Impact Analysis of Composite Aircraft Structures

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OUTLINE

- Background remarks on aircraft crashworthiness
- Comments on modeling strategies for crashworthiness simulation - past
- Initial study of simulation of progressive failure of an aircraft component constructed of composite material
- Research direction in composite characterization for impact analysis

STRUCTURAL CRASHWORTHINESS

The key point of this definition is protection of the occupant during a crash event. The structure must be designed to absorb kinetic energy while controlling dynamic forces to within acceptable human tolerances and the maintenance of livable space around the occupant.

- Definition:

The ability of a vehicle to reduce dynamic forces experienced by occupants to acceptable levels while maintaining a survivable envelope around them during a specified crash event.

STRUCTURAL CRASHWORTHINESS (Continued)

There are three key points shown here. The first is that structural crashworthiness, made mandatory by government regulations, is now a design criteria for automobiles and helicopters. Because of this it is essential to assess vehicle crashworthiness during the design cycle. This involves simulation of nonlinear behavior of complex structures during impact which is computationally and theoretically intensive, involving state-of-the-art developments in computational mechanics. These developments are on-going.

- Structural crashworthiness has become a design criteria for occupant carrying vehicles - especially for automobiles and helicopters.
- A requirement exists to assess vehicle crashworthiness during the design cycle.
- Numerical simulation of the dynamic response of vehicles subjected to impact loading is computationally intensive and has/will involve state-of-the-developments in computational mechanics.

ESSENTIAL REQUIREMENTS OF STRUCTURAL CRASHWORTHINESS

The mechanics of structural deformation during a crash involves geometric nonlinearities due to large shape changes, material nonlinearity due to elastic-plastic behavior and nonlinearities due to variable contact/rebound of structural parts.

Characterization of elastic-plastic behavior of metallic structures is reasonably well understood. Efficient computational algorithms have been developed and implemented into finite element programs. It should be emphasized that these algorithms are sensitive to actual material properties so that there is continuing need for experimental data. Impact of composite materials is a newer and challenging problem as the phenomena of failure differs from metals. Progressive failure and damage laws must be developed that describe fiber failure, matrix cracking, ply debonding and sublaminate buckling. These phenomena then must be implemented into simulation codes for crashworthiness of composite structures. Obviously, an extensive suite of tests must be performed ranging from coupon tests to subcomponents to full-scale section tests.

Simulating variable contact between an impacting structure and external or internal surfaces is computationally intensive. Nevertheless, algorithms have been developed and implemented into a number of simulation codes. Contact friction between surfaces is usually treated using simple Coulomb friction.

- Large elastic-plastic deformation with failure
  - accurate characterization of the constitutive material behavior
  - failure prediction for composite laminate construction
- Variable contact/rebound
  - contact with external surfaces
  - contact between internal parts
  - friction between contacted parts

ESSENTIAL REQUIREMENTS OF STRUCTURAL CRASH SIMULATION (Continued)

Developments in computational algorithms are ongoing. Two areas come to mind that will increase the viability of crash simulation. These are temporal and mesh adaptivity, error estimates and parallel computations. The first area is necessary in order to assure that the discrete model is efficiently and accurately predicting structural impact behavior. The second is to provide the computing power to perform crash simulation on a routine and timely basis within the design cycle as well as to accommodate more detailed models that may be dictated by introducing adaptivity.

In any occupant-carrying vehicle, there are parts designed specifically to absorb energy during a crash. In an automobile these can be rails that are designed to progressively crush. Very detailed models are required to simulate the accordian folds and internal contact of these parts although current full vehicle models include the rails in the entire model. The situation for aircraft and helicopters is equally complex. Energy absorbing subfloor concepts have been developed that appear to be extremely difficult to model. The open question still remains. Is it possible to model these highly nonlinear regions in an accurate and cost-effective manner? Currently, crush data is developed from component testing and then implemented into a model as nonlinear springs. What about structures constructed of composite materials?

- Accurate and efficient computational techniques

  ? parallel computation

  ? adaptive methods

- Modeling capability for a variety of structural types

  - including special energy absorbing structural concepts

  - either metallic or composite

  - hybrid materials

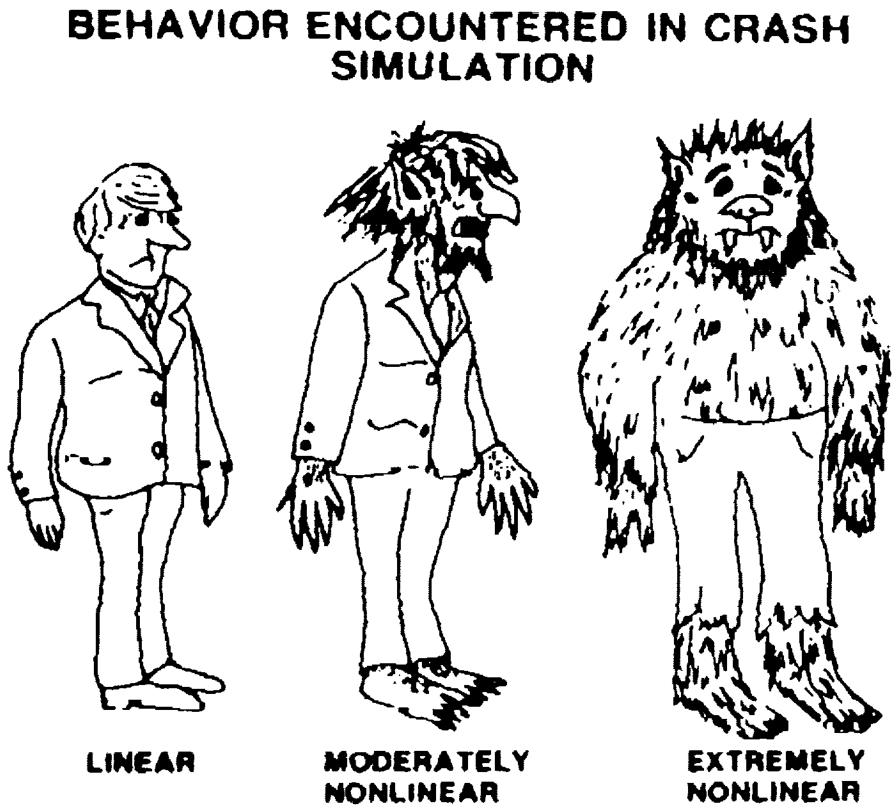
MODELING STRATEGIES - PAST EXPERIENCE

There are three distinct behavioral regions that must be considered when performing a crash simulation.

- A model for crash simulation can be separated into three distinct modeling regions
  - linear
  - moderately nonlinear
  - extremely nonlinear
- Pictorially this is shown on the next visual.

BEHAVIOR ZONE CHARACTERISTICS

Yes, modeling the extremely nonlinear crushing regions is still a monster!



BEHAVIOR ZONE CHARACTERISTICS - LINEAR

Modeling the linear zone is obvious. Use as little computational resources as necessary.

- Linear zone
  - elastic
  - small deflection
- Modeled with
  - rigid bodies with lumped mass
  - relatively few elastic finite elements
  - substructure; most dof's omitted

BEHAVIOR ZONE CHARACTERISTICS - MODERATELY NONLINEAR

These areas begin to be computationally expensive. Current technology in nonlinear structural mechanics is in place to adequately treat these regions. Allow for any possible global collapse modes.

- Moderately nonlinear
  - elasto-plastic
  - large displacements on the global scale
- Modeled with
  - nonlinear finite elements
  - allowance for possible global collapse modes

BEHAVIOR ZONE CHARACTERISTICS - EXTREMELY NONLINEAR

These are the very difficult and computationally intensive areas to model. These areas often involve special energy absorbing components that exhibit large deformation on a local scale. The bottom line is that these parts require very detailed FEM models.

- Extremely nonlinear
  - large deflection on a local scale, i.e., accordian folding of metallic structural components, crushing of subfloor structure in aircraft, local deformation and failure of composites
  - specially designed energy absorbing structure
  - crushable nonstructural parts
  - requires fine model (thousands of dof's)

BEHAVIOR ZONE CHARACTERISTICS - EXTREMELY NONLINEAR (Continued)

In the past these areas were exclusively modeled with nonlinear spring elements. The explicit codes currently used make use of a detailed representation of highly nonlinear regions in automobile structural components. However, there still may be areas of a built-up structure that are currently not amenable to detailed modeling. This is particularly true for aircraft structures that involve complex energy absorbing floor concepts. Composites offer new challenges in detailed modeling of crushable components. More research is required in this area before viable crash simulation is feasible.

- Modeled with:
  - Nonlinear spring elements

    Spring properties from test or other analysis require intimated understanding of the structural and material behavior

  - Detailed discrete representation??

    Trade-off between "hybrid" model and detailed nonlinear finite element model

MODELING CRASHWORTHINESS OF COMPOSITE STRUCTURES

In modeling the behavior of a composite airframe under impact conditions, the levels to which material failure must be included are far more detailed than for metallic airframes. In a traditional airframe, material failure modes which influence the structural failure process are primarily ductile crack growth and tearing and ductile rupture. Each of these is a distinct failure which renders a region of the structure incapable of transmitting any load. Just as important, because of the ductile nature of the material, significant impact energy can be absorbed by the material prior to failure. In laminates composed of graphite-epoxy lamina, failure at the material level is primarily brittle with very little prefailure energy absorption. For composite laminates, impact induced material damage modes such as matrix cracking and delamination lead to a structural material which still can transmit load, albeit at a reduced ultimate level and with a reduced stiffness and cross-sectional modulus. Thus, local material failures can have significant impact on the mode of structural failure.

Because sublaminate material failure in composite laminates can propagate over large regions without leading to total laminate failure, the overall structural failure mode can be significantly altered. Buckling and collapse modes are highly dependent on the modulus and bending stiffness of the structural cross section. Zones of highly degraded material stiffness caused by fiber breaking/buckling, delamination, and matrix microcracking can thus cause structural failure modes significantly different than those seen in an undamaged structure of the same laminate construction.

- Composite aircraft structures pose new computational and modeling challenges for crashworthiness design and analysis
  - brittle failure
  - diverse failure mechanisms
  - adhesive joints
  - three-dimensional effects in thick laminates
- Failure modes in composite structures
  - buckling/collapse
  - fiber breakage (local)
  - delamination (structural)
  - microcracking (local and structural)
- Material failure can change the buckling/collapse behavior

MODELING CRASHWORTHINESS OF COMPOSITE STRUCTURES CURRENT RESEARCH DIRECTIONS

As a first step in modeling the crashworthiness of composite structures, a progressive failure algorithm was implemented into the DYCAST code. This entailed introducing capability to describe classical laminate behavior, i.e., building a laminate from individual ply properties and orientation. This leads to the usual integrated material stiffness matrices; [A], the in-plane stiffness matrix, [D], the bending stiffness matrix, and [B], the matrix that couples the in-plane and bending behavior of the laminate for unsymmetric lay-ups.

Initially three maximum strain failure criteria were implemented. These are described in the next figure. Currently, a strain based criterion based on the theory proposed by Christensen is being implemented and tested (see subsequent figures).

Nonlinear material behavior was also investigated by implementing the Sandhu method for nonlinear composite materials. This method uses four uni-axial curves to define material behavior; two direct stress versus strain, shear stress versus shear strain and the variation of Poisson's ratio versus strain. Further investigation must be made of the effect of matrix material nonlinearities.

- In response to the program directions set by the Impact and Dynamics Branch at NASA LRC, the following enhancements are being incorporated into DYCAST:

  - Ply-by-ply progressive failure laws
    - maximum strain
    - Christensen strain-based quasi three-dimensional
    - Tsai-Wu

  - Nonlinear material behavior
    - Sandhu method for nonlinear composite materials
    - nonlinear elastic shear response

    ? matrix plasticity

MAXIMUM STRAIN FAILURE CRITERIA

The table below describes the three maximum strain failure criteria initially implemented into the DYCAST code. The first two are for uni-directional composites and the third is for a fabric composite. The failure criterion chosen is checked at each finite element stress integration point in each ply of the built-up laminate. As indicated in the figure below, when fiber failure is detected, the moduli E_{11} and Poisson's ratio, ν_{12} as well as the stress, σ_{11}, are set to zero. Similar procedures are followed for matrix and shear failure. Options 2 and 3 are similar to option 1 but add an induced coupling based on heuristic arguments that, for example, fiber failure induces shear ineffectiveness. Based on these considerations, the [A], [D], [B] matrices are reformulated and reflect the progressive softening of the damaged structure.

	Option 1 (Unidirectional Composite)		Option 2 (Unidirectional Composite)		Option 3 (Fabric Composite)	
Primary Failure Direction *	Induced Additional Failure	Zeroed Out Quantities	Induced Additional Failure	Zeroed Out Quantities	Induced Additional Failure	Zeroed Out Quantities
Fiber Failure, $\varepsilon_{11} = \varepsilon_{11_{FAIL}}$	None	E_{11}, ν_{12} σ_{11}	Shear	E_{11}, G_{12}, ν_{12} σ_{11}, τ_{12}	Shear	E_{11}, G_{12}, ν_{12} σ_{11}, τ_{12}
Matrix or Fiber Failure**, $\varepsilon_{22} = \varepsilon_{22_{FAIL}}$	None	E_{22}, ν_{12} σ_{22}	Shear	E_{22}, G_{12}, ν_{12} σ_{22}, τ_{12}	Shear	E_{22}, G_{12}, ν_{12} σ_{22}, τ_{12}
Shear Failure**, $\gamma_{12} = \gamma_{12_{FAIL}}$	None	G_{12} τ_{12}	Matrix	G_{12}, E_{22}, ν_{12} τ_{12}, σ_{22}	Fiber	$G_{12}, E_{11}, E_{22}, \nu_{12}, \tau_{12}, \sigma_{11}$ σ_{22}

* The subscript FAIL on εs denotes prescribed failure strain. Here, primary means the failure that induces the additional failures.

** Note that with Option 2, primary matrix and shear failures lead to the same overall failure mode.
Fiber failure pertains only to Option 3

CHRISTENSEN STRAIN-BASED FAILURE CRITERION

New strain-based failure laws are being explored. Criteria used to decide on the failure law to be implemented were based on considerations for modeling progressive failure of modern composites under impact loading. With the application of thicker section laminate constructions and more ductile fiber-matrix systems, it is felt that strain-based theories which clearly delineate between fiber failure and fiber-matrix interaction failure are essential for accurate modeling of progressive lamina failures. In addition, the failure law should be capable of including three-dimensional strain and stress states typical of thick section laminate constructions.

- New strain-based failure criterion:

  - applicable to more ductile lamina
  - based on Christensen's quasi-three-dimensional laminate theory
  - coupled theory, interactions of strain (stress) components
  - clearly delineates between fiber failure and fiber/matrix interaction failure

CHRISTENSEN STRAIN-BASED FAILURE CRITERION (Continued)

The failure criterion shown below is a modification of one first proposed by Christensen. In this law, e_{ij} is the dilatation (first invariant strain) and $\in_{KK}$ is the deviatoric strain. We have added the term $\beta \in_{KK}^2$, the quadratic deviatoric component which was not included in Christensen's work. This allows us to have different transverse failure strains in tension and compression, a necessary feature to reproduce failure in most lamina constructions.

- CHRISTENSEN FAILURE CRITERION:

  - Fiber failure

$$\in_f^- \geq \in_{11} \geq \in_f^+$$

- Fiber/Matrix Interaction Failure

$$\alpha \in_{KK} + \beta \in_{KK}^2 + e_{ii}\, e_{jj} = \kappa^2$$

α, β, κ are determined by simultaneously fitting to three failure states usually shear in the 1-2 plane, and positive and negative stress transverse to the fiber direction.

INITIAL STUDIES OF PROGRESSIVE FAILURE OF COMPOSITE AIRCRAFT COMPONENTS

The figure below summarizes the initial capabilities developed to simulate the impact behavior of a composite aircraft structural component.

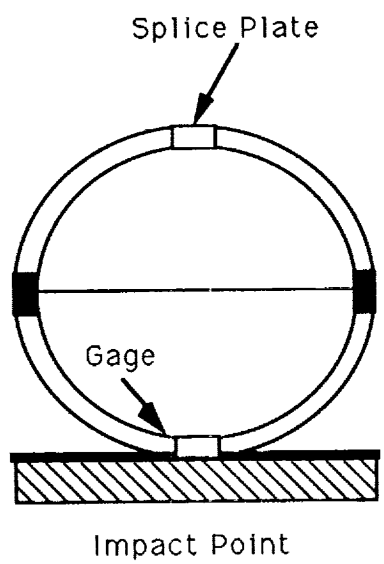
- Classical Composite Laminate Theory
  - composite laminate can be built up layer-by-layer by specifying materials moduli, angle of orientation and stacking sequence of each ply
  - each layer can be linear elastic or elasto-plastic
  - maximum strain failure criteria for continuous filament reinforced composite material
- Implemented into a three-node DKT triangular element in DYCAST code
- Used to simulate NASA drop test of Z-section graphite epoxy frame

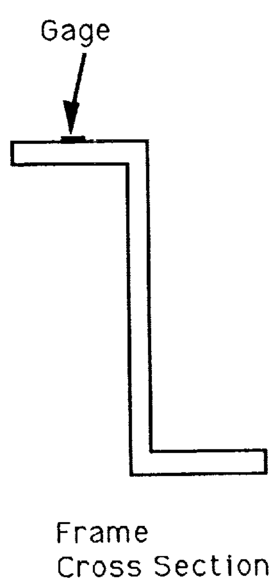
NASA DROP TEST OF A Z-SECTION GRAPHITE-EPOXY CIRCULAR FRAME

This test program is described in "Drop Test and Analysis of Six-Foot Diameter Graphite-Epoxy Frames," by Richard L. Boitnott and Huey D. Carden, presented at the AHS National Specialists' Meeting on Crashworthy Design of Rotorcraft, April 7-9, 1986. The key features of the test are summarized below. The Z-section frame was constructed from four 90-degree sections that were attached by splice plates. The laminated composite material was constructed of graphite-epoxy fabric. Another feature which added to the computational difficulties was a rear steel restraining plate and forward plexiglass plate. The purpose of the plates was to restrain lateral motion. Consequently, contact conditions had to be described between these plates and the forward and rear face of the Z-section flanges.

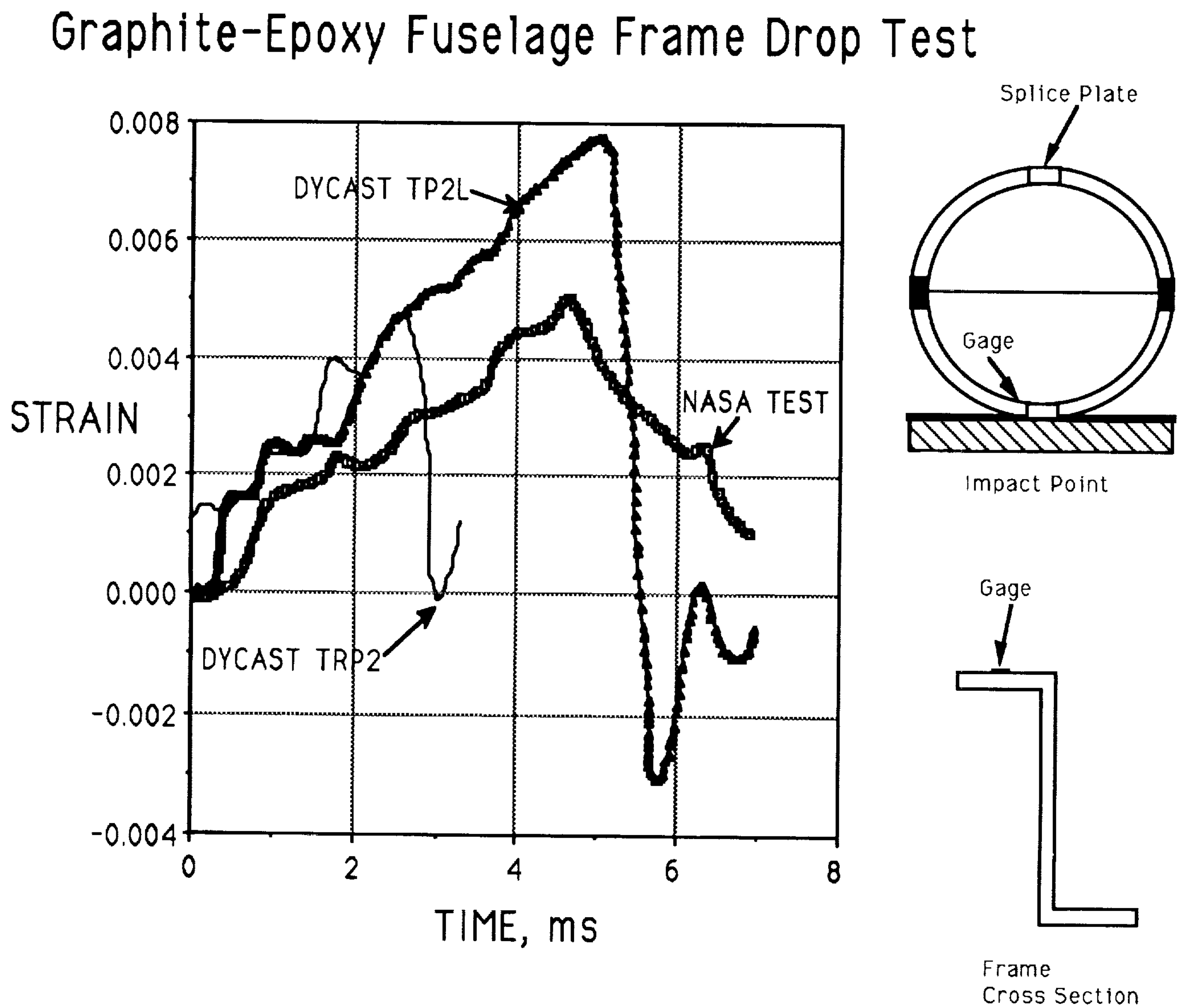
- Five graphite-epoxy frames were dropped onto a concrete floor
- Tests were performed at NASA LRC Impact and Dynamics Branch under the supervision of Huey Carden and Richard Boitnott
- Complete frames were fabricated from four 90-degree sections and joined with splice plates
- Z-section cross-sections typical of fuselage structure of advanced composite transport aircraft
- Lateral motions were restrained by a plexiglass and a steel plate
- Impact was at a splice plate
- Impact speed was 27.5 FPS
- Twenty pounds of added weight at the floor beam

This figure shows the general configuration of the frame. The frame was modeled with DKT triangular finite elements with the material characteristics described above. A number of models were investigated. The final model used eight elements through the web at the point of contact. The model progressively was made coarser away from the contact point. Beam elements were used in the upper quadrant. The final model of one-half of the frame had 867 nodes, 2108 elements, and 5133 degrees of freedom.





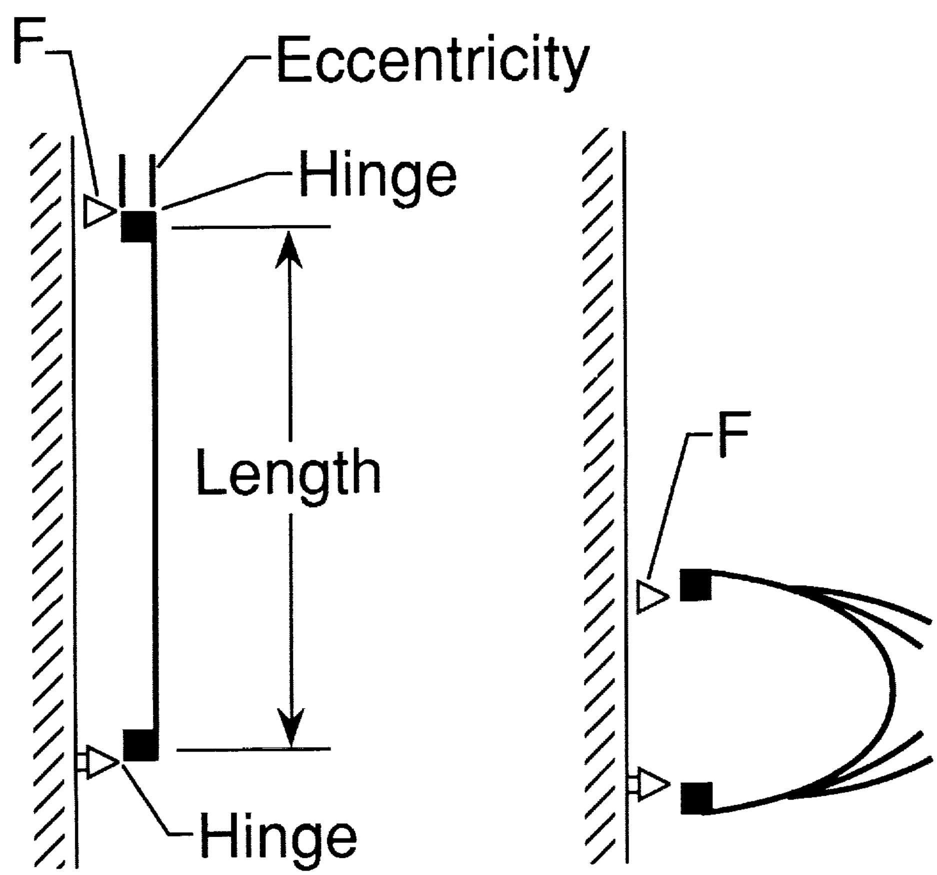
This figure shows a strain trace at the impact point at the inner flange. The location of the strain gage is shown on the previous figure. The comparison indicates that the essential features of the response were predicted. The time and location and progression of failure also approximated the simulation of a composite aircraft structure. However, it should be pointed out that the test involved a number of features that increased the difficulty of the analysis so that the primary behavior was not composite failure alone. These are: contact between the frame and the face plates, unknown friction coefficient, stiffness of the splice plates. Consequently, further analysis and tests on simpler components must be performed in order to investigate the use of composite failure criteria in a crash simulation.



STRUCTURAL IMPACT OF A/C COMPOSITES

This figure outlines areas of continued research.

- Improved composite failure criteria
  - New, fully interactive strain-based Christensen lamina failure criterion to be tested in DYCAST
  - Distinction between fiber and matrix failure modes maintained
  - Evaluate by simulating NASA experiments



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NONLINEAR COMPOSITE BEAM ELEMENT

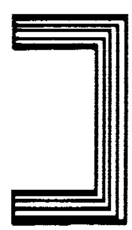
A curved open-section composite beam element has been developed. Each flange and web can be described as a distinct laminate construction.

- Nonlinear, composite finite element developed for DYCAST Code
  - Applicable to curved, thin-walled beam/columns with open cross-section typical of aircraft frames and stiffeners
- Each individual flange and web can be a distinct laminate composite construction

NONLINEAR COMPOSITE BEAM ELEMENT

Future work will involve applying failure criterion to each ply of the laminate web or flanges. Ultimately, a more detailed global/local representation must be developed to account for local three-dimensional effects at the point of impact.

- Material behavior
  - Laminate composite
- Failure criteria can be applied to each ply of flange/web defining progressive failure during crash loading



STUDY OF THE EFFECT OF SHEAR STRESS/STRAIN NONLINEARITY ON IMPACT BEHAVIOR

The next four figures illustrate the influence of material nonlinear behavior and failure mode on the dynamic buckling and collapse behavior of composite shells. To examine this, we consider a cylindrical shell with diaphram ends constructed of typical graphite epoxy lamina with a [0,90,45,-45]s construction. The shell is subjected to a hydrostatic step wave pressure loading. Under crash conditions, one would like to have the energy absorption mechanisms for the structure contained in localized "failure" zones with the remainder of the structure experiencing little catastrophic damage. To examine the role of nonlinear material behavior, we compared the effects of composite failure and shear stress-strain nonlinearity. The composite failure law used is the modified Christensen law described previously and material nonlinearity was treated by the simple cubic shear stress-strain law due to Tsai and Hahn shown below.

- Nonlinear shear stress strain behavior can significantly alter the dynamic buckling behavior of composites structures

- Example:

  - cylindrical shell with diaphram ends

  - subjected to a step hydrostatic pressure loading

- Used Tsai-Hahn stress strain relation

$$\gamma_{12} = \left[G_{12}^{-1} + 3S_{66}\tau_{12}^{2}\right]\tau_{12}$$

$$G_{12} = 0.71 \times 10^{6}$$

STUDY OF THE EFFECT OF SHEAR STRESS/STRAIN NONLINEARITY ON IMPACT BEHAVIOR (Continued)

The effect of shear stress nonlinearity is summarized below and shown on the next visual.

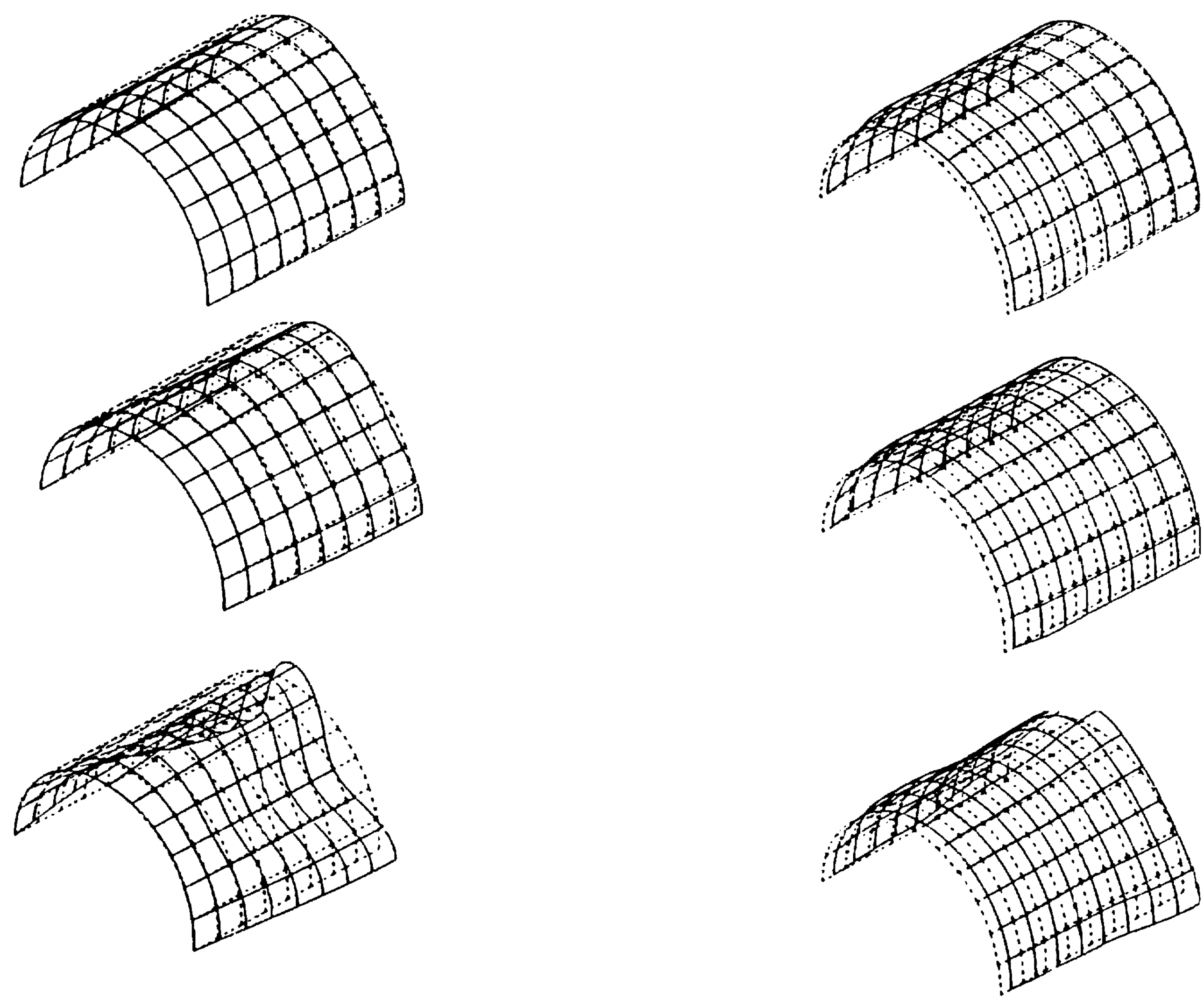
- Under hydrostatic, step wave loading, the dynamic collapse occurs in a mode dominated by the first bifurcation buckling mode of the linearly elastic structure if the degree of shear nonlinearity is small

- For large shear nonlinearities, the collapse resembles a plastic instability mode rather than a bifurcation buckling mode

- Energy absorption and force transmittal characteristics for these two modes are quite different and may lead to different crash behavior

STUDY OF THE EFFECT OF SHEAR STRESS/STRAIN NONLINEARITY ON IMPACT BEHAVIOR (Continued)

Two sets of results are shown below. On the left are results for essentially linearly elastic response with the parameter S_{66} in the Tsai-Hahn relation set equal to 0.5×10^{-13}. The set on the right increases the level of nonlinearity by setting S_{66} to 0.5×10^{-10}. As can be observed, a transition occurs with the increase in shear nonlinearity from a traditional buckling mode as shown on the left to a mode that is more characteristic of a general collapse as shown on the right. The general collapse mode in which there is a larger observed region of high "failure" strains around the circumference of the shell is far more damaging to the shell. These initial considerations indicate that material characterization and an understanding of the material behavior during impact conditions is an important consideration in predicting structural response to a crash loading situation.

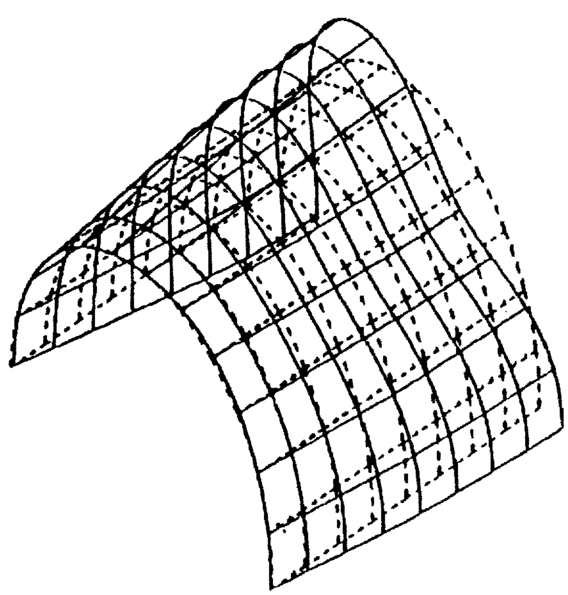


$S_{66} = 0.5 \times 10^{-13}$ $\qquad$ $S_{66} = 0.5 \times 10^{-10}$

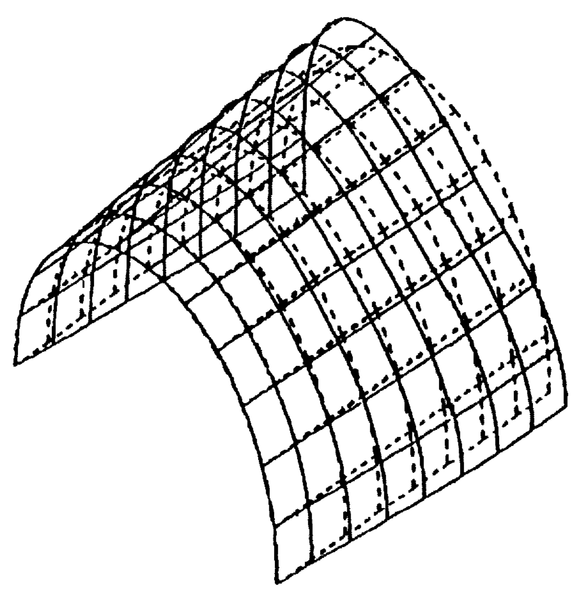
EFFECT OF FAILURE STRAIN ON MODE OF DEFORMATION

This figure shows the effect that the mode of failure has on the structural response. The figure on the right shows the response of the shell when published values of fiber failure are used in the analysis. Once again the modified Christensen failure law is used. In this case, initial matrix failure occurs which quickly spreads through the cross-section near the center of the shell. The observed failure (shown on the right) is similar to a collapse mode shown previously. If the fiber failure strain is reduced so that fiber failure occurs first, then the failure mode is more predominately like a buckling mode as seen in the figure on the left.

In the designing of aircraft structures for impact, it is crucial that the dynamic collapse behavior of the primary structural components be in modes not highly prone to distributing material failure. As has been shown, this requires a thorough understanding of the material behavior when subjected to impact loadings.



FIBER FAILURE



MATRIX FAILURE

SUMMARY

There are four points made below. Before we can simulate the behavior of composite structures due to impact loading in order to evaluate crashworthiness, the material and laminate phenomena must be identified and understood. Carefully controlled test programs must be designed in order to achieve these goals. Because of the complexity of phenomena and the current status of computational techniques, there still is a "trade-off" between detailed finite element modeling and "hybrid" modeling of energy absorbing structures constructed of composite materials. This may also be true for metallic aircraft structures.

- It is essential to characterize the progressive failure behavior of laminated composite materials subjected to impact loadings and to implement this capability into finite element simulation codes

- Carefully controlled tests of composite components must be performed to better understand modes of failure, energy absorbing capabilities and to provide data for correlation with crash simulation codes

- There still may be a "trade-off" between detailed finite element and hybrid modeling of laminated composite material in some sections of the structure

- It is essential that crashworthiness be incorporated into the structural design for composite materials