NASA/TM—1999-209269

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December 1999

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Prepared for the
1998 Aircraft Structural Integrity Program Conference
sponsored by the United States Air Force
San Antonio, Texas, December 1–3, 1998

National Aeronautics and
Space Administration

Glenn Research Center

December 1999

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SUMMARY

This report describes methods and corresponding computer codes that are used to evaluate progressive damage and fracture and to perform probabilistic assessment in built-up composite structures. Structural response is assessed probabilistically during progressive fracture. The effects of design variable uncertainties on structural fracture progression are quantified. The fast probability integrator (FPI) is used to assess the response scatter in the composite structure at damage initiation. The sensitivity of the damage response to design variables is computed. The methods are general purpose and are applicable to stitched and unstitched composites in all types of structures and fracture processes starting from damage initiation to unstable propagation and to global structure collapse. The methods are demonstrated for a polymer matrix composite stiffened panel subjected to pressure. The results indicated that composite constituent properties, fabrication parameters, and respective uncertainties have a significant effect on structural durability and reliability. Design implications with regard to damage progression, damage tolerance, and reliability of composite structures are examined.

INTRODUCTION

Graphite/epoxy composite structures are used in the design of various structural components, such as aircraft wing and fuselage structures, jet engine cowls, pressure vessels, containment structures, and rocket motor cases. In these applications, it is important to achieve low weight, high strength, stiffness, and safety. For a rational design, it is necessary to quantify the damage tolerance of a candidate structure and the effects of scatter ranges of all design variables on damage tolerance. The assessment of damage tolerance requires the capability to simulate the progressive damage and fracture characteristics and to perform a subsequent probabilistic evaluation of composite structures under loading. The damage tolerance of a structure is quantified by the residual strength, that is, the additional load-carrying ability after damage. Probabilistic assessment determines the probability level at which that residual strength is achieved. Composite structures are well suited for designs with an emphasis on damage tolerance because continuous-fiber composites have the ability to arrest cracks and prevent self-similar crack propagation. For most fiber reinforcement configurations, cracks and other stress concentrators do not have as important an influence on composites as they do on homogeneous materials. In addition, composites offer a multiplicity of design options: numerous possible fiber orientation patterns, stitching, braiding, constituent material combinations, ply drops, and hybridizations render a large number of possible design parameters that may be varied for an optimal design. Flawed structures, metallic or composite, fail when flaws grow or coalesce to a critical dimension such that the structure cannot safely perform as designed and qualified or catastrophic global fracture is imminent. In comparison with only a few traditional materials, fibrous composites exhibit multiple fracture modes that initiate local flaws; hence, the

simulation of structural fracture in fibrous composites must include (1) all possible fracture modes, (2) the types of flaws they initiate, and (3) the coalescing and propagation of these flaws to critical dimensions for imminent structural fracture. The comprehensive simulation of progressive fracture and probabilistic assessment presented herein is independent of stress intensity factors and fracture toughness parameters. Concepts governing the structural fracture simulation are described in reference 1. Based on these concepts, computational simulation procedures have been developed for (1) simulating damage initiation, progressive fracture, and collapse of composite structures and (2) evaluating the probability of structural fracture in terms of global quantities that are indicators of structural integrity. The general objective of this report is to briefly describe these methods and to present typical results obtained. Specifically, this report describes a combination of computational simulation and probabilistic methods used to identify the salient material and structural parameters for a reliable design with damage tolerance considerations.

COMPUTATIONAL SIMULATION PROCEDURE

The progressive fracture of angle-plied, woven, stitched, and unstitched composite laminates is simulated via an innovative approach independent of stress intensity factors and fracture toughness parameters. Computational simulation is able to evaluate damage initiation, damage growth, and fracture in composites under various loading and environmental conditions. It has been applied to investigate the effects of composite degradation on structural response (ref. 1), the effect of hygrothermal environment on durability (ref. 2), damage progression in composite shells subjected to internal pressure (ref. 3), the durability of stiffened composite shell panels under combined loading (ref. 4), and damage progression in stiffened composite structural components (ref. 5).

Computational simulation is carried out by an integrated and open-ended computer code consisting of three modules: composite mechanics, finite-element analysis, and damage progression modeling. The overall evaluation of composite structural durability is carried out in the damage progression module (ref. 6) that tracks composite degradation for the entire structure. The damage progression module relies on composite mechanics (ref. 7) for composite micromechanics, macromechanics, and laminate analysis and calls a finite-element analysis module that uses anisotropic thick shell elements to model laminated composites (ref. 8). The composite mechanics module is called before and after each finite-element analysis. Prior to each finite-element analysis, the composite mechanics module computes the composite properties from the fiber and matrix constituent characteristics and the composite layup.

The finite-element analysis module accepts the composite properties that are computed by the composite mechanics module at each node and performs the analysis at each load increment. After an incremental finite-element analysis, the computed generalized nodal force resultants and deformations are supplied to the composite mechanics module that evaluates the nature and amount of local damage, if any, in the plies of the composite laminate. Individual ply failure modes are assessed by the composite mechanics module using failure criteria associated with the negative and positive limits of the six ply stress components in the material directions. In addition to the failure criteria based on stress limits, interply delamination due to relative rotation of the plies and a modified distortion energy (MDE) failure criterion that takes into account combined stresses are considered (ref. 7). Depending on the dominant term in the MDE failure criterion, fiber failure or matrix failure is assigned. The generalized stress-strain relationships are revised locally according to the composite damage evaluated after each finite-element analysis. The model is automatically updated with a new finite-element mesh having reconstituted properties, and the structure is reanalyzed for further deformation and damage. If there is no damage after a load increment, the structure is considered to be in equilibrium, and an additional load increment is applied leading to possible damage growth, accumulation, or propagation. Simulation is continued until global structural fracture.

The phenomenon of fracture in composite structures is further compounded because of inherent uncertainties in the multitude of material properties, structural geometry, loading, and service environments. The effect of all types of uncertainties must be designed in for satisfactory, reliable, and affordable structures. The various uncertainties are traditionally accounted for via knockdown (safety) factors with a generally unknown reliability. An alternate approach to quantify those uncertainties on structural fracture is to use probabilistic evaluation as follows: (1) computationally simulate the initiation and progression of damage in composite structures and (2) probabilistically assess the effect of design variable uncertainties on structural response after damage and fracture. For a probabilistic evaluation of damage and fracture progression, an integrated probabilistic analysis code (ref. 9) is used in conjunction with progressive damage simulation. The probabilistic analysis code considers the uncertainties in material

properties, the composite fabrication process, and global structural parameters. The effects on structural fracture of the uncertainties in all the relevant design variables are quantified. The composite mechanics, finite-element structural simulation, and fast probability integrator (FPI) have been integrated into the probabilistic analysis code IPACS (Integrated Probabilistic Assessment of Composite Structures (ref. 9)). Contrary to the traditional Monte Carlo simulation, FPI makes it possible to achieve orders-of-magnitude computational efficiencies that are acceptable for practical applications. Therefore, a probabilistic composite assessment that cannot be done traditionally becomes feasible, especially for composite materials and/or structures having a large number of uncertain variables.

Figure 1 shows a computational simulation cycle during a probabilistic analysis. A probabilistic analysis cycle begins with defining uncertainties in material properties at the most fundamental composite scale (fiber-matrix constituents). The material uncertainties are progressively propagated to those at higher composite scales (subply, ply, laminate, and structural). The uncertainties in fabrication variables are carried through the same hierarchy. The damaged and/or fractured structure state with ranges of uncertainties in design variables, such as material behavior, structure geometry, supports, and loading, are input to the probabilistic analysis module. Consequently, probability density functions (PDF) and cumulative distribution functions (CDF) can be obtained at the various composite scales for specified structure responses, such as displacements, buckling, and frequencies. The sensitivities of these design variables to specified structure responses are also obtained. Input data for probabilistic analysis are generated continuously as progressive damage and fracture stages occur.

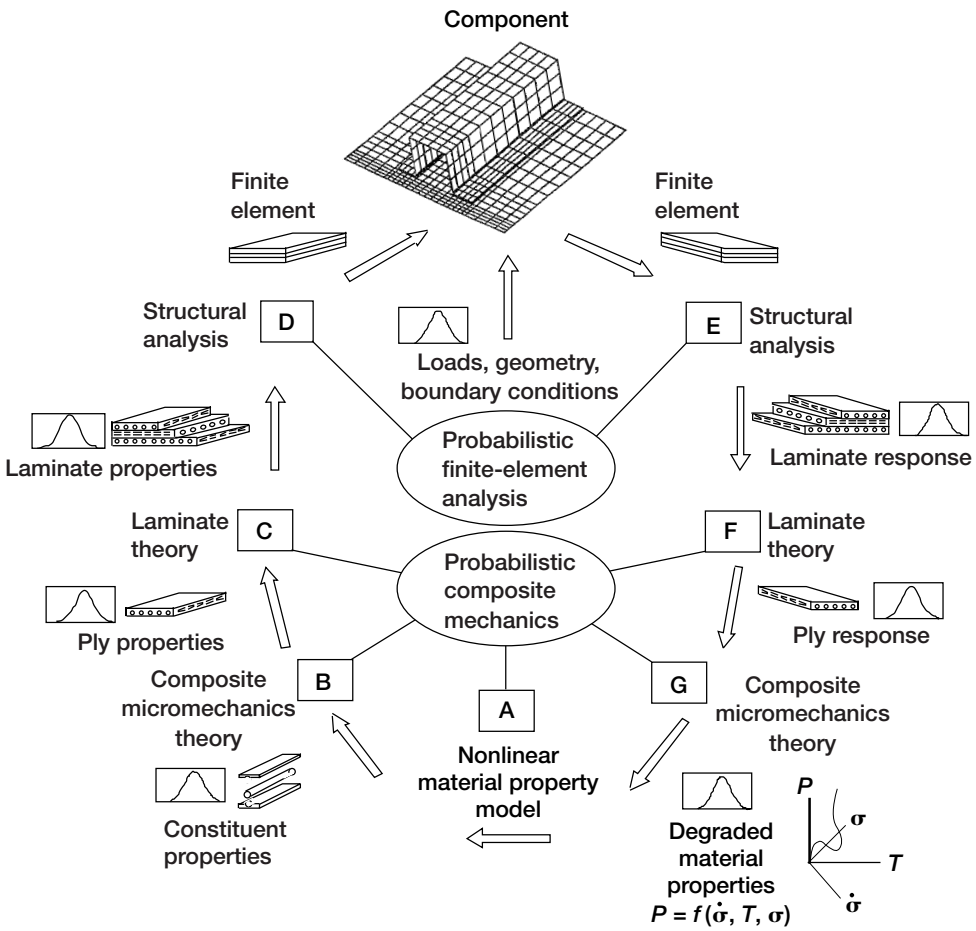

Figure 1.—Computational simulation cycle.

APPLICATION TO COMPOSITE PANELS

A discontinuously stiffened panel of graphite-epoxy laminate is considered. The laminate consists of 16 plies configured as $[0/\pm45/90]_{s2}$ with a total thickness of 0.1 in. The specimen has a width of 13.0 in. and a length of 11.0 in. The 0° plies are oriented along the 11.0-in. direction and the 90° plies are oriented transverse to the 11.0-in. direction. The finite-element model contains 626 nodes and 504 elements (fig. 2). The composite system is made of IM–7 graphite fibers in a high-temperature 5250–4 bismaleimide matrix. The specific fiber properties from the

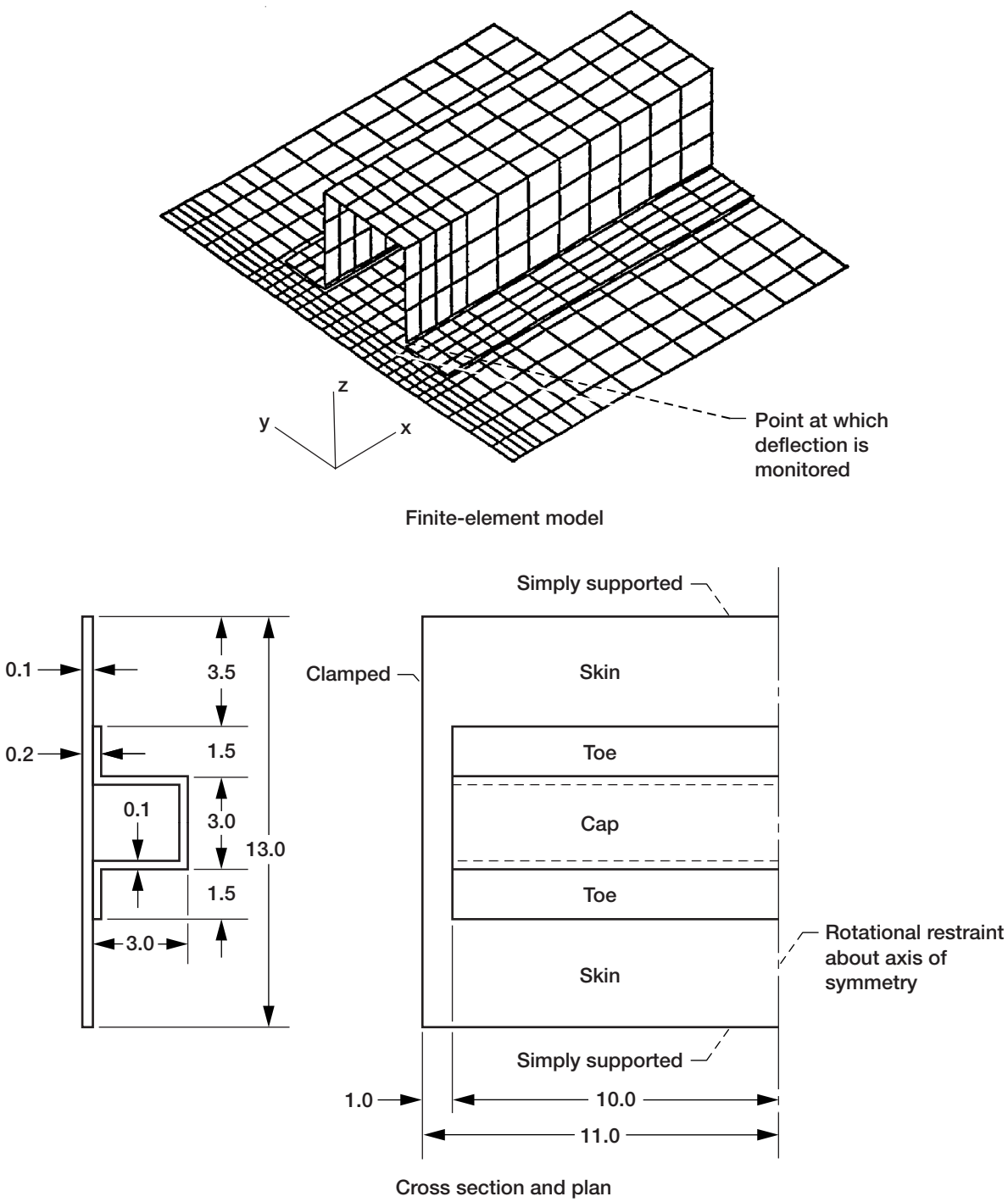

Figure 2.—Stiffened composite panel. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$. All dimensions are in inches.

materials data bank are given in table I and the matrix properties are given in table II. The fiber volume ratio is 0.60 and the void volume ratio is 1 percent. The composite cure temperature is 400 °F and the use temperature is 70 °F.

The stiffened panel was fixed on all edges and was first subjected to a gradually increasing pressure applied from the underside to the skin. Figure 3 shows deflections (at the stiffener web-panel juncture) with applied pressure. Damage progression was computationally simulated as the loading was increased. The rate of increase in the overall damage during composite degradation was used as a measure of the structural propensity for fracture. Figure 4 shows the simulated damage progression with increasing pressure. After the completion of a well-defined damage growth stage, the state of damage remained constant until the ultimate load was reached. The elastic energy accumulated in the stiffened panel is plotted in figure 5. The damage energy was computed as the work done by pressure during the creation of structural damage. The rate of damage energy released per unit volume of damage created (DERR) is plotted in figure 6. The DERR reached a distinct peak value during damage progression and then descended to a minimum value corresponding to the damage tolerance pressure. Figure 7 shows a different measure of structural degradation based on the cumulative energy exhausted as each damage mechanism was activated.

TABLE I.—IM–7 GRAPHITE FIBER PROPERTIES

Number of fibers per end	12 000
Fiber diameter, in.	0.200×10^{-3}
Fiber density, lb/in.^{3}	0.063
Normal modulus, psi	
Longitudinal	42.3×10^{6}
Transverse	2.13×10^{6}
Poisson's ratio	
ν_{12}	0.356
ν_{23}	0.267
Shear modulus, psi	
G_{12}	2.25×10^{6}
G_{23}	0.85×10^{6}
Thermal expansion coefficient	
Longitudinal	-0.55×10^{-6}/°F
Transverse	0.56×10^{-5}/°F
Heat conductivity, BTU-in./hr/in.^{2}/°F	
Longitudinal	4.03
Transverse	0.403
Heat capacity, BTU/lb/°F	0.17
Strength, ksi	
Tensile	650
Compressive	637

TABLE II.—5250–4 HIGH-TEMPERATURE MATRIX PROPERTIES

Matrix density, lb/in.^{3}	0.0457
Normal modulus, ksi	671
Poisson's ratio	0.70
Coefficient of thermal expansion	0.288×10^{-4}/°F
Heat conductivity, BTU-in./hr/in.^{2}/°F	0.868×10^{-2}
Heat capacity, BTU/lb/°F	0.25
Strength, MPa (ksi)	
Tensile	13.1
Compressive	41.0
Shear	20.0
Allowable strain	
Tensile	0.02
Compressive	0.05
Shear	0.04
Torsional	0.04
Void conductivity, BTU-in./hr/in.^{2}/°F	0.225
Glass transition temperature, °F	572

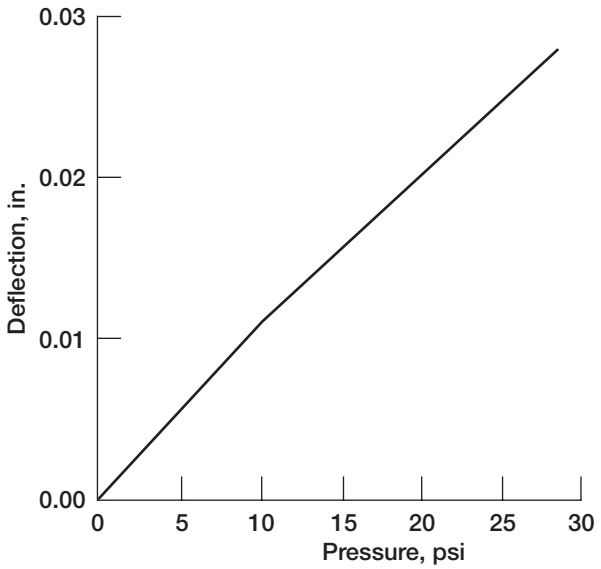

Figure 3.—Deflections with pressure. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$.

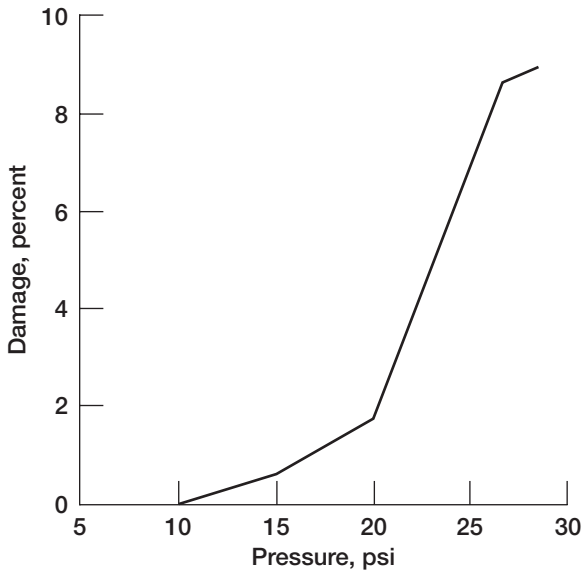

Figure 4.—Damage progression with pressure. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$.

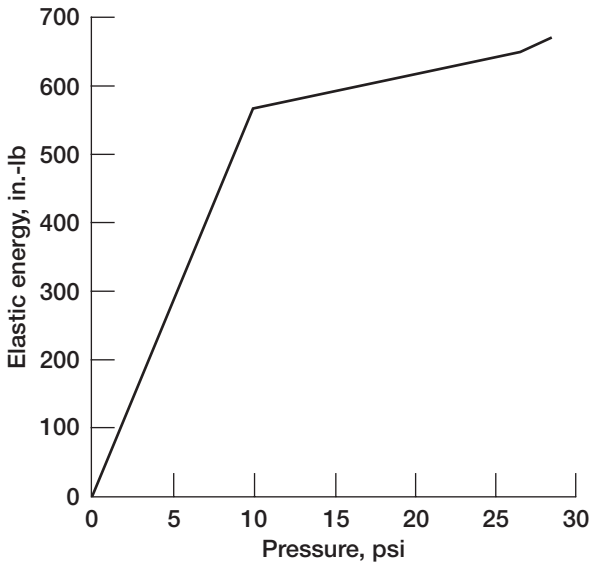

Figure 5.—Elastic energy accumulated with pressure. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$.

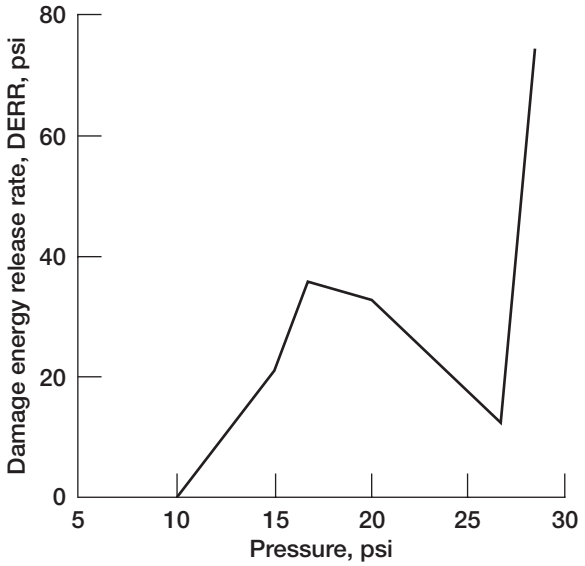

Figure 6.—Damage energy release rates with pressure. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$.

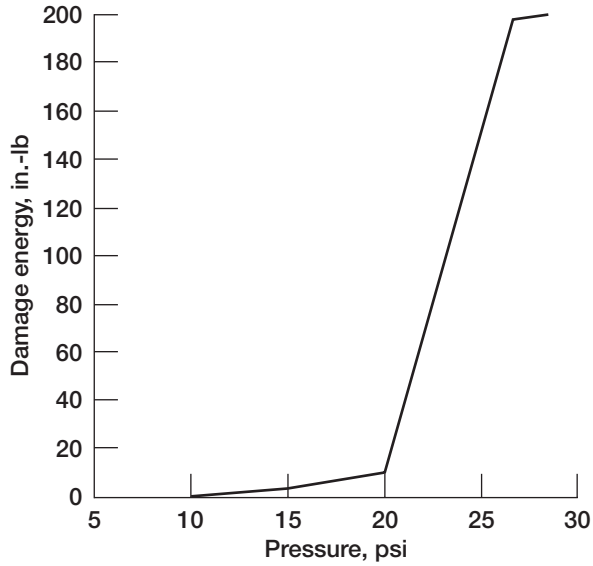

Figure 7.—Damage energy exhausted with pressure. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{S2}$.

Static analysis indicated that a structural damage tolerance pressure of 26.7 psi caused local laminate fracture in the skin of the panel adjacent to the discontinuous end of the stiffener. Significant characteristics of damage initiation and progression may be itemized as follows:

1. Damage initiation occurred by ply transverse tensile fractures at a 10-psi applied pressure.
2. Plies subjected to longitudinal compressive stresses experienced longitudinal compressive fractures after sustaining transverse tensile fractures.
3. Damage initiation began in the skin plies at the discontinuous end of the stiffener.

Table III summarizes the simulated damage initiation and progression stages.

TABLE III.—DAMAGE AND FRACTURE PROGRESSION STAGES

Pressure, psi	Damage stage	Number of damaged nodes
10	Initiation (σ_{f22T}, σ_{f11C})	12
15	Damage growth	65
17	Damage progression	80
20	Damage propagation	121
27	Laminate local fracture	[a]215
29	Structural fracture	[b]31

[a]Seven fractured.
[b]Thirty-one fractured.

PROBABILISTIC EVALUATION AFTER DAMAGE AND FRACTURE

The probabilistic analysis code (ref. 9) was used to characterize the damaged structural response before and after through-the-thickness local laminate fracture. Panel deflections and ply longitudinal and transverse stresses were probabilistically evaluated by considering uncertainties in design variables. Table IV shows the probabilistic definition of the design variables with uncertainties.

TABLE IV.—PROPERTIES OF VARIABLES WITH UNCERTAINTIES

Variable	Distribution	Mean	Coefficient of variation
Pressure, psi	Normal	20	0.10
Fiber modulus, Msi			
E_{f11}		42.3	.05
E_{f22}		2.13	
G_{f12}		2.25	
Matrix modulus, E_m, ksi		671	
Poisson's ratio, ν_m		.705	
Fiber volume ratio, V_f		.60	
Ply thickness, in.		.0063	

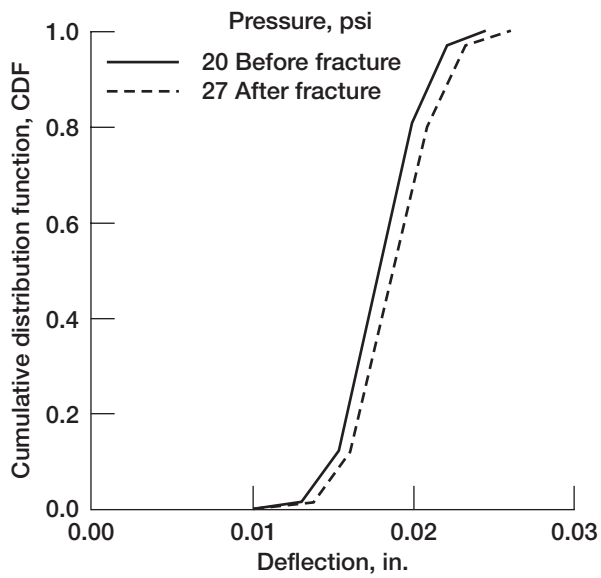

Figure 8.—Cumulative distribution function before and after laminate fracture. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$.

RESPONSE CUMULATIVE DISTRIBUTION

The effects of constituent material property uncertainties on panel deflection at the damage site were computed to assess the probabilistic response at the damage initiation stage. The CDF of the panel deflection was evaluated before and after local laminate fracture. Figure 8 shows the CDF for the panel deflection at the laminate local fracture initiation stage. The solid line in figure 8 represents the deflection response at a 20-psi normal pressure before local laminate fracture, whereas the dashed line represents the corresponding response at 27 psi after local laminate fracture. The mean value of the panel displacement at the damage location is 0.0175 in. prior to local laminate fracture. After local laminate fracture, the mean displacement response at 27 psi increases to 0.0190 in. Also, the CDF distributions before and after local laminate fracture have very similar characteristics. Therefore, the displacement response is not significantly affected by local laminate fracture.

Figure 9 shows the CDF for the $\sigma_{\ell l1}$ longitudinal stresses in ply 13 (90° ply) at the laminate local fracture initiation stage. The solid line represents the longitudinal stress response at the 20-psi normal pressure before local laminate fracture, whereas the dashed line represents the response at 27 psi after local laminate fracture. The mean value of the longitudinal stress at the damage location is –44 ksi prior to local laminate fracture. After local laminate fracture, the mean longitudinal stress response at 27 psi decreases to –40 ksi. However, the longitudinal stress CDF distributions before and after local laminate fracture have very similar characteristics.

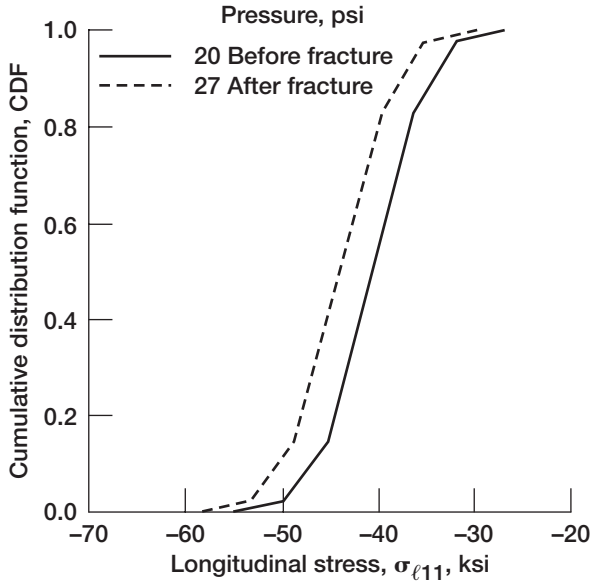

Figure 9.—Cumulative distribution function of longitudinal stress $\sigma_{\ell 11}$ before and after laminate fracture. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

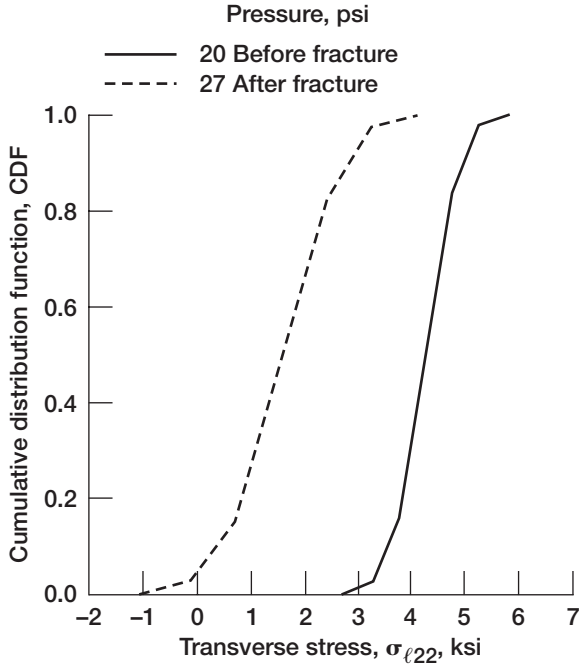

Figure 10.—Cumulative distribution function of transverse stress $\sigma_{\ell 22}$ before and after laminate fracture. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

Figure 10 shows the CDF for the $\sigma_{\ell 22}$ transverse stresses in ply 13 (90° ply) at the laminate local fracture initiation stage. The solid line represents the transverse stress response at the 20-psi normal pressure before local laminate fracture, whereas the dashed line represents the response at 27 psi after local laminate fracture. The mean value of the transverse stress at the damage location is 4.3 ksi prior to local laminate fracture. After local laminate fracture, the mean transverse stress response at 27 psi decreases to 1.5 ksi. Therefore the transverse stress response is reduced to near zero with some minor effects of the scatter ranges.

RESPONSE SENSITIVITY FACTORS

The sensitivity of the 0.001 and 0.999 cumulative probability for the deflection, longitudinal stress, and transverse stress to uncertainties in the following design variables was evaluated:

(1) Pressure on skin of panel
(2) Fiber longitudinal modulus
(3) Fiber transverse modulus
(4) Fiber shear modulus
(5) Matrix elastic modulus
(6) Matrix Poisson's ratio
(7) Fiber volume ratio
(8) Ply thickness

Figure 11 shows the sensitivities of the displacement response at an applied normal pressure of 20 psi before local laminate fracture. Figure 12 shows the sensitivities of the displacement response at an applied normal pressure of 27 psi after local laminate fracture. For both cases, namely before and after laminate local fracture, the applied normal pressure on the skin, fiber volume ratio, fiber longitudinal modulus, and ply thickness were the most significant design variables that affected the deflection reliability. Additionally, the sensitivities of the deflection to fiber transverse modulus, fiber shear modulus, matrix modulus, and void volume ratio were relatively negligible. These results

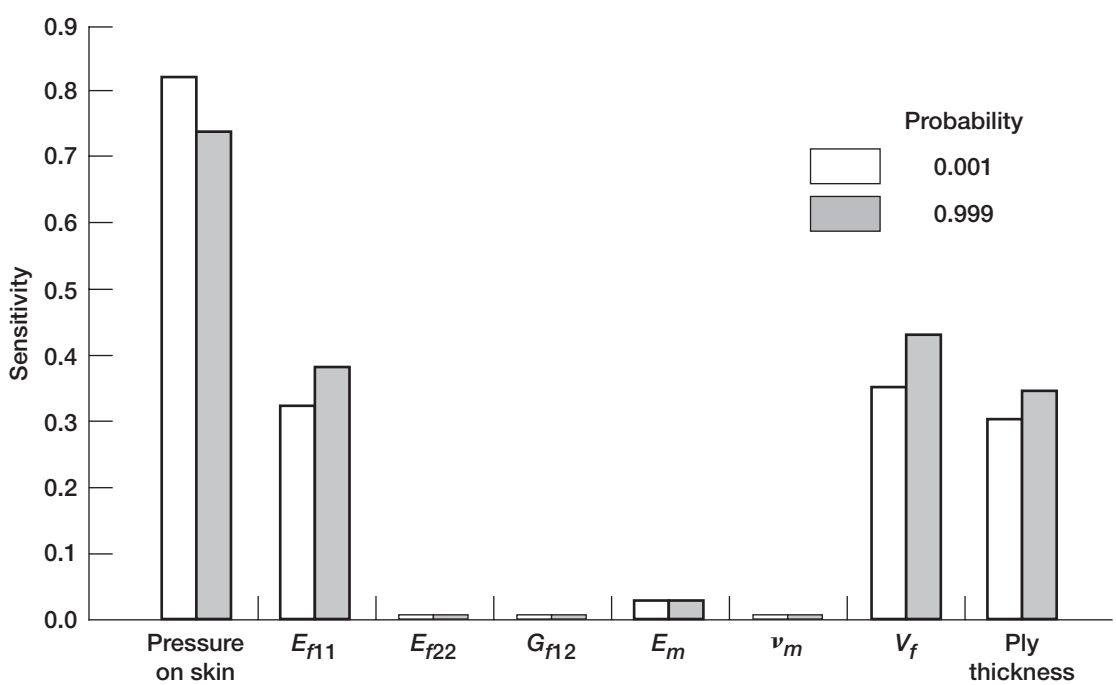

Figure 11.—Sensitivities of panel deflection before laminate fracture at applied normal pressure of 20 psi. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

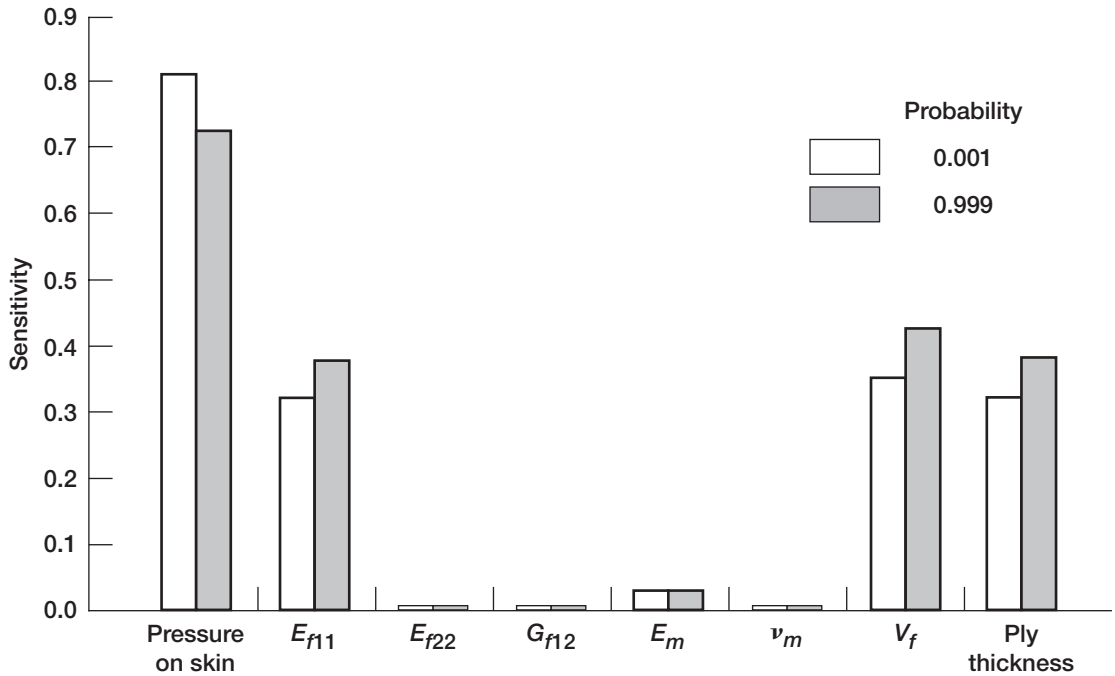

Figure 12.—Sensitivities of panel deflection after laminate fracture at applied normal pressure of 27 psi. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm45/90]_{s2}$.

established that (1) laminate local fracture does not affect the sensitivities of panel deflection to the design variables and (2) panel deflection may be controlled by adjusting the applied normal pressure, fiber volume ratio, fiber longitudinal modulus, and ply thickness.

Figure 13 shows the sensitivities of the $\sigma_{\ell 11}$ longitudinal stress response at an applied normal pressure of 20 psi before local laminate fracture. Figure 14 shows the sensitivities of the $\sigma_{\ell 11}$ longitudinal stress response at an applied normal pressure of 27 psi after local laminate fracture. For both cases, namely before and after laminate local fracture, the applied normal pressure on the skin and ply thickness was the most significant design variable that affected the $\sigma_{\ell 11}$ longitudinal stress. The influence of applied normal pressure was maximum at 0.999 probability and the influence of ply thickness was maximum at 0.001 probability. Additionally, the changes in the sensitivities of $\sigma_{\ell 11}$ longitudinal stress before and after laminate local fracture were slight. These results established that (1) laminate local fracture has a relatively negligible effect on the sensitivities of the $\sigma_{\ell 11}$ longitudinal stress to the design variables and (2) the $\sigma_{\ell 11}$ longitudinal stress may be controlled by adjusting the applied normal pressure and the ply thickness.

Figure 15 shows the sensitivities of the $\sigma_{\ell 22}$ transverse stress response at an applied normal pressure of 20 psi before local laminate fracture. Figure 16 shows the sensitivities of the $\sigma_{\ell 22}$ transverse stress response at an applied normal pressure of 27 psi after local laminate fracture. Before laminate local fracture, the order of sensitivity to design variables was (1) ply thickness, (2) applied pressure, (3) fiber longitudinal modulus, (4) matrix elastic modulus, (5) fiber transverse modulus, (6) fiber volume ratio, and (7) Poisson's ratio of the matrix. After laminate local fracture, the design variables that influenced the transverse stress response were (1) ply thickness, (2) applied pressure, and (3) fiber longitudinal modulus. The sensitivity of the transverse stress response to the other design variables was significantly diminished. These results established that (1) laminate local fracture has a very significant effect on the sensitivities of the $\sigma_{\ell 22}$ transverse stress to the design variables and (2) the $\sigma_{\ell 22}$ transverse stress may be controlled by adjusting the applied normal pressure, the ply thickness, and the fiber longitudinal modulus.

An important observation from the sensitivity factors is that the failure mechanisms that initiate local fracture remain identical prior to and after local laminate fracture.

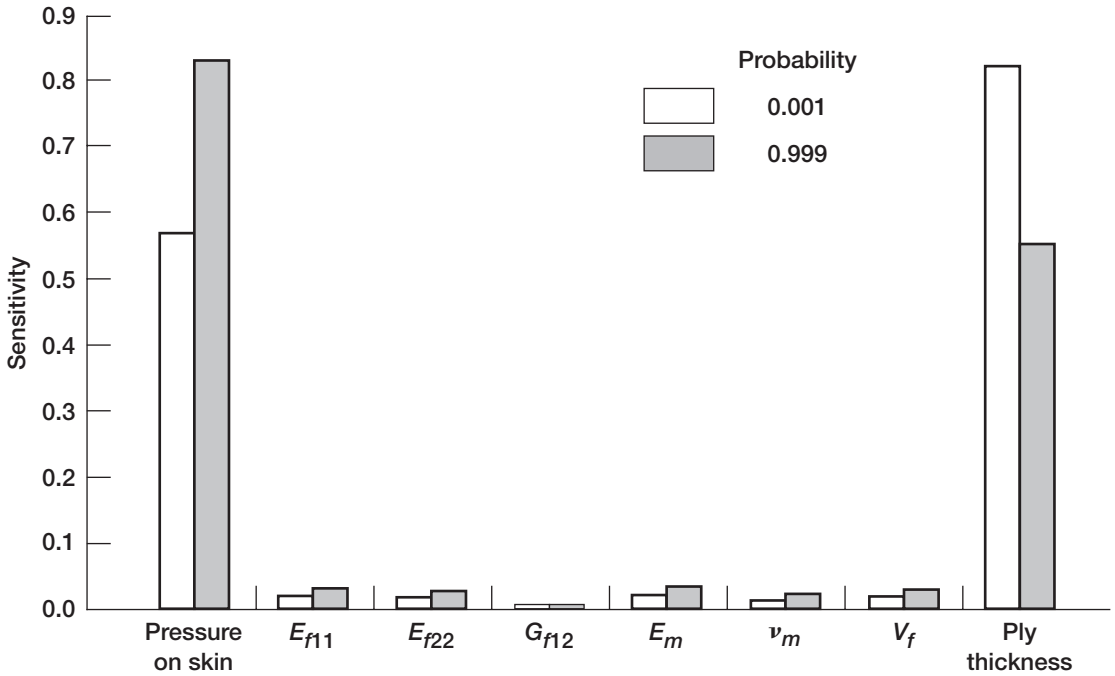

Figure 13.—Sensitivities of longitudinal stress $\sigma_{\ell 11}$ before laminate fracture at applied normal pressure of 20 psi. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

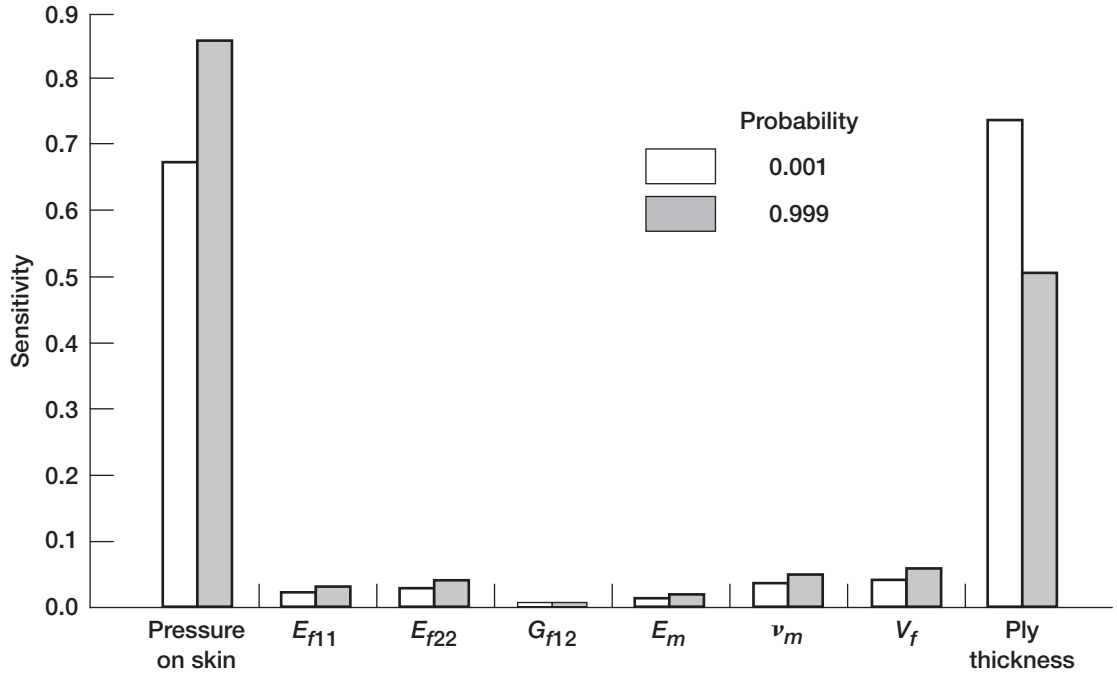

Figure 14.—Sensitivities of longitudinal stress $\sigma_{\ell 11}$ after laminate fracture at applied normal pressure of 27 psi. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

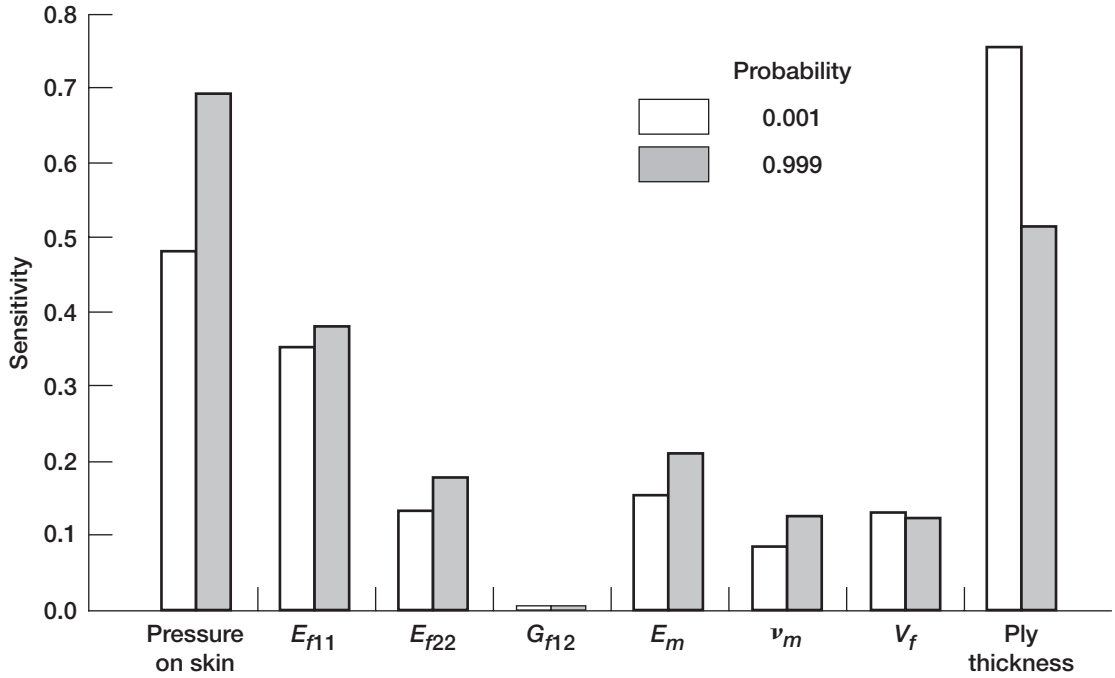

Figure 15.—Sensitivities of longitudinal stress $\sigma_{\ell 22}$ before laminate fracture at applied normal pressure of 20 psi. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

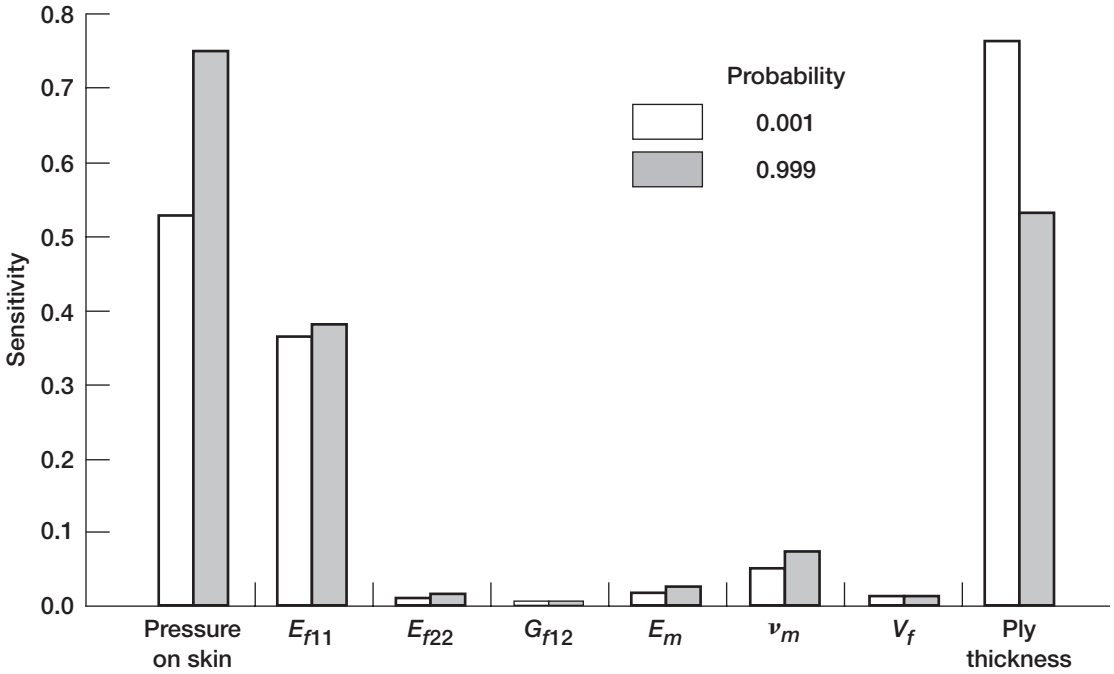

Figure 16.—Sensitivities of longitudinal stress $\sigma_{\ell 22}$ after laminate fracture at applied normal pressure of 27 psi. Material, IM–7/5250–4; plies, 16; configuration, $[0/\pm 45/90]_{s2}$.

SUMMARY OF RESULTS

Methods and corresponding computer codes were briefly described to probabilistically assess composite structural damage and results obtained therefrom were presented. The progressive fracture of a composite structure was simulated via an innovative approach independent of stress intensity factors and fracture toughness parameters. The approach described herein is inclusive in that it integrates composite mechanics (for composite behavior) with finite-element analysis (for global structural response) and incorporates probability algorithms to perform a probabilistic assessment of composite structural fracture. The effect on the composite structural damage of the design variable uncertainties was accounted for at all composite scales. The probabilistic scatter range and sensitivity factors are key results obtained from the probabilistic assessment of composite structures subject to fracture. The sensitivity factors provide quantifiable information on the relative sensitivity of structural design variables on the respective structure response. The following results were obtained:

1. Damage initiation at a pressure of 10 psi is the result of ply transverse tensile fractures of the skin laminate near the discontinuous end of the stiffener.
2. Plies subjected to longitudinal compression become vulnerable to fiber fractures after experiencing transverse tensile fractures.
3. The 27-psi pressure that causes through-the-thickness local laminate fractures defines the damage tolerance limit for the stiffened panel.
4. Deflections are most sensitive to uncertainties in the applied pressure, fiber volume ratio, fiber longitudinal modulus, ply thickness, and matrix modulus.
5. Ply longitudinal stresses are most sensitive to uncertainties in the applied pressure and ply thickness.
6. Ply transverse stresses are most sensitive to uncertainties in the applied pressure, ply thickness, fiber longitudinal modulus, matrix modulus, fiber transverse modulus, fiber volume ratio, and matrix Poisson's ratio.
7. Probabilistic evaluation of ply transverse stresses near a damaged node is significantly affected by local laminate fracture.
8. The sensitivity factors for the responses evaluated remain identical before and after local laminate fracture.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
December 1999

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Probabilistic Assessment of Fracture Progression in Composite Structures

5. FUNDING NUMBERS
WU–523–22–13–00

6. AUTHOR(S)
Christos C. Chamis, Levon Minnetyan, Bertrand Mauget, Dade Huang, and Frank Abdi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–11719

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—1999-209269

11. SUPPLEMENTARY NOTES
Prepared for the 1998 Aircraft Structural Integrity Program Conference sponsored by the United States Air Force, San Antonio, Texas, December 1–3, 1998. Christos C. Chamis, NASA Glenn Research Center; Levon Minnetyan and Bertrand Mauget, Clarkson University, Potsdam, New York 11369–5710. Dade Huang and Frank Abdi, AlphaStar Corporation, 5150 E. Pacific Coast Highway, Long Beach, California 90804. Responsible person, Christos C. Chamis, organization code 5000, (216) 433–3252.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 39 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
This report describes methods and corresponding computer codes that are used to evaluate progressive damage and fracture and to perform probabilistic assessment in built-up composite structures. Structural response is assessed probabilistically during progressive fracture. The effects of design variable uncertainties on structural fracture progression are quantified. The fast probability integrator (FPI) is used to assess the response scatter in the composite structure at damage initiation. The sensitivity of the damage response to design variables is computed. The methods are general purpose and are applicable to stitched and unstitched composites in all types of structures and fracture processes starting from damage initiation to unstable propagation and to global structure collapse. The methods are demonstrated for a polymer matrix composite stiffened panel subjected to pressure. The results indicated that composite constituent properties, fabrication parameters, and respective uncertainties have a significant effect on structural durability and reliability. Design implications with regard to damage progression, damage tolerance, and reliability of composite structures are examined.

14. SUBJECT TERMS
Damage; Sensitivities; Durability; Collapse; Fibers; Matrices; Failure stresses; Deflections mechanisms; Distribution functions; Energy release rates

15. NUMBER OF PAGES
21

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	