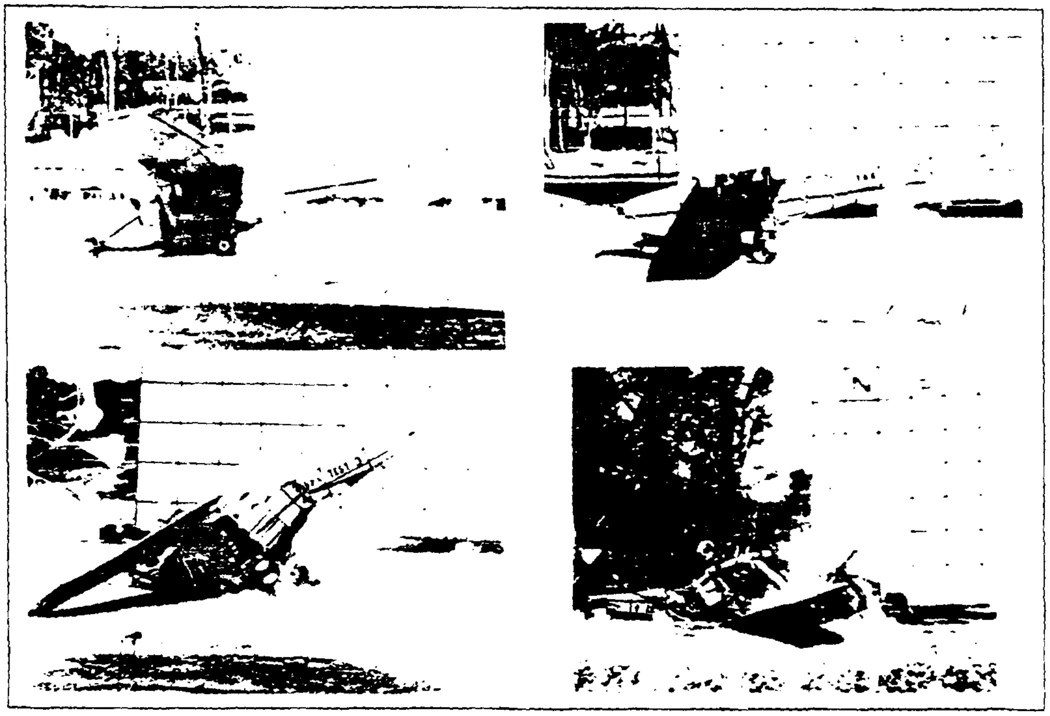

Fig. 8 Post-test damage, single-engine, high-wing airplanes crash tests.

light airplane substructure[14] utilized almost three times as many Degrees of Freedom (DOF) in the detail finite element model as compared with the more approximate hybrid lumped mass model. In addition, the computer time and cost using the finite element model was also shown to be two orders of magnitude greater than the hybrid method, yet with the conclusion that the hybrid analytical results were closer to the test results. Table 5[9] indicates various types of analyses and ranges of techniques that could be used for transport airplanes in the future. Part of the rationale, for not necessarily having to develop an analytical model in extreme detail, is as follows:

- During many of the potential crash conditions (runway overrun, hard landing, gear collapse) the overall vehicle remains intact and, to a first approximation, behaves linearly
- Nonlinear behavior is restricted to localized areas mostly on the lower extremities of the airplane in direct contact with the ground
- Since local crushing and nonlinear behavior is not sufficiently widespread throughout the airplane to alter the basic linear behavior of the overall structure, lumped masses, driven at selected discrete locations representative of local crushing behavior, could be used to predict the dynamic response of the overall airplane structure.

For compliance with governing criteria the impact loads, acting at the fuselage, landing gear, wing engine attachments must be within their respective structural strengths, otherwise additional

Table 4 Summary of single-engine, high-wing airplane crash test impact conditions.

	TEST NUMBER			
	1	2	3	4
IMPACT VELOCITIES (MPH)				
ALONG FLIGHT PATH	55.5	50.8	58.1	56.0
LONGITUDINAL	47.4	48.6	47.6	48.4
VERTICAL	28.7	14.8	33.2	31.9
ANGLES (DEGREES)				
FLIGHT PATH (γ)	-30.72	-17	-34.86	-32
IMPACT (θ)	-30.17	13.6	-39.4	-34.8
ATTACK (α)	.47	+30.6	-4.54	-2.8
ROLL (φ)	+4.13	+3.26	+18.76	1.0
YAW (ψ)	-3.27	-11.8	-7.8	1.0
ROTATIONAL VELOCITIES (DEG/SEC)				
PITCH (θ̇)	40.4	6.9	14.3	18.2
ROLL (φ̇)	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE
YAW (ψ̇)	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE

γ IS NEGATIVE IN DIVE
θ θ̇ ARE POSITIVE NOSE UP RELATIVE TO GROUND
α IS POSITIVE NOSE UP RELATIVE TO FLIGHT PATH
φ φ̇ ARE POSITIVE RIGHT WING DOWN
ψ ψ̇ ARE POSITIVE TAIL LEFT AND θ = γ + α
FT/SEC = 1.467 X MPH

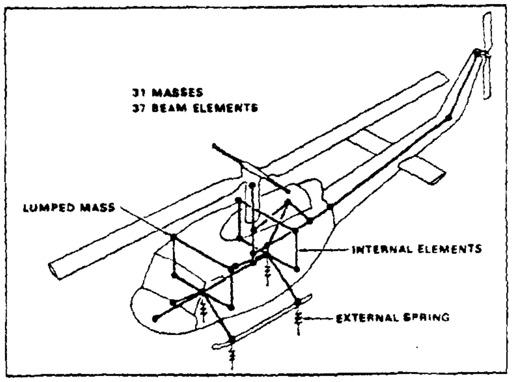

Fig. 9 Helicopter analytical model.

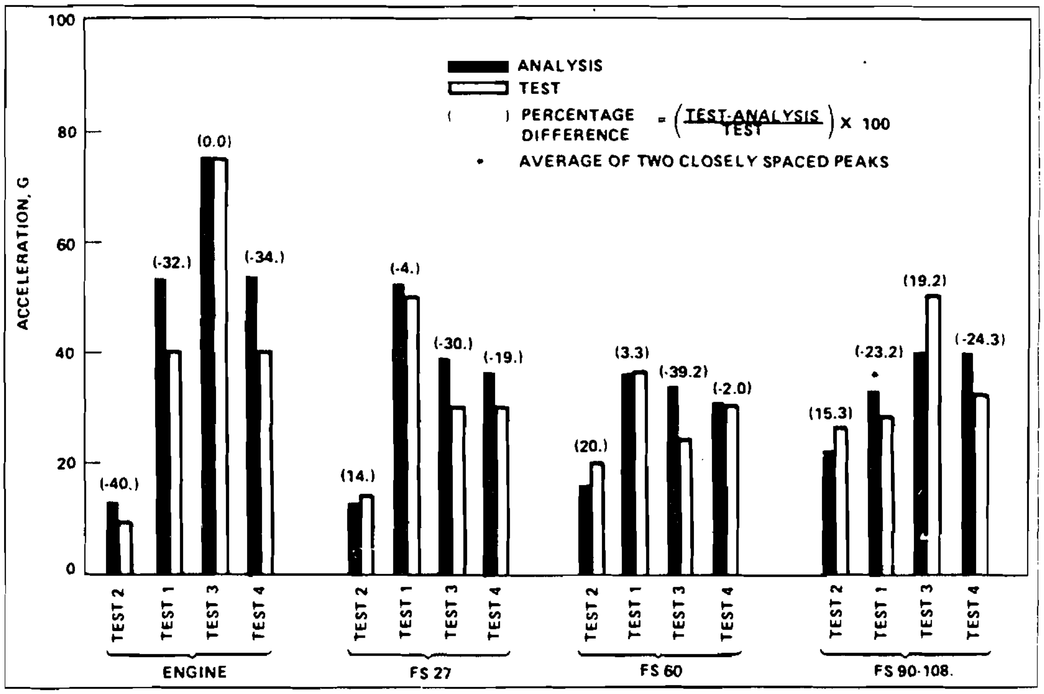

Fig. 13 Single-engine, high-wing airplanes analysis and test longitudinal responses

course, a full model to treat unsymmetrical impact condition increases the model size, and consequently, the cost of analysis approximately 60 percent. One can easily visualize that the floor and support structure could vary from aircraft to aircraft and from one section to another. Figure 18 illustrates some interior arrangement in a 1950s vintage narrow body airplane. The output desired from the model illustrated in Figure 16 would be the floor pulse as an input to an occupant seat configuration. Since different regions of the fuselage can exhibit their peak response at different times, the math model representing one portion of the crash sequence could realistically be run for 100 to 300 milliseconds of simulated crash time.

The airframe model is used to obtain fuselage responses which are subsequently input to a floor model, to obtain floor pulses. A

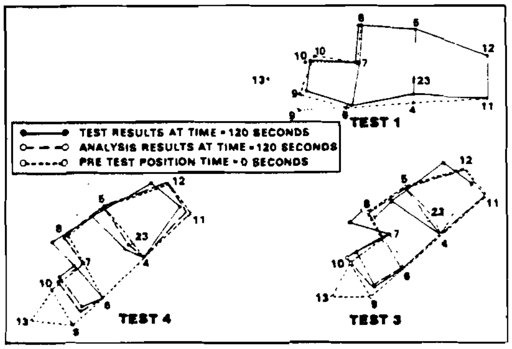

Fig. 14 Single-engine, high-wing airplanes analysis and test deformations.

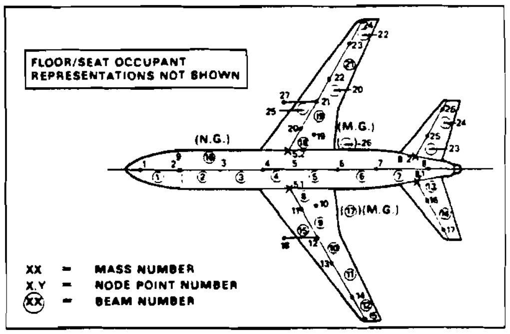

Fig. 15 Transport category airplane airframe analytical model.

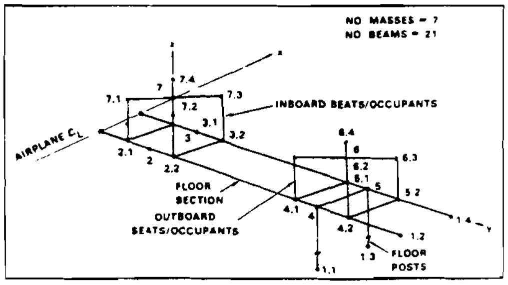

Fig. 16 Single-row transport floor, analytical model

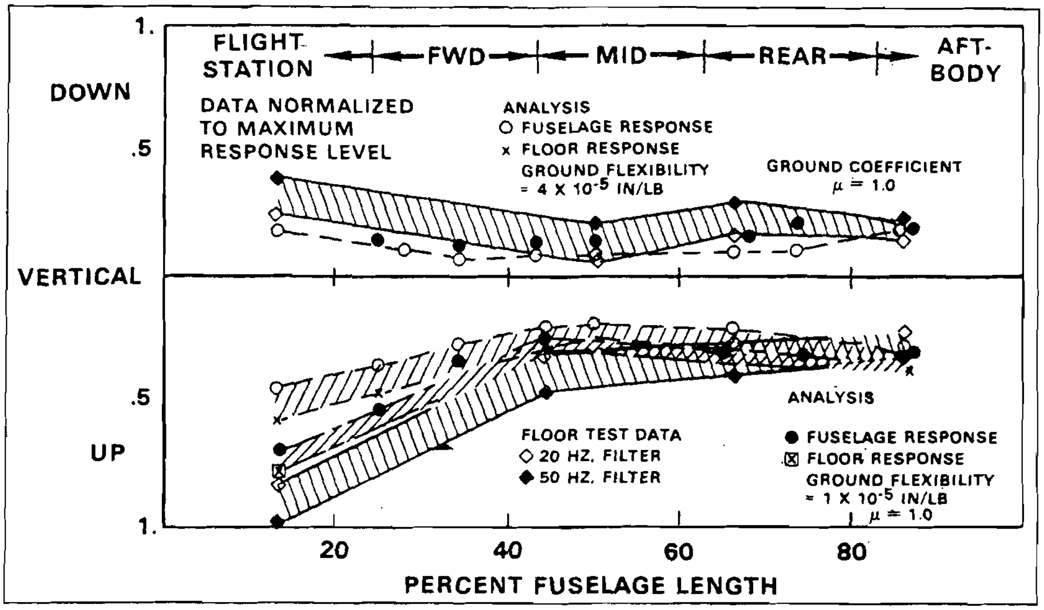

Fig. 19 Vertical acceleration versus fuselage location, slope impact.

integration interval as necessitated by the floor model requirements.

In addition, since the hybrid KRASH program has proved valuable in assessing trends a change in one parameter; i.e. occupant weight, would require a total rerun at the maximum time and at a finer integration interval if the airframe, floor and seat/occupant models were combined. In the modular approach outlined above, only the last model (seat/occupant) need be revised.

Occupant survivability is the ultimate goal in the design for crash considerations. The transport aircraft seating configuration and the range of passengers size and weight vary considerably. For example, there are two and three seat configurations which may or may not be fully occupied. Even, if occupied, the weights of the individual could vary from 5th percentile females to 95th percentile males. The response and loading of each occupant seating configuration could vary for the same floor pulse excitation.

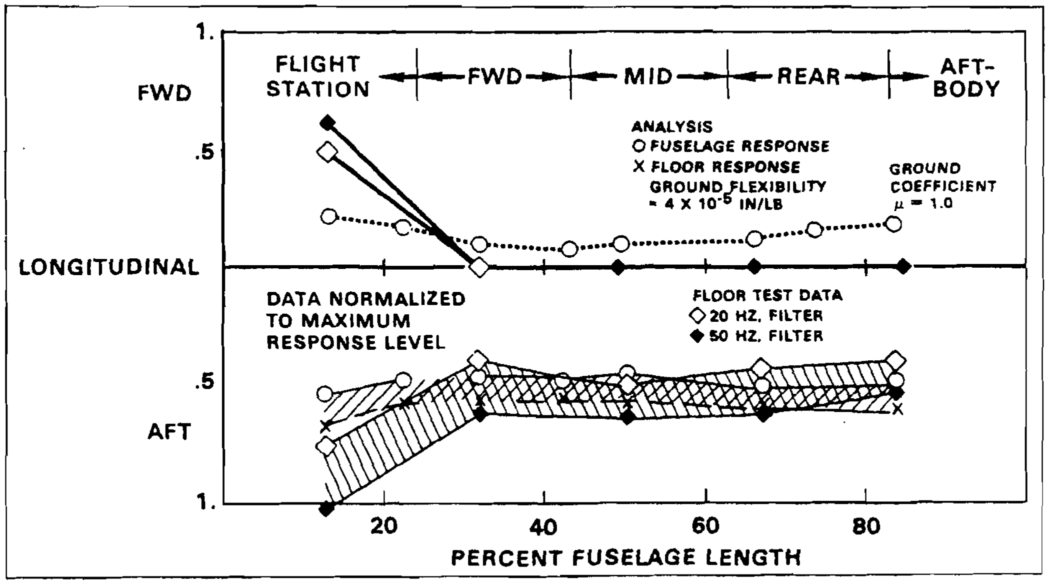

Fig. 20 Longitudinal acceleration versus fuselage location, slope impact.

SECTION 3

RECENT STUDIES OF THE BEHAVIOR OF COMPOSITE MATERIALS AND STRUCTURES UNDER STATIC AND/OR CRASH-IMPACT CONDITIONS

The literature on composite materials and structures has undergone an explosive growth especially in the past 10 years of the past two decades. Very extensive studies on the mechanical, failure, and postfailure behavior of many types of materials, layups, and structural arrangements have been investigated and reported for many types of static, dynamic, impact, and loading situations. Very significant advantages and improvements have been demonstrated by the use of composite materials and structural concepts to replace former all-metallic construction in both secondary and primary structures.

Because of the vastness of the composite materials/structures literature, it is feasible in this review to call attention to only a few of the more recent developments reported in the literature. In particular, attention is called to the following three volumes of recent technical papers [22, 23, and 24, respectively]:

1. Lenoe, E.M., Oplinger, D.W., and Burke, J.J. (Editors), Fibrous Composites in Structural Design, Plenum Press, New York and London, 1980.

2. J.R. Vinson (Editor), Emerging Technologies in Aerospace Structures, ASME, New York 1980.

3. I.H. Marshall (Editor), Composite Structures, Applied Science Publishers, Ltd, Essex, England, and Applied Science Publishers, Inc., Englewood, New Jersey 1981.

In addition, the Journal of Composite Materials has reported many valuable developments in the past 15 years.

In the following subsections, brief reviews of selected papers from these sources are given. These topics include: (a) crashworthiness tests of composite fuselage structure, (b) impact resistance of graphite and hybrid configurations, (c) the effects of elastomeric additives on the mechanical properties of epoxy resin and composite systems, (d) unsymmetrical buckling of thin initially-imperfect orthotropic plates, (e) finite element analysis of instability-related delamination growth, (f) elastic-plastic flexural analysis of laminated composite plates, and (g) behavior and analysis of bolted joints in composite structures. There are, of course, in the literature many papers on each of these topics. Those chosen for this review are considered to be reasonably typical of the current state of the art. Also, the topics selected represent only a small portion of those pertinent to the mechanical behavior and analysis of composite-material structures under loading conditions simulating crash-response conditions.

cone. Both are reminiscent of forward fuselage shapes and both are practical test articles. Presently the cylindrical configuration is chosen for testing.

The cylindrical specimens in these tests were 18 inches long and 9 inches in diameter. The former dimension approximates the typical distance between frames in a cargo helicopter fuselage. The circumference is approximately four times the typical stringer spacing. Three design concepts were tested: internally hot stiffened with solid skin, a similar externally stiffened concept, and an unstiffened honeycomb sandwich design.

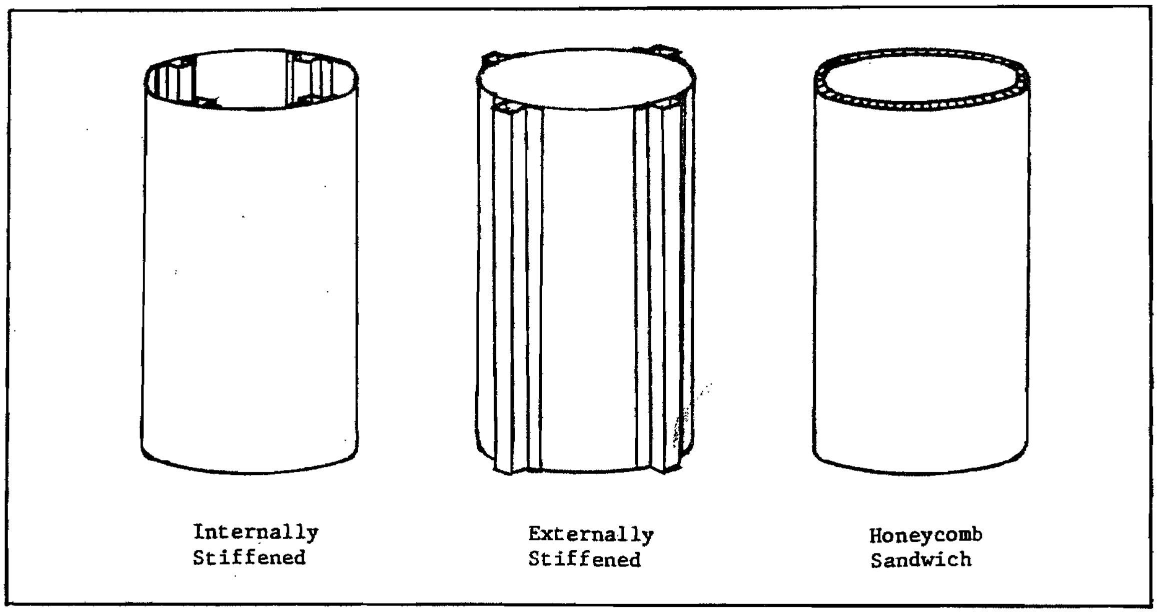

Figure 3.1. Test Specimen Concepts (Ref. 25)

All of the specimens were required to have an ultimate compression strength of at least 20,000 lbs. and an initial torsional stiffness of at least 100,000 lbs. per inch of circumference. The external stringer concept is not practical in fuselage but it does facilitate the observation of stringer behavior.

The longitudinally stiffened cylinders had four hat stiffeners spaced equally (90^{o} intervals) around the circumference while the sandwich specimens all used .25 inch thick aluminum honeycomb core of 6 pcf density. Longitudinal joints in the aluminum specimens were all spaced 90^{o} apart and were located at the stiffeners so that symmetry was maintained. Each test specimen was potted at each end in an epoxy compound to prevent edge splitting and delamination (Fig. 3.2).

At least four different material combinations were used with each of the three design concepts. For each, a metal baseline specimen was constructed from 2024-T3 aluminum. The skin thickness was 0.025" and 0.012" for the stiffened and sandwich specimens respectively, while the aluminum stiffener thickness was 0.032". The stiffened aluminum specimens were riveted together with protruding-head aluminum rivets.

Two additional test specimens were constructed which intentionally differed from the specifications given above. One was a Kevlar skin/graphite external stiffener design while the other was a Kevlar skin/aluminum external stringer design. The following table contains a summary of the material/design combinations of each test specimen.

TEST SPECIMEN LIST

SPEC. NO.	TYPE	SKIN MATL.	SKIN THICK. (IN)	STIFFNER MATL.	STIFFNER THICK. (IN)	CORE MATL.	JOINT CONCEPT	FIBER ORIEN.	
								SKIN	STIF.
IA	IS	AL	0.025	AL	0.032		R		
IB	IS	FG	0.050	FG	0.060		B	±45	0/90
IC	IS	FG	0.050	FG	0.060		B	±45	0/90
ID	IS	GR	0.032	GR/K49	0.070		B	±45	0/±45
IE	IS	GR	0.032	GR/K49	0.070		B	±45	0/±45
IF	IS	K49	0.050	GR/K49	0.070		B	±45	0/±45
IG	IS	K49	0.050	GR/K49	0.070		B	±45	0/±45
IIA	ES	AL	0.025	AL	0.032		R		
IIB	ES	FG	0.050	FG	0.060		B	±45	0/90
IIC	ES	GR	0.032	GR/K49	0.070		B	±45	0/±45
IID	ES	K49	0.050	GR/K49	0.070		B	±45	0/±45
IIE	ES	K49	0.050	GR/K49	0.070		B&R	±45	0/±45
IIF	ES	K49	0.050	AL	0.032		B&R	±45	
IIIA	HS	AL	0.012			AL	R		
IIIB	HS	FG	0.060			AL	B	0/90	
IIIC	HS	GR	0.048			AL	B	0/±45	
IIID	HS	K49&GR	0.060			AL	B	0/±45	

IS - Internal Stringer
ES - External Stringer
HS - Honeycomb Sandwich
B - Bonded
R - Riveted
AL - Aluminum 2024-T3
FG - Fiberglass/Epoxy
GR - Graphite/Epoxy
K49 - Kevlar 49/Epoxy

The test procedure involved placing one of the cylindrical specimens between the heads of a hydraulic testing machine and slowly compressing it axially until it was approximately one-half its original length. An initial 1000 lb. load was applied to securely seat the specimen to the heads. The total axial load was measured with a load cell and the output continually plotted against head motion on an X-Y recorder.

Typical specimens were loaded to ultimate strength at roughly 0.04 inches/minute of head motion, and at 1 inch/min. beyond ultimate load. Within this range of testing rates the residual load carrying capacities of the specimens were insensitive to changes in rate. These rates are several orders of magnitude slower than those experienced in crashes, however.

A typical plot of compression load vs. relative head motion is given in Fig. 3.5. Buckling of the skin was always evident prior to the attainment of peak load for the stiffened cylinders but not for the sandwich cylinders. When ultimate load was reached, there was a sharp and pronounced decrease in the load level. The failed cylinders invariably continued to support load in a spurious manner as fractures progressed. Despite the load irregularities in this region, an average post-ultimate load carrying capability could easily be discerned. This load level began to increase only when one or more of the broken stiffeners made contact with the end epoxy potting compound and began to support load again.

With the observation that a localized volume of material undergoes the primary fracture and deformation it may be surmised that the energy absorption

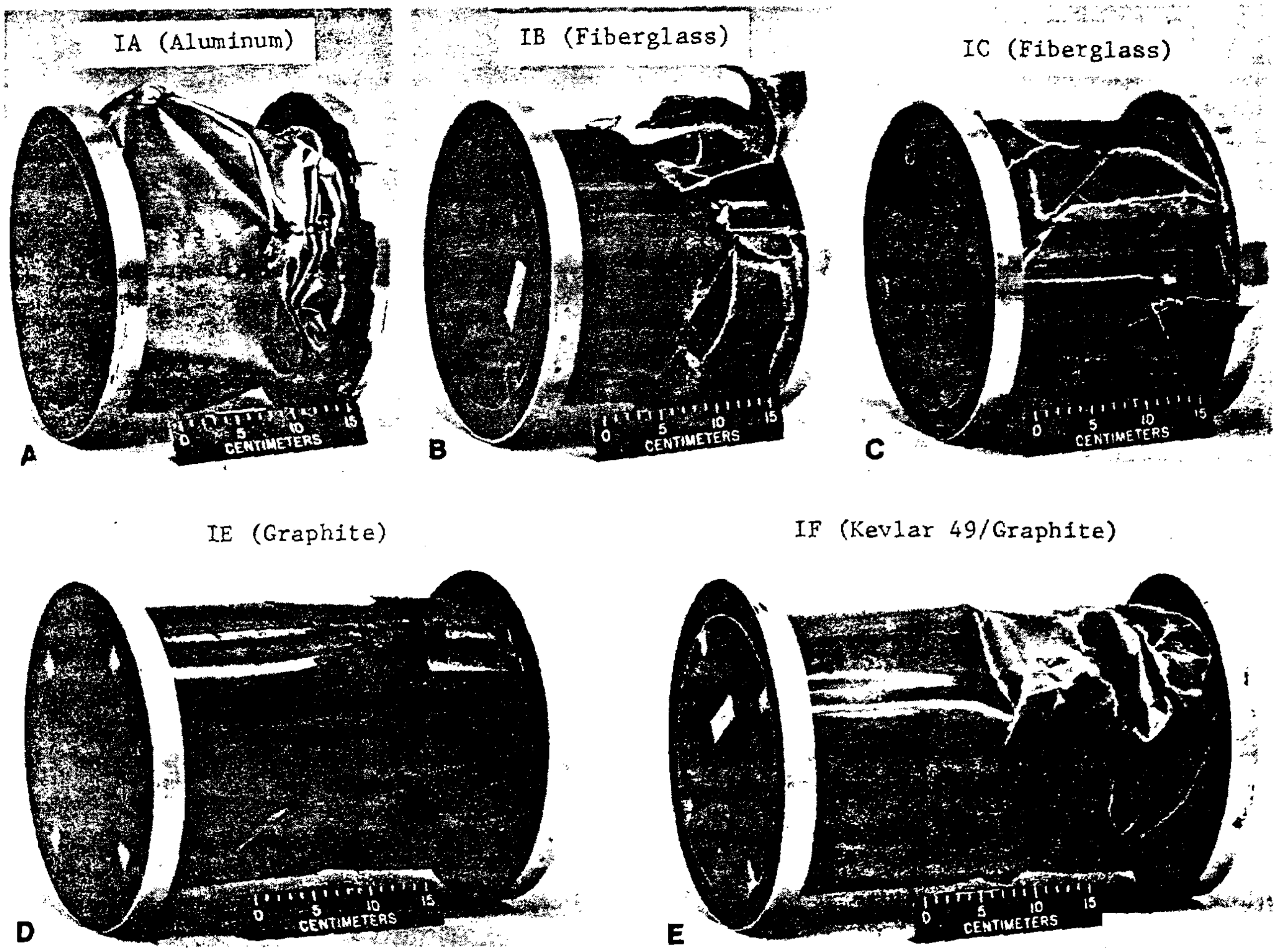

Figure 3.6. Internally-Stiffened Specimens after Failure (Ref. 25)

The noteworthy features of the tests performed on hybrid Kevlar 49/graphite stiffener specimens were the absence of skin tearing and rebounding following removal of the load. The interior view (Fig. 3.7) showed considerable splitting and separation of the stiffeners. The load capacity was only slightly superior to that of the all-graphite specimen.

Results for Sandwich Cylinders

Cylindrical sandwich cylinders were also tested in each of the four basic material configurations. None were observed to buckle prior to the attainment of ultimate load. These appeared to be overdesigned judging from their compression curves (Fig. 3.11). The post-ultimate behavior of these specimens bore little resemblance to those of the stiffened cylinders. In all cases it emerged that widespread delamination of the sandwich was a major energy absorption device.

Initial failure occurred near one end of the aluminum cylinder (Fig. 3.12). The maximum load exceeded twice that of the stiffened shell. The failure was followed by progressive petaling of the skins as they delaminated from the honeycomb core, which led to longitudinal tearing of the skins. The energy absorption was higher than that of the stiffened aluminum specimen.

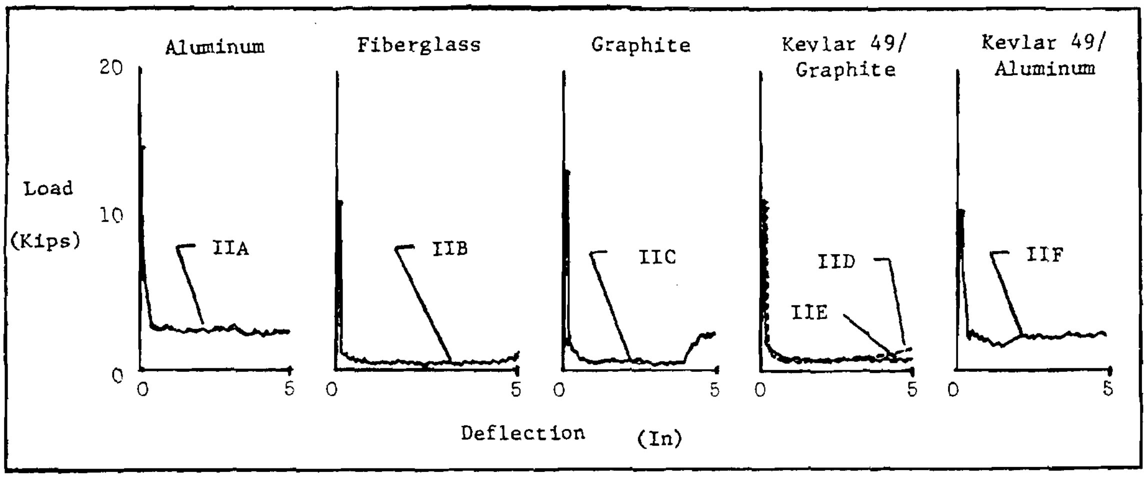

Figure 3.9. Load/Deflection Curves for Externally Stiffened Specimens (Ref. 25)

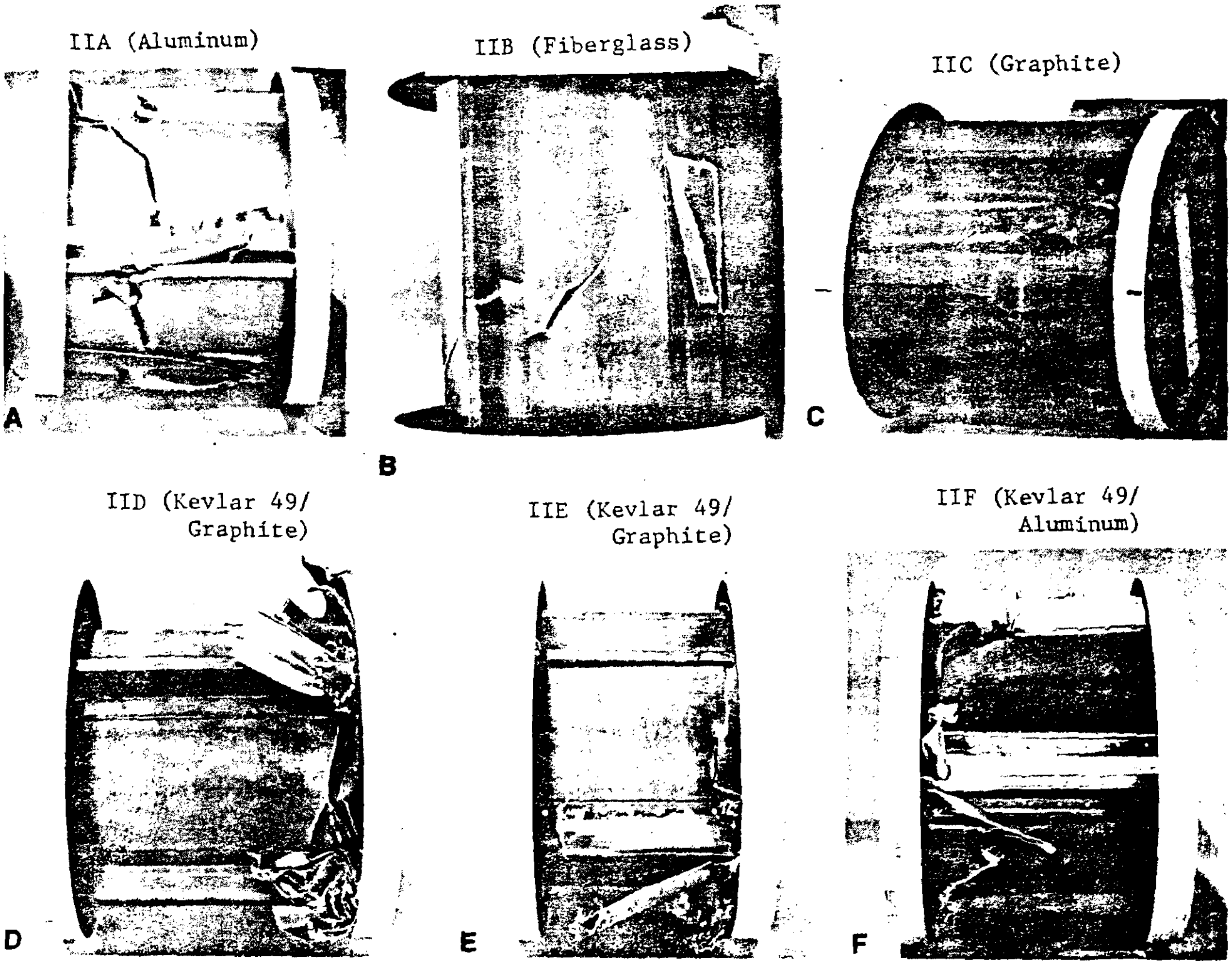

Figure 3.10. Externally Stiffened Specimens After Failure (Ref. 25)

The graphite sandwich specimen failed at 39,500 lbs. as a result of circumferential skin cracking or buckling. The post-ultimate behavior was characterized by cusping of the skin at the points of fracture and progressive delamination of the skin from the core. Energy absorption was much higher than that of the stiffened cylinders.

Similar response was observed for hybrid Kevlar/graphite sandwich design (Fig. 3.12). However, unlike the corresponding stiffened cylinders, considerable tearing of the Kevlar was observed.

The ultimate and average post-ultimate load capacities of all specimens are summarized below.

Test Specimen Load Carrying Capacities

Specimen	Material/ Concept	Ultimate Load (lbs)	Avg Post-Ult. Load (lbs)
IA	AL/IS	27,750	9,000
IB	FG/IS	36,850	4,000
IC	FG/IS	41,900	2,300
ID	GR/IS	----	---
IE	GS/IS	24,350	850
IF	K49/GR/IS	26,700	850
IG	K49/GR/IS	23,400	900
IIA	AL/ES	29,000	5,000
IIB	FG/ES	22,500	1,200
IIC	GR/ES	26,700	1,000
IID	K49/GR/ES	22,950	1,600
IIE	K49/GR/ES*	22,550	1,850
IIF	K49/AL/ES*	21,450	4,500
IIIA	AL/HS	59,950	9,400
IIIB	FG/HS	112,500	8,200
IIIC	GR/HS	39,500	5,600
IIID	K49/GR/HS	33,600	6,400

*Bonded and Riveted

IS - Internal Stringer
ES - External Stringer
HS - Honeycomb Sandwich
AL - Aluminum

FG - Fiberglass Epoxy
GR - Graphite/Epoxy
K49 - Kevlar 49/Epoxy

The skin/stiffener tests show conclusively that unless energy absorption requirements are a design consideration, conventional sheet/stringer aluminum construction is superior to composite sheet/stringer construction regarding compressive energy absorption characteristics.

However, honeycomb sandwich composite skins fared much better in comparisons against aluminum. Thus,it may be possible to match aluminum crash energy absorption without serious weight penalty. These conclusions are summarized in Fig. 3.13.

Low velocity impact studies were conducted using instrumented impactors to obtain force and energy values during impact. Several geometric configuration variables have been investigated including panel size, impact location, impactor size and shape, panel thickness, type of edge support, and variations in mass and velocity of the impactor.

Laboratory procedures for simulating impact damage employed three separate impacting systems. A conventional drop tower was used for low speed impacts up to approximately 5 feet per sec. on laminates of thickness ≤ 0.25 in. For .5" thick laminates, a falling mass in a guide tube was used at velocities up to 20 ft. per sec. Both the drop tower and guide tube assemblies used instrumented impactors. A gas gun was used to fire various projectiles to simulate foreign object impact at velocities up to several hundred feet per second.

The drop tower was a DYNATUP Model 8000A. It is a gravity driven device with remote controls for release of the hammer and impactor.

Interchangeable impactors were mounted on the hammer. Semi-conductor strain gauges attached to the neck of the impactor gave a continuous measurement of the contact force between the specimen and the impactor over a period of milliseconds. Integration of the output gives the energy absorbed by the specimen at any instant during the impact.

Most panels were impacted at the center of the five-inch square unsupported area and were impacted four times, once in each bay of the support fixture, with the depth of penetration varied from through-penetration to that causing slightly more than incipient damage.

Foreign object damage studies were conducted with a 1.18 in. diameter gas gun, consisting of a launcher system capable of sabot launching projectiles at velocities from under 100 ft/sec. up to several thousand ft/sec. The gun employs rapid expansion of a highly compressed gas to accelerate the sabot out of the launch tube.

Projectile impact velocity was measured by two laser beams placed along the trajectory at a predetermined distance. A high speed camera was used to determine projectile impact and rebound velocity and to record projectile-panel interaction.

Both impact velocity and angle of incidence were varied and several types of projectiles were used including glass and steel spheres and a granite projectile machined to be cylindrical with conical ends.

Three types of specimens were fabricated and impacted. These are (a) "thin laminates" up to 32 plies (0.176") thick,(b) "thick laminates" (0.5" thick),and (c) "improved concept" laminates in which material or configuration was changed to increase impact resistance.

A comparison of an eight ply sandwich panel having 6.1 pcf core with an eight ply monolithic (non-sandwich) panel indicates that the monolithic panel absorbed nearly five times as much energy to initiate damage. In the monolithic panel, the initial damage occurs by splitting the back face between the fibers, thus requiring more energy than to crush the honeycomb in the sandwich panel.

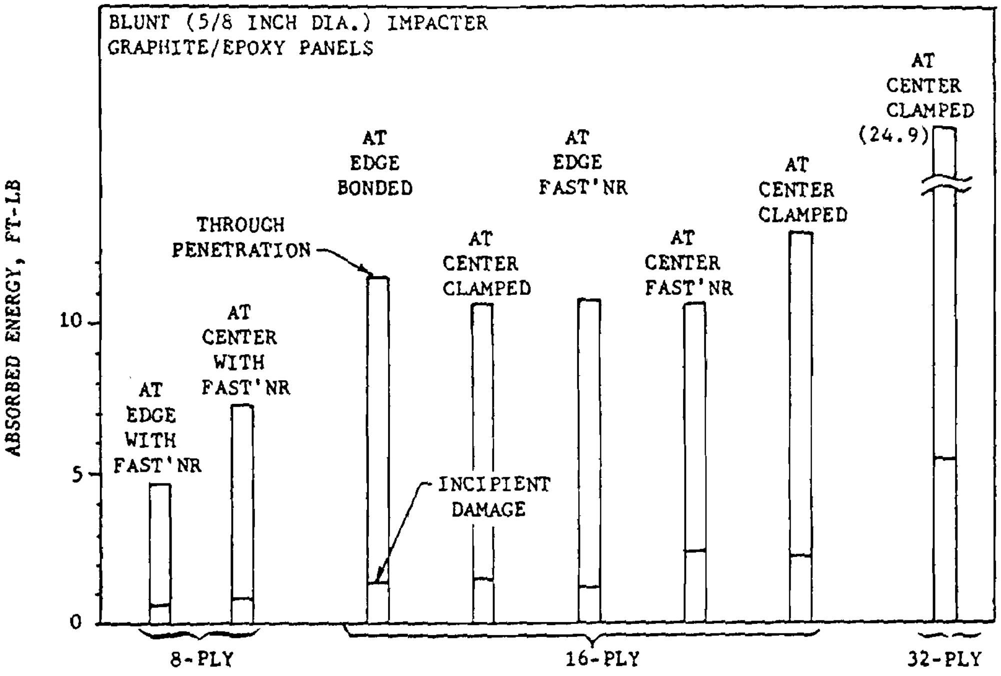

Figure 3.14. Baseline Monolithic Panel Surface Impact Data (Ref. 26)

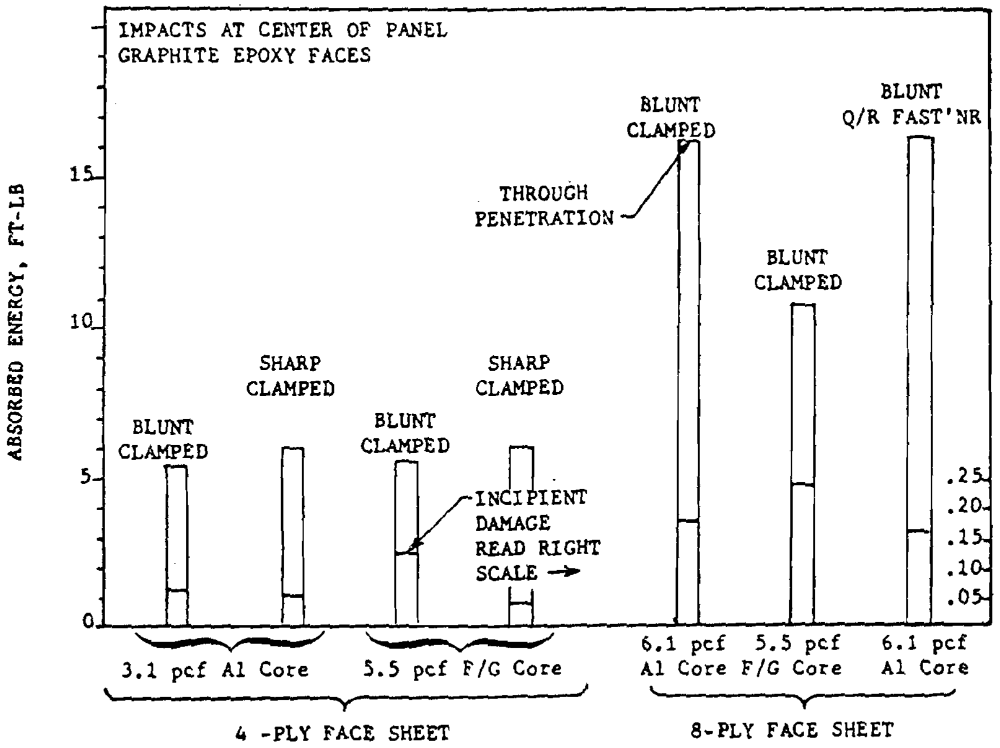

Figure 3.15. Baseline Sandwich Panel Surface Impact Data (Ref. 26)

demonstrate the complexity of the impact phenomenon and suggest that damage size is affected by a number of parameters, including impact location, panel thickness, impactor shape and size, flexual deflection and velocity of impact.

Improved Impact Resistance Laminates

The effects of concepts which add one ply of S-glass to monolithic panels are shown in Fig. 3.17.

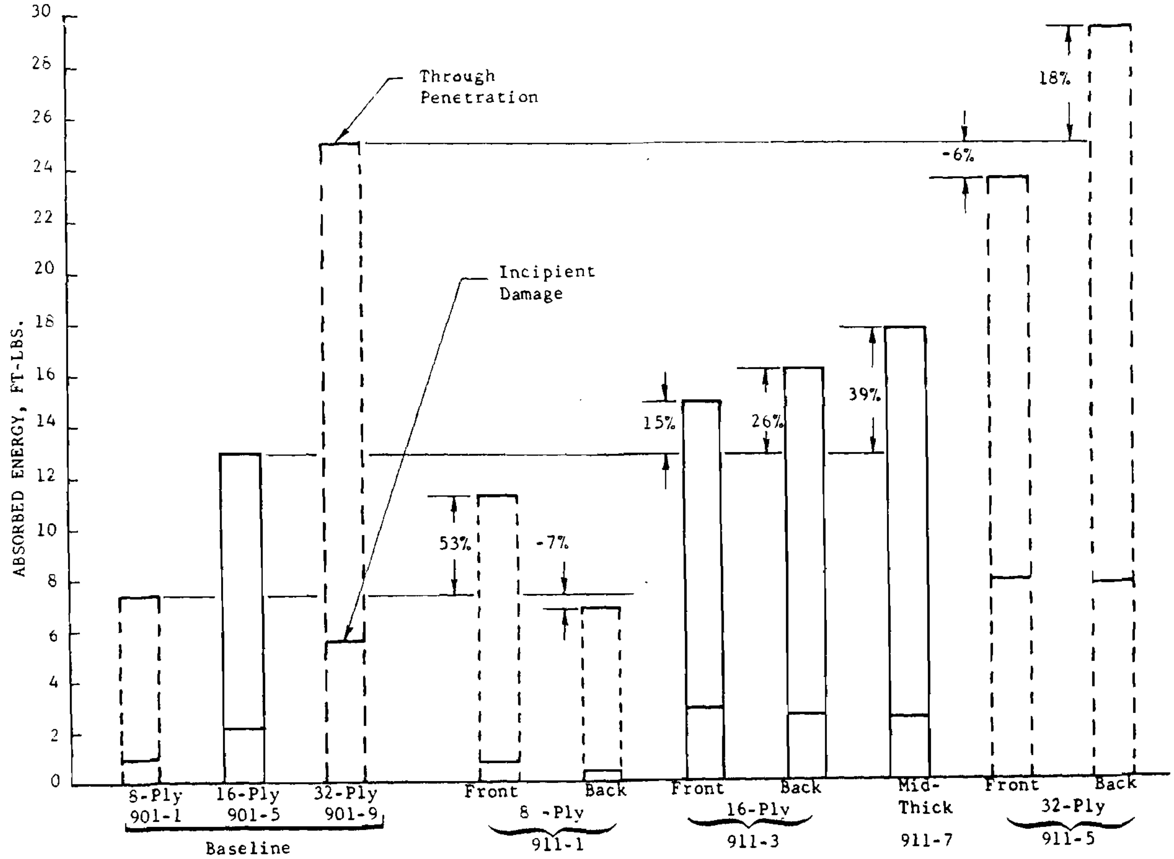

Figure 3.17. Effect of Concepts Which Add One S-Glass Ply to Monolithic Panels (Ref. 26)

The energies required for complete penetration and incipient damage are shown. Data for baseline panels are shown for 8-, 16-, and 32-ply panels made of AS/3501-5 tape material. The results of tests on improved concept panels are compared with the baseline data.

Data are shown in Fig. 3.18 for the addition of one ply of either Kevlar or ballistic Nylon. The Kevlar bidirectional woven cloth was prepregged with 3501-6 resin and laid up and cured with the basic graphite/epoxy tape. The 12-ounce per sq. yd. ballistic Nylon was not prepregged, but was laid directly on the graphite/epoxy tape.

When on the back surface, the Kevlar ply is effective in limiting the damage to a localized area. The Nylon on the back surface delaminated over a larger area than the corresponding Kevlar ply. Undoubtedly some of the toughness. The mechanisms for this enhancement involve triaxial dilatation of rubber particles at crack tips, particle shearing, and matrix plasticity. In [27], the fracture behavior and mechanical properties of such enhanced composites have been investigated experimentally.

A series of acrylonitrile-butadiene modified epoxy polymers were investigated. Resin fracture energies were determined by testing standard compact tension specimens and Izod impact specimens. The elastomeric additives greatly increased the fracture energies of the base epoxy. Laminates consisting of 7781 glass and T300/3K graphite were used. Enhanced toughness is observed to correlate with decreased strength and modulus. Elastomeric additives were found to improve laminate fatigue life by a factor of ten. Thus the modified composites have a considerably improved fatigue design limit, with a trade-off in strength.

Increased toughness does not come without some sacrifice of initial matrix-controlled mechanical properties. Interlaminar strength (short beam shear test), high temperature strength retention, and wet strength retention are examples of matrix-controlled properties. Ultimate compression and flexural strengths are also heavily influenced by matrix properties. Generally the modulus of the resin is lowered in proportion to the volume content of the second phase. The second phase evidently reduces the initial load bearing surface area.

Lowering the modulus can actually increase some fiber-controlled initial properties such as tensile strength, and improve matrix-controlled properties where the strain-to-failure is critical (e.g. off-axis tensile, transverse tensile, and flexural fatigue properties).

An added benefit of composite toughening is improved laminate processability, particularly in applications involving complex curvatures and varying thicknesses.

All elastomer epoxy compositions showed a decrease in fracture energy (energy required to initiate dynamic fracture propagation) with increasing strain rate. It seems that the second phase has a time dependent capability to distribute stress and toughen.

The toughness of the resin should be at least 1 kJ/m^2 so that, when a composite with woven fiber is made, the lay up geometry and fiber volume fraction will not affect flow sensitivity. Approximately 5% matrix strain will be required to prevent premature interface failure due to uneven stress concentration between fibers under transverse stress conditions. The second phase appears to dominate critical fracture energy, but only moderately affects high rate stresses such as impact. This is because the second phase requires time for its various deformation mechanisms to become operative for energy dissipation.

3.4 Unsymmettrical Buckling of Laterally-Loaded, Thin, Initially-Imperfect, Orthotropic Plates

In Ref. 28, Marshall presents a theoretical analysis for unsymmetrical bifurcation buckling of thin initially-imperfect orthotropic plates loaded laterally on the convex face. Unsymmetrical buckling is shown to be a function of the plate's initial geometry and to reduce greatly the effective load-bearing capacity.

It is assumed that the plate is simply supported:

$$x=0,a:\ w=0\ ,\ \frac{\partial^2 w}{\partial x^2}+\nu_y\frac{\partial^2 w}{\partial y^2}=0\ ,\ \frac{\partial^2 F}{\partial y^2}=0,\ \frac{\partial^2 F}{\partial x\,\partial y}=0 \tag{7}$$

$$x=0,b:\ w=0\ ,\ \frac{\partial^2 w}{\partial y^2}+\nu_x\frac{\partial^2 w}{\partial x^2}=0\ ,\ \frac{\partial^2 F}{\partial x^2}=0\ ,\ \frac{\partial^2 F}{\partial x\,\partial y}=0 \tag{8}$$

One may choose

$$w(x,y)=\sum_{m=1}^{2}\sum_{n=1}^{1} w_{mn}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b} \tag{9}$$

$$F(x,y)=\sum_{j=1}^{1}\sum_{k=1}^{1} F_{jk}\left[\cos\frac{j\pi x}{a}-1\right]\left[\cos\frac{k\pi y}{b}-1\right] \tag{10}$$

$$w_o(x,y)=\sum_{p=1}^{2}\sum_{q=1}^{1} w_{o_{pq}}\sin\frac{p\pi x}{a}\sin\frac{q\pi y}{b} \tag{11}$$

Since these truncated series cannot satisfy the boundary conditions, a solution is sought using the Galerkin method:

$$\begin{aligned}\iint_A\left(\frac{\partial^4 F}{\partial x^4}+\alpha\frac{\partial^4 F}{\partial x^2\partial y^2}+\beta\frac{\partial^4 F}{\partial y^4}\right)\ell(x)\,t(y)\,dx\,dy\\ =\iint_A\Bigg[\left(\frac{\partial^2 w}{\partial x\partial y}\right)^2-\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}-2\frac{\partial^2 w_o}{\partial x\partial y}\frac{\partial^2 w}{\partial x\partial y}\\ +\frac{\partial^2 w_o}{\partial x^2}\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w_o}{\partial y^2}\frac{\partial^2 w}{\partial x^2}\Bigg]\ell(x)\,t(y)\,dx\,dy\end{aligned} \tag{12}$$

where $\ell(x)$, t(y) are weighting functions. Substituting (9), (10), (11) into (2), (3), (4) and noting (12), the total potential of the loaded plate can be written in terms of deflection function coefficients only. For uniform pressure loading, one obtains

$$\begin{aligned}U_t=&\frac{\pi^4\lambda E_y h}{8(3+\alpha\lambda^2+3\beta\lambda^4)^2}\Bigg[\frac{w_{11}^4}{4}+w_{11}^2w_{21}^2-w_{11}^3w_{o_{11}}-2w_{11}^2w_{21}w_{o_{21}}\\ &+w_{21}^4-2w_{11}w_{o_{11}}w_{21}^2-4w_{21}^3w_{o_{21}}+w_{11}^2w_{o_{11}}^2\\ &+4w_{11}w_{o_{11}}w_{21}w_{o_{21}}+4w_{21}^2w_{o_{21}}^2\Bigg]\\ &+\frac{\pi^4E_y h^3}{96\lambda^3(1-\nu_x\nu_y)b^2}\left[w_{11}^2\left(\frac{1}{\beta}+\frac{2D_3}{D_2}\lambda^2+\lambda^4\right)\right]\\ &+\frac{\pi^4E_y h^3}{12\lambda^3(1-\nu_x\nu_y)b^2}\left[w_{21}^2\left(\frac{2}{\beta}+\frac{D_3}{D_2}\lambda^2+\frac{\lambda^4}{8}\right)\right]-4w_{11}\frac{ab}{\pi^2}q_z\end{aligned} \tag{13}$$

where

$$(K_0)_{mn}^{\theta\lambda} + (K_L)_{mn}^{\theta\lambda} = w \int C_{ijkl} \frac{\partial \epsilon_{kl}}{\partial u_m^{\theta}} \frac{\partial \epsilon_{ij}}{\partial u_n^{\lambda}} \, dA$$

and

$$(K_\sigma)_{mn}^{\theta\lambda} = w \int \delta_{mn} \, \sigma_{ij} \frac{\partial N^{\lambda}}{\partial x_i} \frac{\partial N^{\theta}}{\partial x_j} \, dA$$

The experimental specimen used to verify the computations consisted of four-ply unidirectional graphite/epoxy bonded to 2024-T3 AL with EA934 adhesive. The adhesive was cured at room temperature. To simulate a delamination, teflon tape was used to prevent bonding in the central part of the specimen.

Some of the specimens were loaded statically so that lateral deflections could be measured with a micrometer. Five fatigue specimens were tested under constant-amplitude, load controlled sinusoidal in-plane loading.

The present numerical analysis was verified by analyzing two problems for which exact solutions are available. Also, comparison of measured and predicted lateral deflections of post-buckled through-width delaminations corroborated the numerical predictions. A small number of specimens were were fatigue tested to obtain delamination growth data. Calculated strain-energy release rates were qualitatively correlated with the observed growth rates to determine the relative importance of Mode I (opening) and Mode II (sliding) components of strain-energy release rates.

Load transfer near the delamination was very complex. Interlaminar stresses were not a simple function of applied load or lateral deflection. Very steep gradients in the calculated stresses at the delamination front suggested the presence of a stress singularity. Hence the peak values of interlaminar stresses have little meaning, since they depend on mesh refinement. However, strain-energy release rates are much less sensitive to mesh refinement than calculated stresses.

Calculated strain-energy release rates for Mode I and Mode II crack extension were very sensitive to delamination length, delamination depth, and load level. The Mode I strain energy release rate (G_I) increased with increasing load and lateral deflection initially but then decreased, while the Mode II rate (G_{II}) increased monotonically with increasing load. If the structure had responded linearly G_I would have increased monotonically with the square of the load, and the ratio G_I/G_{II} would have remained fixed. For a given lateral deflection, G_I was greater for shorter and deeper delaminations. For fixed remote loading G_I was not necessarily greater or smaller for the shorter and deeper delaminations.

Qualitative correlation of calculated G_I and G_{II} values with observed delamination growth rates showed that delamination growth is dominated by G_I, even though numerically G_{II} may be much larger. Because G_I is not a simple function of delamination length, delamination depth, applied load or lateral deflection, predicting growth rates from limited delamination growth data is expected to be difficult and subject to significant error.

The finite element interpolations give

$$\Delta \underset{\sim}{\lambda} = \underset{\sim}{B} \; \Delta \underset{\sim}{d} \tag{9}$$

where $\Delta \underset{\sim}{d}$ are the incremental generalized degrees of freedom. Then the element stiffness is

$$\underset{\sim}{K} = \int_A \underset{\sim}{B}^T \underset{\sim}{D} \underset{\sim}{B} \, dA \tag{10}$$

After application of each load increment, each layer is checked in order to update the constitutive matrix and the stiffness matrix. The solution method outlined here is the linear incremental method.

The model presented here has demonstrated very good agreement in comparisons with experimental data obtained for aluminum-aluminum oxide sandwich composites.

3.7 Behavior and Analysis of Bolted Joints in Composite Laminates

The joining of and load transfer between composite material structural components have been studied extensively both experimentally and analytically to develop effective joining procedures and to obtain an understanding of the physical behavior of the structure throughout the joint region. For example, Oplinger [31] has reported extensive experimental and theoretical studies of the behavior of various types of fastener arrangements. Wong and Matthews [32] and Soni [33] report examples of finite-element analyses for the stresses and strains in the vicinity of bolted joints.

Oplinger [31] reports the application of both finite-element methods and complex-variable/boundary-callocation methods to analyze the two-dimensional stresses in orthotropic plates with fasteners. Stress concentration factors in the plate adjacent to the fastener were evaluated and the effects of variations of plate orthotropic properties were demonstrated. Both glass/epoxy and graphite/epoxy plates were included. Extensive experimental studies of joint strength for single-fastener lugs are reported for both glass/epoxy and graphite/epoxy to assess the effects of the ratio of fastener diameter D to panel width W for various values of fastener-center to plate-edge distance e, for $e/W \geq 1$. When one evaluates joint design for an array of parallel fasteners based upon results for a single-pin fastener, allowance must be made for the fact that fasteners in parallel may give higher net tension strength and lower bearing strength than single-fastener lugs [31].

Also reported in Ref. 31 are experimental studies of the strength of series (rather than parallel) type fasteners. These fasteners experience a significant variation of load from fastener to fastener. Hence it is shown that the use of elongated holes alleviates the stress concentrations and improves the strength of the overall joint.

Single-fastener studies of laminates such as $0_2 \pm 45°$ where the principal Young's modulus along the 0° fiber is very different from that along the fiber in the 45° plies can reduce the net-section stress concentration factor significantly. Thus, the use of various different composite plies (i.e., hybrid material layups) can be very effective in improving tension strength. However, this can lead to increases in the shear stress concentration factor

SECTION 4

REVIEW OF TRANSIENT STRUCTURAL RESPONSE ANALYSIS METHODS

4.1 Introduction

Methods for the theoretical prediction of nonlinear transient structural responses of the type and extent produced by severe impact, blast, or other loads are needed for many uses. Such methods can be used for parametric and/or preliminary design studies or to aid in the design of transient structural response experiments and in estimating the response levels which instrumentation is intended to record. However, there are many structures of interest whose complexity is such that mathematical modeling to provide fine details of transient response would be either prohibitively expensive and/or impractical because of the lack of adequate knowledge to permit proper modeling. Thus, theoretical analysis must be applied appropriately and with discretion. The use of such methods can help limit the scope of mechanical experimentation, but the use of well-designed and carefully-conducted experiments will always be necessary to determine and/or verify many important details of the nonlinear transient structural responses of either complex built-up metallic or of composite-material structures of the type found in aircraft and automotive applications. Well-designed and conducted experiments are essential for validating the final design in this type of nonlinear structural response problem.

In the following, attention is confined to discussing transient structural response prediction methods. It is convenient to discuss these methods in two regimes: (a) linear and (b) nonlinear. Historically, the simpler linear response methods were explored and developed first; then the methods were extended and modified to accommodate nonlinear geometric and/or material behavior.

Linear transient structural response prediction methods consist of three* types:

1. Conventional Lumped Parameter (CLP) wherein the structure is modeled by an appropriate collection of generalized masses connected by linear stiffness elements (beams, springs, etc.).
2. Finite Difference (FD) method wherein the governing differential equation of equilibrium of each structural region is approximated by spatial finite difference expressions in terms of displacement data at the grid stations, with appropriate compatibility enforced.
3. Finite Element (FE) method wherein the various regions of the structure are modeled spatially by appropriate finite elements with appropriate compatibility enforced.

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*All three of these approaches may be applied to either a very simple or a very complex structure.

4.2 CLP/Hybrid Approximate Methods

The method now known as the conventional lumped-parameter/hybrid method for predicting the nonlinear transient responses of complex built-up structures originated in the 1950's in connection with studies to predict the severe failure and postfailure responses of lifting-surface structures subjected to blast loading [36-41]. It was realized that sufficiently severe blast loading of typical complex built-up lifting surface structures could cause the structure to buckle at one or more spanwise stations during the transient response.

After buckle initiation, the structure tends to "fold" about that buckled station which remains at a fixed spanwise location. Also, after buckle initiation, the moment-carrying ability of the structure at that "buckled station" decreases as the postfailure deflection angle θ (see Figs. 4.1 and 4.2) increases, as one expects theoretically and confirms experimentally [36-47] from testing various simple as well as model and full-scale complex built-up structures. Unloading occurs along a "pseudo-elastic" straight line whose slope depends upon the maximum θ angle from which unloading occurs. This unloading slope decreases as θ_{max} increases.

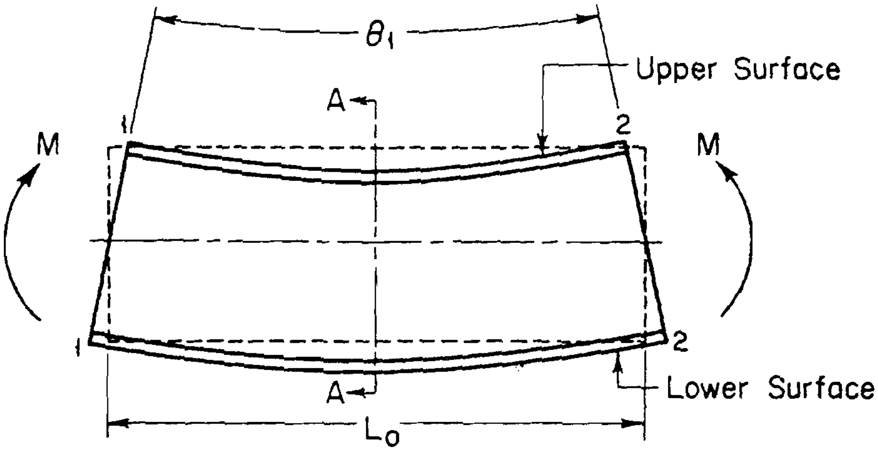
Figure 4.3a is a schematic illustrating typical moment versus angular rotation behavior at a buckled station of a built-up beam structure, including unloading and reloading. If unloading is followed by reversed loading sufficient to produce buckling in that direction followed by continued reversed loading, unloading, and reloading, the associated typical moment vs. θ behavior is as depicted in Fig. 4.3b. Hence, if the structure is subjected to transient loads such that these types of behavior can arise, one must accommodate this type of behavior in a simulation model intended to predict this type of nonlinear response.

Figure 4.4 [45] depicts a cross-section of a 4-spar wing (beam). The static postfailure bending moment versus postfailure rotation angle θ behavior of a similar 3-spar wing is given in Fig. 4.5, together with predicted behavior from a simple conceptual model. The load-deflection characteristics of this 4-spar structure in the postfailure range with unloading, reversed loading, reversed failure, etc. are shown in Fig. 4.6 together with predicted behavior for this static-test example.

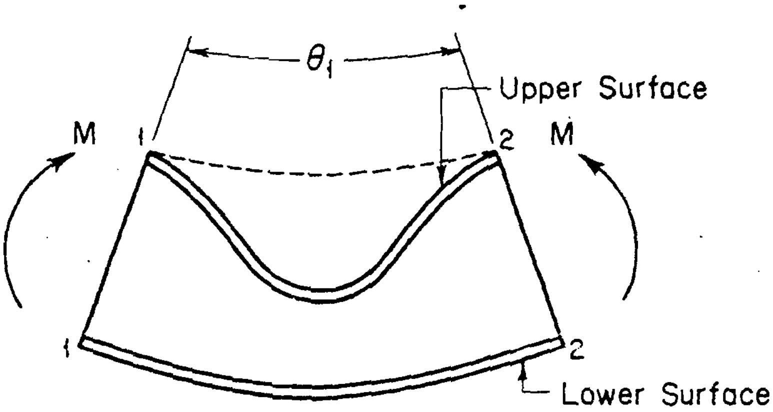
Similar experiments and analysis have been conducted on helicopter and/or general aviation aircraft structures and substructures [48-59] to evaluate the failure modes, failure loads, and postfailure load-deflection behavior of various components and structural assemblies of typical helicopters. Fuselage frames, landing gear structure, stroking seats, etc. have been studied both experimentally and analytically.

Similarly, typical automobile frames, body structure, and stiffening structure exhibit buckling and subsequent folding and crush-up behavior both in static-loading tests and in crash-impact tests [58-77]. Each of the many possible modes of initial "failure" and subsequent load-deformation behavior must be identified and accommodated properly in a prediction model in order to obtain realistic predictions of the nonlinear transient structural responses.

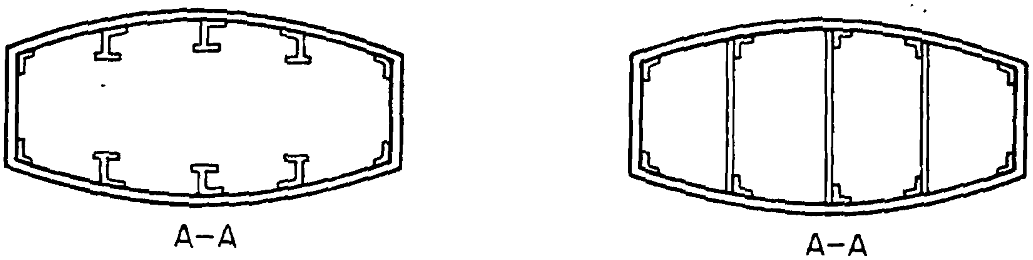
In the CLP/Hybrid method of analysis, the structure is represented by an assemblage of generalized masses connected by stiffness elements (extensional and/or bending) such as planar or 3-d beams [38, for example]. Typically the



(a) Before Failure



(b) After Failure of Upper Surface



(c) Typical Cross Sections of Shell Beam

Fig. 4.2. Segment of Shell Beam Under Pure Bending (Ref. 45)

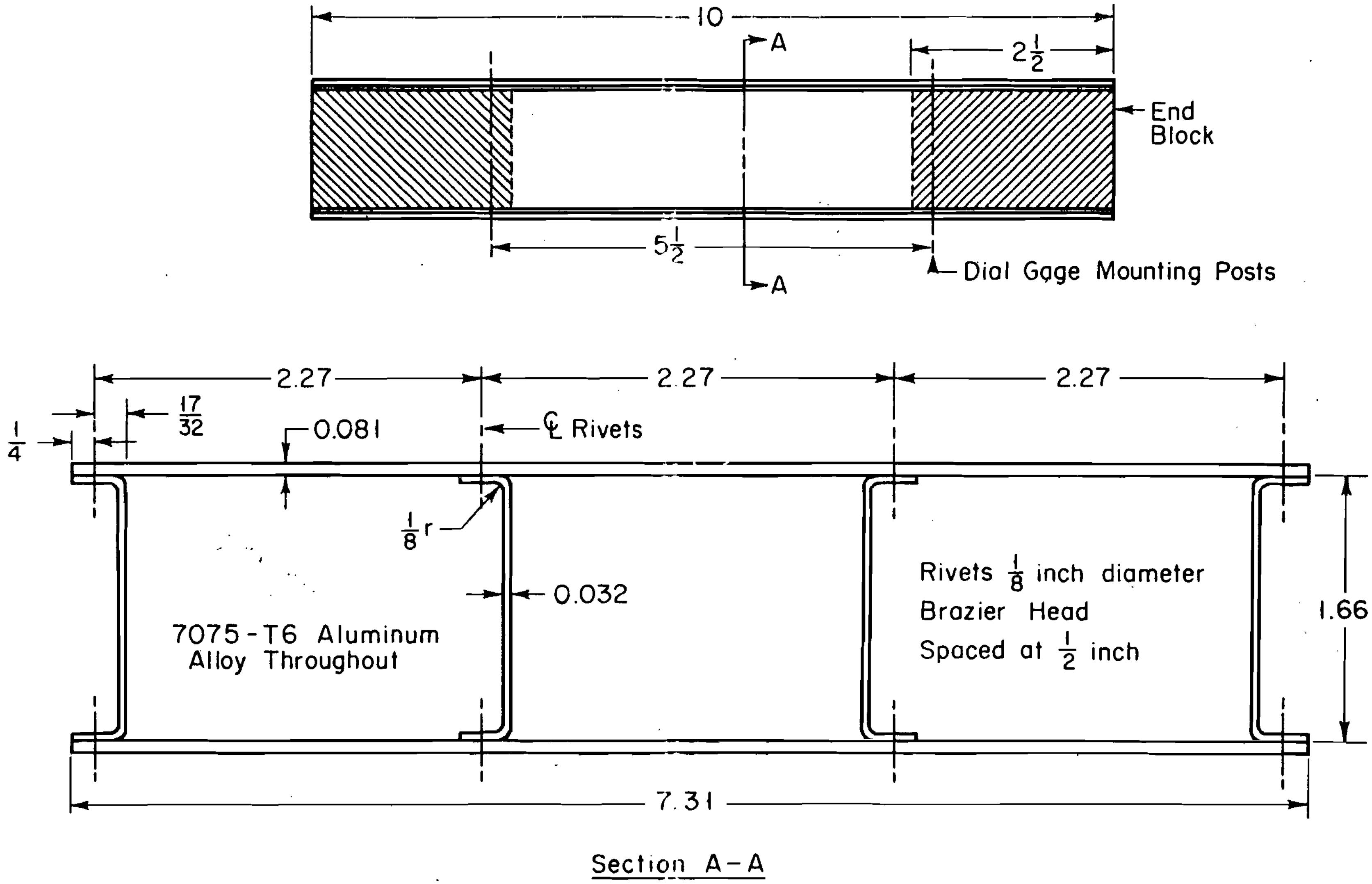


Fig. 4.4. Dimensions of Four-Spar Beam (Ref. 45)

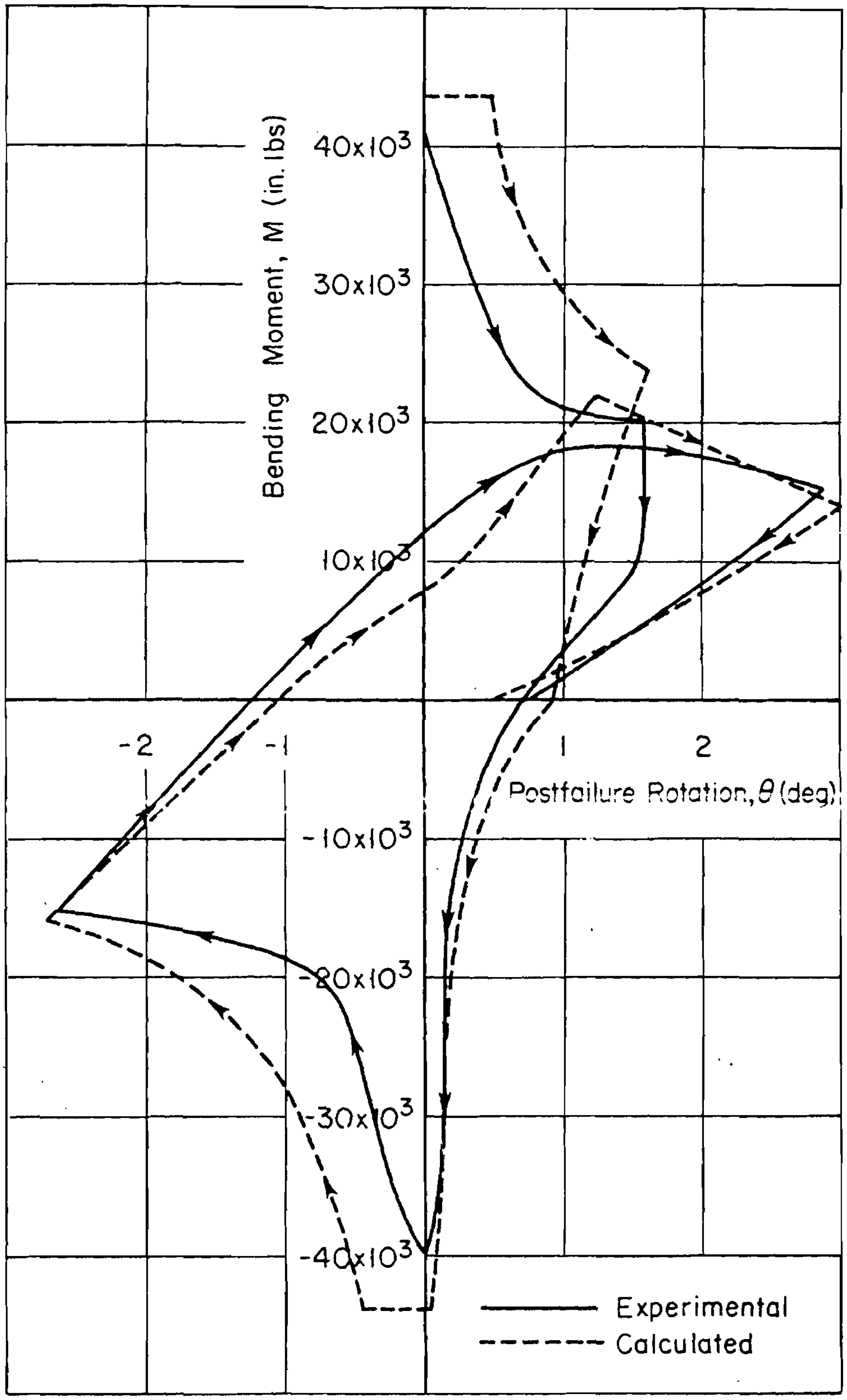


Fig. 4.6. Bending Moment versus Postfailure Rotation for Four-Spar Beam (Ref. 45)

[42-59, 75]. Thus, a considerable body of information has been generated to guide the analyst (who is seeking to analyze a built-up ductile-metal structure) in devising realistic and reliable approximations of the postfailure behavior at possible stations of interest of his structure; however, corresponding data for composite-material structures are relatively sparse. Carrying out a CLP/Hybrid analysis successfully requires the analyst to exercise skilled judgment and to call upon a significant background of experience on failure and postfailure behavior of complex built-up structures. In this problem area, the inexperienced analyst will encounter a considerable amount of difficulty and frustration.

It should be noted that the CLP/Hybrid approach can be applied to ductile-metal complex built-up structures or to composite-material structures. For each type of structure, one must provide for accommodating (a) the proper modes of incipient failure that can occur (and the associated incipient-failure criteria) and (b) appropriate descriptions of the postfailure load/deflection and/or load/deflection/deflection-rate behavior.

Also, the "hybrid" feature which represents the nonlinear hysteretic load/deflection/deflection-rate behavior of an automatically-selected "failed structural region" can be employed with equal facility with either:

(1) The Conventional Lumped Parameter Method
or
(2) The Finite-Element Modeling Method .

Accordingly, in Subsection 4.3 where the more detailed methods (FE and the FE/Hybrid methods) are discussed, a description of this Hybrid Feature is not repeated.

Numerous specialized limited-capability computer programs of the CLP/Hybrid type exist [48, 49, 68, 72, 74, 76, 82, 84-86]. For example, Gatlin et al [48, 49] simulate the vertical impact of a helicopter fuselage by representing the structure by lumped masses connected by a preselected 2-d arrangement of nonlinear axial and rotational springs. The other cited programs pertain to portions of automobile structure simulating a crash situation; Kamal et al [74, 76, 77] developed the FEBIS program to simulate vehicle-to-barrier head-on impact wherein the vehicle is modeled by lumped masses interconnected by various nonlinear springs to represent the internal forces associated with the torque box, front frame and bumper system, drivetrain, sheetmetal, firewall, radiator, engine mounts, and transmission mounts. Laboratory crush tests of these various components provide the nonlinear hysteretic spring data. The SCORES program by Fitzpatrick [86] is concerned with a 2-d model of an occupant which collides with the steering wheel, steering column, and knee-restraint system of an automobile in a head-on crash; here again the system is modeled by lumped masses with nonlinear hysteretic springs representing the load-deformation characteristics of the deformable structure. Prescribed are the crash input g-loads g(t) to the front of the occupant compartment; primary interest centers upon predicting the g-loads experienced at several locations on the occupant model.

Computer programs representative of the hybrid type but with a more extensive capability are those of Wittlin et al [52-57], McIvor et al [87],

- Beam element strain and damping forces, stresses, relative displacements, rupture summaries.
- Spring element loads and deflections.
- DRI response, cg velocity, volume change/penetration.
- Print and plot of responses, element data.
- Energy summaries.

These KRASH capabilities are summarized in slightly different terms on pp 1-2 of Ref. 57 as follows:

- Define the response of six degrees of freedom (DOF) at each representative location, including three translations and three rotations.
- Determine mass accelerations, velocities, and displacements and internal member loads and deformations at each time interval.
- Provide for general nonlinear stiffness properties in the plastic regime, including different types of load-limiting devices, and determine the amount of permanent deformation.
- Define how and when rupture of an element takes place and redistribute the loading over the structural elements involved.
- Define mass penetration into an occupiable volume.
- Define the volume change due to structural deformations of an occupiable volume.
- Provide for ground contact by external structure including sliding friction and a nonrigid ground surface.
- Include internal structural damping.
- Include a measure of injury potential to the occupants; for instance, the probability of spinal injury indicated by the Dynamic Response Index (DRI).
- Determine the distribution of kinetic and potential energy by mass item, the distribution of strain and damping energy by beam element, and the crushing and sliding friction energy associated with each external spring.
- Determine the vehicle response to an initial condition that includes linear and angular velocity about three axes and any arbitrary vehicle attitude and position.
- Provide a measure of the airplane cg velocity by means of translational momentum relationships.
- Analyze an impact into a horizontal ground and/or an inclined slope.
- Provide a measure of the internal stress state of internal beam elements.
- Analyze a mathematical model containing up to 80 masses and 150 internal beam elements.
- Treat up to 180 nonlinear element degrees-of-freedom.

The structural modeling provided by KRASH is quite realistic for aircraft frames and trusses but modeling of skin panels, sandwich panels, or composite-material panels can be done <u>only roughly</u> and requires the exercise of considerable

---only 4 of which (ANSYS, ABAQUS, ADINA, and MARC) have operational nonlinear geometric-material transient response prediction capabilities, including restricted classes of impact problems. See Refs. 98 and/or 99 (and/or also Refs. 51 and 93-97) for a tabulation of the various features and capabilities of these computer programs.

Certain of these computer codes have been written to analyze impact-crash responses of certain categories of structures. The most comprehensive and versatile of these programs is the finite-element program DYCAST [101-104] developed by the Grumman Aerospace Corporation under Grumman, NASA, and FAA sponsorship. Another similar computer program with more limited capability is ACTION [105, 106], which is also a finite-element program. For the categories of structures which each of these codes can model, the transient response including incipient-buckling, yielding, plastic behavior, etc. is accounted for automatically; no prescribed internal failure initiation and no prescribed internal postfailure hybrid-type load-deflection behavior is injected. An example of the application of DYCAST and ACTION (and of KRASH) to the analysis of and comparison with experimental data for a fuselage section impacted in a drop test is given in Ref. 91. Demonstrated is good overall transient response agreement between experiment and the predictions of KRASH, ACTION, and DYCAST but the superior modeling fidelity of the DYCAST code produced distinctly better detailed predictions and comparisons with experiment, as expected.

DYCAST has also been applied by Carden and Hayduk [107] to the analysis of the drop-test impact responses of various aircraft fuselage load-limiting subfloor structural concepts. A representative fuselage floor and subfloor sections with simulated attached "seats and passengers" was drop tested for each of several concepts. Accelerometers provided acceleration time histories at various locations on the specimen. High speed photographic measurements provided deflection data. Static load-deflection tests on each subfloor configuration provided data which were used in DYCAST to represent this subfloor behavior by nonlinear springs. Generally good experimental-theoretical agreement was found. However, in some instances the static failure patterns differed somewhat from those observed in the dynamic tests. This is suspected to be one of the principal reasons for the theoretical-experimental discrepancies noted. Also, no strain-rate dependent material effects were included in the analysis. The experiments conducted demonstrated the effectiveness of several very attractive load-limiting concepts for fuselage subfloor structure.

For detailed crash response analysis and design, it appears that the DYCAST program provides an excellent extensive baseline modular capability to which future needed features could be added effectively. This might include, for example, elements to represent various structural elements and composite-material layups, as well as appropriate descriptions for failure criteria and postfailure behavior of these items.

For convenient reference, the major features of DYCAST are quoted verbatim from pages 105-107 of Ref. 3, as follows:

- Nonlinear spring, stringer, beam, and orthotropic thin sheet elements.
- Plasticity.
- Very large deformations.

- Initial conditions.
- Rigid masses.
- Material properties.
- Element cross-section geometries.
- Applied dynamic loads (if any).

The output data are in the form of:

- Printed displacement, velocities, accelerations, strains, stresses, and forces.
- Plotted histories of displacement, velocity, and acceleration at chosen nodes.
- Time-sequenced drawings of deforming structure or portions from any viewing angle.

This ends the verbatim quotation from pages 105-107 of Ref. 3.

It should be noted that although DYCAST models the (interior) structure in detail with finite elements which accommodate nonlinear geometric and material behavior, it also provides for accounting for nonlinear support or attachment structure by the use of nonlinear hysteretic springs whose mechanical properties must be prescribed by the user (from supplementary tests and/or analyses). In this sense, DYCAST also contains a hybrid capability.

To date the documentation found in the open literature for DYCAST is rather sparse [3, 103, 104]. Perhaps this is because DYCAST is regarded as a modular addition to PLANS (for static loading) which is documented in Refs. 101 and 102. However, it is hoped that similar comprehensive documentation for the nonlinear transient response program DYCAST will be provided soon to enable other researchers to use DYCAST, to appreciate fully its current capabilities, and to add further modules to extend its capabilities in useful directions. For example, although DYCAST has orthotropic plate elements including the Mises-Hill yield criterion, the Drucker flow rule, and Prager-Ziegler kinematic hardening [100], it may be useful to consider adding the present (or a modification of the) orthotropic elastic-plastic panel elements of the BR-1FC code of Ref. 108 which has been applied successfully to the blast response analysis of composite panel structures [109]. Also, it may be effective to consider the use of Quasi-Newton iteration methods for the implicit-time-operator solution of the nonlinear equations of motion in DYCAST, as discussed, for example, in Ref. 110. In this regard Bathe and Cimento [111] have shown by application of the ADINA code that the Broyden-Fletcher-Goldfarb-Shanno (BFGS) scheme (one of the Quasi-Newton methods) is particularly effective for the nonlinear transient response solution of the equations of motion by using implicit timewise finite difference operators.

the case of built-up metallic structures and in the more recent work on structures composed of composite materials [2,3,11]. In this newer category of structural materials and construction, the diversity of structural materials, arrangements, attachments, etc. is much more extensive than in the past. Hence, considerable effort will be required to identify the most effective and practical combinations of materials, layups, and structural concepts to achieve acceptable crashworthy design; progress in this direction has been made as reported by Cronkhite et al [3], Thomson and Goetz [11], Thomson and Caiafa [2], Carden and Hayduk [107], and in the studies leading to the U.S. Army Crash Survival Design Guide [13-17]. Much more work along these lines will be needed to assess the comparative effectiveness and practicality of the numerous candidate materials and structural concepts [112,113]; this will be an evolutionary process.

The overall structural crashworthiness research plan outlined in Refs. 1, 2, 113, and 114 appears to represent a logical and orderly succession of investigations judiciously combining experiment and analysis. Recommended are static and impact tests on a succession of laminates, structural elements (beams, frames, etc.), and substructure configurations such as fuselage floors, fuselage shell with floor, wing box structure, etc. Skins of graphite/epoxy, glass/epoxy, Kevlar/epoxy or hybrid combinations of these materials in cloth (or unidirectional ply form) are to be studied together with these materials used as facings on various types of honeycomb sandwich beams and frames. Also, concepts utilizing discrete longitudinal and/or circumferential stiffeners of composite material are to be studied. Various joint concepts need to be assessed in this crash response context. These tests are intended to assess the energy absorption, failure, and postfailure behavior of these various configurations and materials, under both static and crash loading conditions. Laboratory scale models and tests (static and dynamic) are to be followed by subsequent tests on large-scale components which simulate closely real-scale fabrication; these may be regarded as proof-of-concept or final-validation tests.

5.2 Needed Crash Response Research

The crash response research which is needed to develop better crashworthy designs for aircraft has been described clearly and concisely by Cronkhite et al [3], Thomson and Goetz [11], and Thomson and Caiafa [2]; those observations still apply and are largely paraphrased in Subsections 5.2.1, 5.2.2 and 5.2.3. The roles of element and subscale laboratory experiments and tests of full-scale structures are noted in Subsections 5.2.4 and 5.2.5, respectively.

5.2.1 General Goals

As described in Ref. 2, the general goals of (a) crash response research and (b) the use of advanced composite materials to achieve crashworthiness performance equal to or better than achieved with conventional built-up metallic configurations are as follows:

- Crash response performance of aircraft (a) of conventional metal construction and (b) of composite-material construction both designed to the same basic requirements need to be measured and assessed in

  - Strain rate and temperature effects on failure modes and postfailure behavior

- Testing and evaluation of joints, hardpoints, and cutouts to determine their strengths and failure modes, including their behavior under dynamic crash conditions.

- Develop analysis tools on several levels for composite-material structures.

  - Analysis of structural elements (will require and be guided by observations and measurements in each of various categories of element-level experiments).

  - Analysis of aircraft-type structural assemblies (portions of the entire aircraft) -- experimental static and dynamic data are needed to guide the development of necessary analysis modules which could be added to the appropriate computer code DYCAST and to validate DYCAST prediction capabilities.

  - Gross analysis of the overall aircraft system, including the landing gear, fuselage-wing airframe, and seat/restraint system (KRASH, DYCAST, and/or DYSOM could be applied but each requires further validation)

- Investigate crashworthy concepts for possible integration into future designs

  - Sandwich stiffeners with honeycomb cone with Kevlar or hybrid facings

  - Graphite-epoxy and hybrid frames

  - Energy absorbing load-limiting subfloors (Carden and Hayduk [107])

  - Crack stopping arrangements and attachments of structural elements

5.2.3 Related Areas

Some additional problem areas needing study in the crashworthiness context for general aviation and transport aircraft are [3,11,114]:

- Interaction of the landing gear and loads with the composite airframe structure. Load transfers, failure mechanisms, and failure sequence needs to be investigated for typical crash scenarios. Appropriate attachment and load-transfer structural concepts should be analyzed and evaluated by impact and typical crash test conditions.

- Energy absorbing seat/restraint concepts should be evaluated in conjunction with composite-material structures to which these are attached at various representative locations along the fuselage. Impact tests under typical crash conditions should be conducted to assess the overall effectiveness of the seat/airframe-structure combination.

The cited laboratory-scale (subscale) static and dynamic experiments on the various composite-material and structural concepts will be valuable for identifying the principal modes of failure under crash conditions, and will be useful for "suggesting" effective modeling simplifications. These simplified models are expected to focus on and emphasize the principal types of behavior involved without including burdensome unnecessary detail. Such models will accommodate the pertinent incipient-failure criteria such as buckling, delamination, debonding, tear, etc. Appropriate material characterization information (stiffness, strength, inelastic behavior,...) will need to be supplied for each particular material/layup system.

5.2.5 Full-Scale Tests

Full-scale static and crash-response tests play an essential role in confirming the validity of the design of the aircraft and perhaps in uncovering certain full-scale structural behavior that earlier subscale structural tests had not revealed. Data from such tests provide additional information to validate and upgrade analysis/design procedures and computer codes. However, a full-scale crash response test is very expensive and permits one to study the response of the system to only one condition of the many crash conditions of practical interest.

In contrast with crash tests of full-scale general aviation aircraft where a limited number of seats and occupants is involved, crash response testing of transport aircraft provides the opportunity to investigate and compare the performance of a variety of seat and restraint systems at various stations along the fuselage, thereby, including a range of impact conditions. Many photographic, strain, displacement, acceleration, and load measurements are needed to extract maximum benefit from such an opportunity. This will require careful design, planning, and instrumentation -- as is currently being done by FAA/NASA, for example, in preparing for a full-scale crash test of a B-720 aircraft [2].

5.2.6 Comments on the Roles of Element, Subscale, and Full-Scale Crash-Impact Tests

The extreme expense involved in carrying out a full-scale crash test, and the fact that only one impact condition of one of many important crash scenarios possible can be explored in a single test, requires the investigator to carry out nearly all of the experimental basic data and assessment work on laboratory type subscale structural models for both static and dynamic purposes. In this context, one can develop a high degree of understanding of nonlinear crash response behavior and can develop and validate both theoretical transient response prediction methods and crashworthy materials/structures concepts. Still needed, however, are a small number of full-scale tests to provide data to validate these transient response methods in detail for full-scale conditions to give one a clear level of confidence in the reliability/adequacy of such prediction methods for design use. These prediction methods (like KRASH and DYCAST, for example), in turn, can be used for preliminary design studies encompassing a reasonably wide range of conditions. Drawing upon such calculations, laboratory tests, background information from the Crash Survival Design Guide, etc., the designer should

    + Transient Response Data Obtained, Analyzed, and Correlated with Predictions

0 Report Release is Imminent (by Bell Helicopter Textron and AVRADCOM)

B. Development of Data Base on Composite Materials/Structures with Emphasis on Helicopter Applications
(AVRADCOM at NASA-Langley Process/Applications Branch of the Materials Division)

0 Tube and Beam Configurations

    + Failure Modes and Postfailure Behavior
    + Energy Absorption Characteristics
    + Crush Characteristics
    + Assess Structural Integrity from Incipient Failure to Loss of Load-Carrying Ability

0 Composite Subfloor Concepts

    + Design to Same Specifications as Metallic Designs Tested by Carden and Hayduk of NASA-Langley
    + Static Tests for Failure Modes and Load-Deflection Behavior
    + Impact Tests for Failure Modes and Transient Crush Behavior
    + Compare Composites Designs with Behavior of Previous NASA-Langley Metallic and Composite Designs

0 Helicopters: Steep-Descent Impacts are Dominant

C. Extension of Data Base Studies (AVRADCOM/NASA/Bell)

0 Several-Year Extended Parametric Study Now Starting

0 Failure Mechanisms and Modes

0 Energy Absorption

0 Various Composite Materials

    + Graphite-Epoxy
    + Kevlar-Epoxy   Fabrics vs. Tapes
    + Glass-Epoxy
    + Hybrids
    + Advanced Graphite Fibers and Toughened Resins

0 Cylindrical Tubes

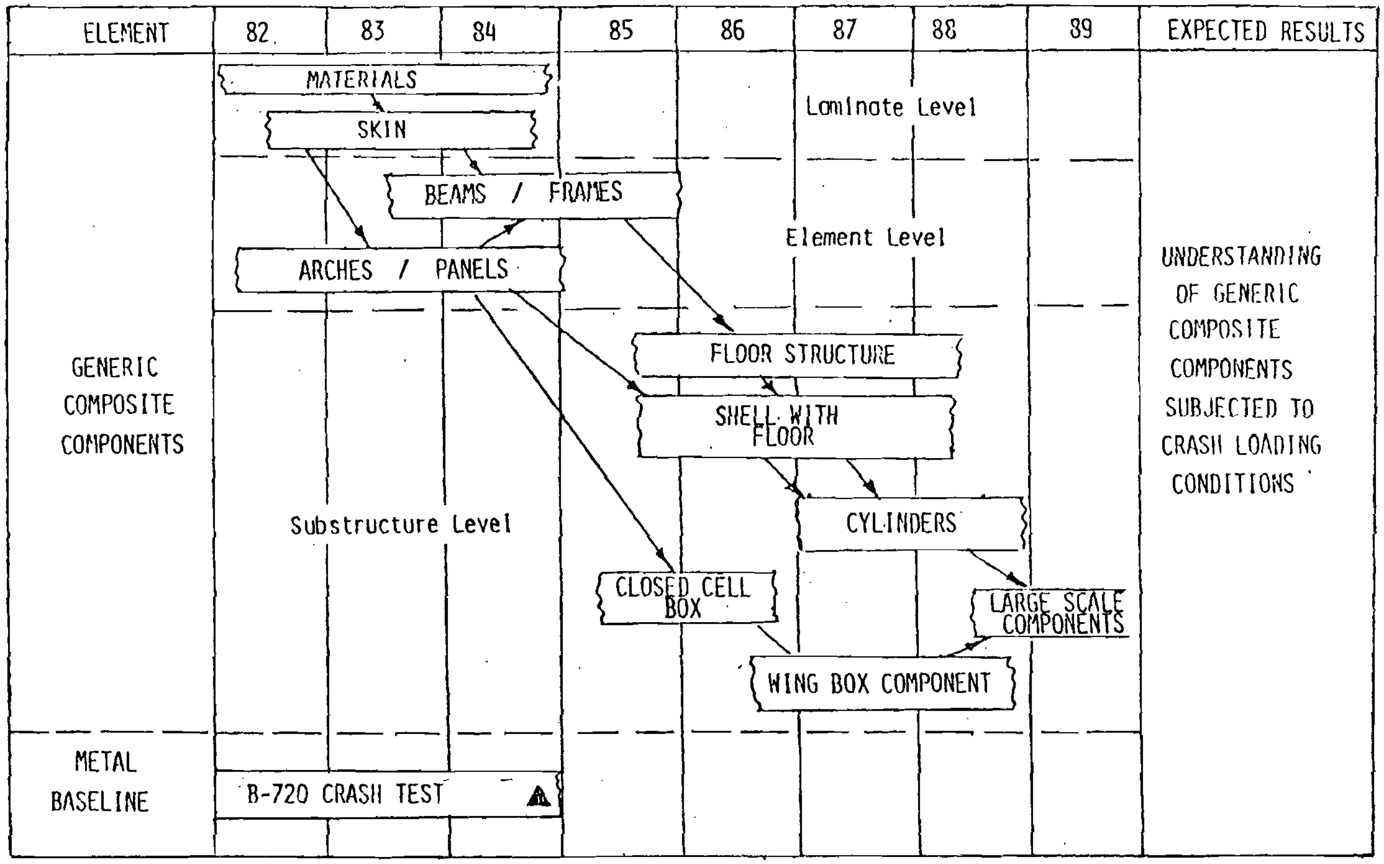
    + Variation of Layup Sequences and Angles
    + Vary Diameters
    + Various Diameter-to-Thickness Ratios

0 Beam and Sandwich Configurations (Cruciform)

0 Static Tests

0 Impact (Drop) Test -- Impact Velocity Variation Effects

RESPONSE CHARACTERISTICS OF GENERIC COMPOSITE COMPONENTS
TO SIMULATED CRASH LOADINGS



- 0 Define Appropriate Test Methods
- 0 Compare Damage Sensitiviey of Composites to Conventional Aluminum Fuselage Structure
- 0 Investigate Graphite-Epoxy and Hybrid Laminates
- 0 Focus on Structural Concepts for Lower Crown of Fuselage

STRUCTURAL PARAMETERS

- 0 Strength, Stiffness, Inelastic Behavior

STRUCTURAL RESPONSE CHARACTERISTICS

- 0 Crash Environment
- 0 Load-Deflection Behavior
- 0 Energy Absorption
- 0 Static vs. Dynamic Behavior

POTENTIAL FAILURE MODES

- 0 Buckling, Delamination, Tearing, Abrasion, Thermal Degradation

COUPON TYPE TESTS

- 0 Tearing Resistance: Aluminum vs. Composite Laminates Out-of-Plane and In-Plane Tearing
- 0 Abrasion Resistance Skin-Stringer and Orthogrid Coupons Against a Concrete Surface
  - \+ Conditions: Velocity 50 to 100 mph
    Pressure 50, 100, 150 psi
  - \+ Aims: Wear Resistance of Laminite Skins
    Temperature Effects on Resin
    Compare Results with Aluminum Coupons
  - \+ Material: Aluminum, Graphite-Epoxy, and Hybrid Laminates

STRUCTURAL ELEMENT TESTS

- 0 Elements of Frame and Keelson Structure (Aluminum Beam vs. G/E Honeycomb vs. Kevlar Honeycomb)
- 0 Failure Mode and Load-Deflection Behavior
  - \+ Through-Depth Compression: Crushing
  - \+ Axial Compression
  - \+ Axial Sheer
- 0 Static Tests and Impact (Drop) Tests

TESTS OF SUBSCALE AIRFRAME COMPONENTS

- 0 Fuselage Skin-Frame-Stringer-Keelson Structure
- 0 Static Tests: Failure Mode and Load-Deflection Behavior

succession, and appropriate timing of work to develop comprehensive information on the crash-response behavior of composite-material structural elements and structural assemblages. Detailed plans for that entire research program have not been seen, and the present reviewers do not presume to advise those very capable and knowledgeable NASA/FAA researchers and planners. Rather we wish to cite a few matters that are believed to merit study, although these and other more important items may already be included in the NASA/FAA research plan. Those matters are noted briefly in two categories (a) experimental structural studies and (b) prediction method development in Subsections 5.5.1 and 5.5.2, respectively.

5.5.1 Experimental Structural Studies

The assistance and advice of transport and general aviation (GA) airframe manufacturers such as Boeing, Douglas, Lockheed, Lear,... should be sought to identify the principal structural elements and configurations which their experience and design studies show most likely to be employed in future composite-material transport and GA aircraft. This should include representative stations all along the fuselage from the nose to the tail, including the wing box and landing gear support and load transfer structure.

This information could serve to set priorities on and initially emphasize detailed failure and postfailure studies of the most important structural elements and subassemblies. Recommended material composition and layups for beam, keelson, frame, or other basic elements should be sought since design and feasibility studies will have led to a narrowing of the multitude of possibilities offered by composite-material construction. Based upon this information, one could select a small set of high priority configurations for subsequent construction and testing.

For each configuration selected*, it is proposed that subscale structural assemblies be constructed and tested first in vertical impact tests to determine the modes and sequence of impact-induced structural failures. A second set of impact tests should be conducted employing a representative ratio of horizontal-to-vertical impact velocity with impact against a "concrete runway" surface -- again to assess the failure modes and sequences associated with these conditions. In all cases detailed observations and transient response measurements should be made. Based upon these results and observations, a subsequent set of static tests should be carried out on either the "same" structural assemblage or upon selected portions (if feasible) of that assemblage to evaluate and compare these failure modes with those observed in the two dynamic test conditions, and to obtain postfailure load-deflection and other structural-behavior data. These results should indicate the nature and extent of subsequent static-test studies which may be useful. These impact tests and static tests will provide transient response and mechanical-behavior data of intrinsic value but also information which can guide the analyst in deciding the minimal necessary level of structural modeling required to permit realistic predictions of nonlinear transient structural response of selected structural regions or assemblages. The necessity of developing more comprehensive finite elements or the adequacy of employing relatively simple finite elements in conjunction with the hybrid procedure (and guidance for selecting an effective hybrid procedure)

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* Appropriate account must be taken of much prior experience by NASA, AVRADCOM, Bell, Lockheed,...to select crashworthy rather than fragile materials/configurations.

types of composite arrangements for fuselage frame, skin-frame, and keelson structure may require different hybrid properties. Carefully selected static-test experiments to produce failure and postfailure structural deformation patterns closely simulating those observed in crash-impact tests will be needed to generate the fund of hybrid-station mechanical-behavior data to represent the mechanical behavior of typical generic composite configurations. As this data base grows, the analyst will be able to use KRASH more effectively for preliminary design studies.

With respect to the more refined finite element transient nonlinear structural response prediction methods, it should be noted that the finite-element structural model results in a set of ordinary nonlinear differential equations of motion which can be solved timewise in small increments Δt in time by the use of an appropriate finite-difference operator, either explicit or implicit. When the finite-element model consists of a relatively small number of degrees of freedom (DOF), it is most efficient to solve those equations timewise by using an explicit operator such as, for example, the timewise central-difference operator. However, explicit operators when applied to either linear or nonlinear systems require that Δt be sufficiently small; otherwise, the calculation will blow-up from (unavoidable) error growth. Hence, when the finite element model has a great many DOF, the required Δt size is so small that the computational expense involved in carrying out the calculation for the necessary amount of total time becomes prohibitive. In such cases, timewise implicit operators are used since such operators permit one to use much larger values of Δt without computational blow-up.

When timewise implicit methods are used to solve nonlinear transient structural response problems, one of two approaches is used commonly. In one case, the internal nonlinear loads at a given time instant t_n are estimated by extrapolating known internal nonlinear loads at earlier time instants t_{n-1} and t_{n-2}; the result is an approximation of the proper equations, and the solution can be carried out in a straightforward noniterative fashion [120]. However, the solution is guaranteed always to be incorrect. But if Δt is not "too large", the solution accuracy may be acceptable for engineering purposes. If the entire solution is repeated by using a fixed Δt which is half as large as the former Δt, one can conclude that a "converged" solution has been found if both predictions agree. If not, the process can be repeated until a converged result is obtained. While each of these calculations is comparatively inexpensive, the overall computational expense can become large if many repeat calculations are needed to reach convergence. This "efficient but uncertain trial-and-error procedure" can be circumvented by solving the correct rather than the approximate nonlinear equations at each time instant.

To solve the correct nonlinear equations at each time instant with implicit methods requires that iteration be carried out to convergence at each time instant. Here also if severe nonlinearities are present, certain iteration procedures will fail to converge for a given Δt size. For present purposes let it suffice to note that recent studies have shown quasi-Newton methods to be both effective and efficient [110,111]; to date these are the most effective methods known for solving nonlinear transient structural response problems. The documentation seen on the workhorse DYCAST program suggests that implicit solutions with iteration are carried out, but the

SECTION 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The present study was intended to consist of a review of the state of the art of aircraft crashworthiness work both experimental and theoretical, but restricted to considerations of severe structural response aspects. Considerations pertaining to fuel system protection (and fires) and to emergency evacuation systems were to be omitted.

Principal attention, therefore, was given to examining the state of experimental investigations and of theoretical methods for predicting severe transient structural responses of (a) conventional built-up metallic aircraft structures and (b) the newer composite-material structures. This information was sought by searching the literature, by contacting personnel from involved governmental agencies and the airframe industry, and by visits to the FAA Technical Center, NASA-Langley, AVRADCOM, AFML and ASD, within the confines of the available time and effort for this project.

As a result of these contacts and visits, various reports and papers on past research of the crash responses of helicopters, general aviation aircraft, and transports were furnished to us for study by those contacted individuals. In addition to reports on a succession of specific experimental and theoretical investigations on aircraft crash response, summary state-of-the-art papers or reports on crashworthiness were provided. Most of this information applies to aircraft of built-up metallic construction, but two of these summaries included information on both past work and planned work on the crash responses of composite-material aircraft structures. Information in this latter category, however, appears to be quite limited but is growing.

In personal visits to, telephone discussions with, and/or written information from the FAA Technical Center, NASA-Langley, AVRADCOM (Ft. Eustis and NASA-Langley), and Bell Helicopter Textron personnel, some information was obtained on both current and planned research on the crash-impact responses of advanced composite airframe structures.

The results of this information collection-and-study are given in Sections 2 through 5 of this report.

6.2 Conclusions

The current state of available aircraft crash response information is described in a very concise but comprehensive manner in the following categories by the indicated documents:

General Aviation Aircraft: Ref. 11 by Thomson and Goetz
Ref. 2 by Thomson and Caiafa

Helicopters: Ref. 20 (and/or Ref. 3) by Cronkhite et al
Ref. 21 by Wittlin

Load-limiting seats and seat-attachment devices have been designed, built, and tested; the transient response results measured in crash deceleration simulations have been compared with those for "unmodified designs" as reported by Fassanella and Alfaro-Bou [122]. Significant improvements have been demonstrated. Also described in Ref. 122 is an FAA-funded computer program called SOMLA which models an aircraft seat, an occupant, and a restraint system. This 3-d finite-element seat and lumped-mass/spring/damper occupant model was used to predict occupant response in a seat-occupant drop test, with excellent experimental-theoretical comparisons. For a more versatile and comprehensive prediction capability, SOMLA is being combined with the finite-element DYCAST program; all indications are that this will provide a very useful and reliable design tool.

Helicopters

The U.S. Army Research and Technology Laboratories (AVRADCOM) and its predecessor organizations at Ft. Eustis, Va. have been conducting crashworthiness research since the late 1950's. This work has led to the development of a set of aircraft crashworthiness requirements [18] and to the 5-volume Aircraft Crash Survival Design Guide [13-17] which is regarded widely as the bible for the crashworthiness design community. Crashworthiness design principles and guidelines spelled out in Refs. 13-17 have been applied and have increased significantly the crashworthiness and occupant survival of Army helicopters and light aircraft.

Also, AVRADCOM was the first organization to investigate at some length the use of composite materials in airframe structures and their behavior in crash situations. References 3 and 20 summarize those developments. Various airframe elements and components consisting of composite materials have undergone static and impact testing to assess their failure, postfailure, and energy-absorbing behavior.

AVRADCOM is sponsoring a very comprehensive development activity called the Advanced Composite Airframe Program [113] in which two airframe manufacturers Bell Helicopter Textron and Sikorsky Aircraft are playing parallel leading roles. In this ACAP activity, aircraft crashworthiness is only one of many design objectives and requirements in developing all-composite airframe designs.

A systematic series of studies following the recommendations of Ref. 3 to assess parametrically the behavior of various composite-material structural concepts for helicopter fuselage structure in both static and impact situations, as noted under item A in Subsection 5.3, has been carried out and will be reported upon shortly. Since the amount of essential experiments and data available to reveal the failure and postfailure behavior of the many composite-material configurations and arrangements of practical interest is still very small, an extended program of experiments, as outlined under item B in Subsection 5.3, is currently being conducted with emphasis on items with helicopter applications. A more general data base extension to take place over the next few years is outlined under item C of Subsection 5.3.

Under the FAA/NASA transport aircraft crash dynamics research program, Boeing, Douglas, and Lockheed-California are conducting studies of past aircraft accidents to identify the principal categories of potentially survivable crash scenarios and conditions as a focus for subsequent investigations [2,21]; four categories and the associated impact conditions have been identified. Also, these airframe designers and companies are seeking to identify the various typical structural configurations and arrangements of composite-material structures likely to be employed at various fuselage and wing stations; the overall objectives and preliminary results obtained are outlined under item E on page 106. In parallel and in collaboration with this work, NASA and the FAA have laid out a composite materials/structures test program to investigate the response characteristics of a succession of structural components and assemblages to simulated crash loadings as indicated in the NASA/FAA planning chart shown on page 105. Some of the facets and objectives of this part of the FAA/NASA program are indicated under item F on pages 106-108.

As this FAA/NASA/industry transport crash dynamics research program proceeds, data and experience on the crash responses of structural elements and assemblages comprised of various different composite materials and combinations thereof, honeycomb structure, etc. will point the way to ever more effective structural concepts and materials for coping with crash conditions efficiently. The basic FAA/NASA plan is a very logical and orderly one, and can be expected to produce a valuable fund of structural behavior and design information which can be applied to reduce crash hazards and achieve a high level of crashworthiness in future composite-material transport aircraft. A very important ingredient in achieving these goals will be the close and continuing involvement of and collaboration between the airframe industry and the FAA/NASA team in all aspects of this research: experimental, analytical, and design. In addition to developing necessary basic data, this collaboration should lead to an effective focussing of effort on design and material concepts which will find practical application in future transport aircraft.

Summary Comments

The available information on current programs of experiments to investigate the failure, postfailure, and energy absorbing behavior of composite-material structural elements and assemblages under both static and simulated crash conditions has been outlined under items A, B, C, and D in Subsection 5.3 and under items E and F in Subsection 5.4. Aside from Refs 2 and 21, no progress or status reports have been received to provide an up-to-date assessment of progress and problems encountered in those studies. The most meaningful and authoritative recommendations for subsequent necessary crash response work will come from the investigators who are actively carrying out and monitoring those experiments. These include personnel at:

a. Bell Helicopter Textron
b. Sikorsky Aircraft
c. Lockheed California
d. AVRADCOM, Ft. Eustis
e. AVRADCOM at NASA-Langley
f. NASA-Langley Structures Division
g. NASA Langley Process/Applications Branch, Materials Division
h. FAA Technical Center

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