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National Aeronautics and
Space Administration

PROBABILISTIC SIMULATION OF FAILURE IN BOLTED-JOINT COMPOSITE LAMINATES

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SUMMARY

This report describes computational methods to probabilistically simulate fracture in bolted composite structures. An innovative approach that is independent of stress intensity factors and fracture toughness was used to simulate progressive fracture. The effect of design variable uncertainties on structural damage was also quantified. A fast probability integrator assessed the scatter in the composite structure response before and after damage. Then the sensitivity of the response to design variables was computed. General-purpose methods, which are applicable to bolted joints in all types of structures and in all fracture processes—from damage initiation to unstable propagation and global structure collapse—were used. These methods were demonstrated for a bolted joint of a polymer matrix composite panel under edge loads. The effects of the fabrication process were included in the simulation of damage in the bolted panel. Results showed that the most effective way to reduce end displacement at fracture is to control both the load and the ply thickness. The cumulative probability for longitudinal stress in all plies was most sensitive to the load; in the 0° plies it was very sensitive to ply thickness. The cumulative probability for transverse stress was most sensitive to the matrix coefficient of thermal expansion. In addition, fiber volume ratio and fiber transverse modulus both contributed significantly to the cumulative probability for the transverse stresses in all the plies.

INTRODUCTION

Flawed structures, metallic or composite, fail (1) when flaws grow or coalesce to such a critical dimension that the structure cannot safely perform as designed and qualified, or (2) when small increases in load or damage cause such substantial changes in the safety metrics of the structure that catastrophic global fracture is imminent. However, fibrous composites exhibit multiple fracture modes that initiate local flaws, as opposed to only a few modes for traditional materials. Hence, simulation of structural fracture in fibrous composites must include (1) all possible fracture modes, (2) the types of flaws these modes initiate, and (3) the coalescing and propagation of these flaws to critical dimensions for imminent structural fracture.

The phenomena of fracture in a composite structure are further compounded by the inherent uncertainties (scatter range) in the multitude of material properties and in the geometry, loading, and service environment of the structure. The effects of all types of uncertainties must be compensated for in the design phase if satisfactory, reliable, and affordable structures are to result. Traditionally such uncertainties were accounted for via knockdown (safety) factors of dubious reliability. An alternate approach to quantify the effect of these uncertainties on structural fracture is to use the probabilistic methods described herein.

The objective of the present investigation was to demonstrate methods and codes that (1) computationally simulate the initiation and progression of damage in composite structures and (2) probabilistically assess the effect of design variable uncertainties on structural fracture. These methods and corresponding computer codes are used to determine the uncertainty in the damage load on bolted-joint polymer matrix composite panels.

COMPUTATIONAL SIMULATION

A comprehensive simulation of progressive fracture is presented herein. It is independent of stress intensity factors and fracture toughness. The concepts governing the simulation of structural fracture are described in reference 1. Based on these concepts, a computational procedure was developed to (1) simulate damage initiation, progressive fracture, and the collapse of composite structures and (2) evaluate, in terms of global quantities (which are indicators of structural integrity), the probability of structural fracture.

Progressive Fracture

The methodology for a step-by-step simulation of individual mode and mixed modes fracture in a variety of generic composite components is described in references 1 to 3. This methodology has been incorporated into an integrated computer code, CODSTRAN (COmposite Durability STRuctural ANalysis, see refs. 4 and 5), which quantifies the damage stages by using composite mechanics. The degradation of the structural behavior, on the other hand, is quantified by using a finite-element method in which the damaged part of the structure does not contribute to the resistance, but is carried along as a parasitic material.

Normally, an integrated computer code is used to combine composite mechanics with the finite-element method so as to formally describe the relationship between local conditions and global structural behavior, as is shown schematically in figure 1. At the bottom of figure 1, the conditions of the constituent materials (microstress versus resistance—micro scale) are described. In the left part of figure 1, the criteria for damage initiation, growth, accumulation, and propagation are examined at each scale; that is, the local damage effects on global structural behavior (response) are integrated (synthesized) upward through the various scales. In the right part of the figure, the effects of global scale changes (loading or support conditions, for example) on the local (micro scale) constituent material stress and resistance are tracked (decomposed). That is, the increases in damage caused at the micro scale by increases in the loading applied at the global scale (structural level) are tracked.. Overall global structural equilibrium is maintained by iterations around the “cartwheel” in figure 1 until a specified convergence is reached.

This approach has been applied to computationally simulate structural fracture of various composites, including panels subjected to inplane loads. Typical results for through-thickness delamination are available in reference 1.

Probabilistic Assessment of Structural Fracture

The effects of uncertainties in the relevant design variables on the structure’s fracture are quantified herein. Previously, computer codes that address composite mechanics, finite-element structural simulation, and fast probability integration (FPI) were integrated to form IPACS (Integrated Probabilistic Assessment of Composite Structures, see ref. 6). A schematic of IPACS is shown in figure 2. In contrast to the traditional Monte Carlo simulation, FPI makes possible computational efficiencies that are orders-of-magnitude faster, which makes it acceptable for practical applications. Therefore, a probabilistic assessment of the composite becomes feasible. Such an assessment cannot be done by traditional means, especially for composite materials and structures that have a large number of uncertain variables.

IPACS starts by defining uncertainties in the material properties at the most fundamental composite scale (the fiber/matrix constituents). The uncertainties are then progressively propagated to and combined with the uncertainties of the next higher composite scale (subply, ply, laminate, structure), as shown in figure 2. The uncertainties in the fabrication variables are carried through the same hierarchy. The structure and the ranges of uncertainties in its respective design variables (such as material behavior, structure geometry, supports, and loading) are input to IPACS. Consequently, probability density functions (PDF) and cumulative distribution functions (CDF) for the structure response can be obtained at all the composite scales (laminate, macro, and micro). The sensitivity of the uncertainties in the various design variables to structure response can also be obtained.

DEMONSTRATION CASE

The aforementioned methods and computer codes were demonstrated by (1) simulating the fracture in a bolted joint of a composite panel and (2) evaluating the probability of a damage-initiation load for such a panel.

Consider a polymer matrix composite panel (8.0 by 4.0 by 0.25 in.) fastened at 2 in. from one of its ends by a 1.0-in.-diam bolt. The composite system, composed of AS-4 graphite fibers in a high-modulus, high-strength epoxy matrix (AS-4/HMHS), is subjected to a uniformly distributed load at the other end (fig. 3). The fiber volume ratio is 0.60, and the void volume ratio is 2 percent. The laminate consists of forty-eight 0.00521-in. plies in a $[90/\pm45/0]_{12}$ configuration. The 90° plies are in the *y*-direction, and the 0° plies are in the *x*-direction. A cure temperature of 350 °F simulates the effect of fabrication-induced residual stresses, and high-strength steel properties are used to model the bolt. (Figure 3 also shows the finite-element model of the bolt-jointed panel.) The bolt is fixed at its center with respect to all displacement and rotational degrees of freedom. This composite system is subjected to a gradually increasing load until it fractures and breaks into two pieces.

Figure 4 shows the simulated progression of damage with increasing load on the panel. Initially the joint is incrementally loaded to 800 lb (i.e., 0.8 kips); the finite-element connectivities between the bolt and the composite are released when generalized membrane stresses N_x and N_y are both tensile. Under a 6.8-kip load (point A, fig. 4), matrix cracking in the 90° plies causes damage to initiate in the panel around the right half of the bolt circumference. When the load is increased, damage grows outward from the bolt (point B). Gradual damage accumulation in selective plies continues until the load reaches 32.8 kips (point C); at this point fracture begins in the panel around the right half of the bolt circumference. Fracture rapidly propagates, ultimately resulting in a break in the joint due to the fracture that starts from the bottom 90° ply.

The deterministically simulated panel fracture provides no information on the panel’s reliability. The probabilistic end displacement (a global indicator of structural integrity), however, can be probabilistically assessed. It depends on uncertainties in all of the following: the relevant panel geometry, the material properties of the panel and bolt, the bolt-hole geometry, and the load.

The cumulative distribution function of the panel-end displacement before damage initiation is shown in figure 5. The probability that the panel end will be displaced less than 0.002 in. before damage initiates is about 0.01, and the probability of it being displaced more than 0.0065 in. is about 0.001. There is about a 50-percent probability that the end displacement will be 0.0043 in.

Figure 6 shows how sensitive the 0.001 and 0.999 cumulative probabilities for panel-end displacement are to uncertainties in the design variables. The load is the design variable that most significantly affects the end displacement before damage initiation. Uncertainties in ply thickness also affect end displacement substantially. The uncertainties in composite material properties, however, have only a minor effect on end displacement at both probability levels. From these results we see (1) that damage initiation is strongly dependent on uncertainties in the load and (2) that damage initiation due to panel-end displacement can be reduced most effectively by controlling the ply thickness.

Cumulative distribution functions of the longitudinal stress in various plies (at point A in fig. 3) before and after damage are shown in figure 7. The damage initiates at the 90° ply; therefore, the 90° ply is unable to carry any load after damage initiation at that point. The stresses are redistributed to the remaining plies (±45° and 0°), as shown in figure 7. Note that the load carried by the 90° ply before damage initiation is now carried mostly by ±45° plies. Figure 8 shows how sensitive a 0.001 probability of ply longitudinal stress is to uncertainties in the design variables. For a 90° ply, the stress probability is most sensitive to the load and then, in order, to the matrix coefficient of thermal expansion, the volume ratio, and the ply thickness. For a 0° ply, it is most sensitive to the load, followed by fiber volume ratio, and ply thickness. For ±45° plies, the probability of their respective longitudinal stresses is most sensitive to the random load, followed by the ply thickness. The remaining random variables contribute little to the sensitivity of the cumulative probability.

Cumulative distribution functions of transverse stress in various plies (at point A in fig. 3) before and after damage are shown in figure 9. Again, the 90° ply does not carry any load after damage initiates. Because the internal load becomes unbalanced by damage initiation, it is redistributed by iteration to the remaining plies to achieve balance. Figure 10 shows the sensitivity of a ply transverse stress probability of 0.001 to uncertainties in the design variables. For all plies, the probability is most sensitive to the matrix coefficient of thermal expansion, followed by the fiber modulus in the transverse direction. The fiber volume ratio and the matrix modulus contribute the same amount to the probability of the transverse stress in each ply. Cumulative distribution functions of inplane shear stress before and after damage are shown in figure 11. The stress and its scatter for each ply are insignificant. Figure 12 shows that in all plies, the ply shear stress probability of 0.001 is most sensitive to the load, followed by the longitudinal fiber modulus, the fiber volume ratio, and the ply thickness. Note that the longitudinal fiber modulus and the ply thickness sensitivities alternate between the 90° and 0° plies, and the ±45° plies.

CONCLUSIONS

Methods and corresponding computer codes for probabilistically assessing composite structure fracture have been discussed. The progressive fracture in composite structures 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 of the design variable uncertainties on the composite structure fracture was accounted for at all composite levels. Probabilistic scatter range and sensitivity factors were the key results obtained from the probabilistic assessment of fractured structures. The sensitivity factors provide quantifiable information about the relative sensitivity of structural design variables on structure response or fracture.

The methods and codes were applied to a bolted joint of a composite panel. The scatter in the panel-end displacement (a global indicator of structural integrity) was probabilistically quantified on the basis of uncertainties in the associated design variables. From the results obtained, the following conclusions may be drawn:

1. The scatter range of the end displacement is about 0.005 in.
2. The end displacement at fracture is most sensitive to the load, followed by the ply thickness.
3. The most effective way to reduce the end displacement at fracture is to control the load and the ply thickness.
4. After damage initiates in the 90° ply, unbalanced internal loads are redistributed to the remaining plies.
5. The cumulative probability for longitudinal stress is most sensitive to the load, but the ply thickness also makes an important contribution to it in all the plies.
6. The cumulative probability for transverse stress is additionally sensitive to the matrix coefficient of thermal expansion.
7. The fiber volume ratio and fiber transverse modulus both contribute significantly to the cumulative probability for stress in all plies.

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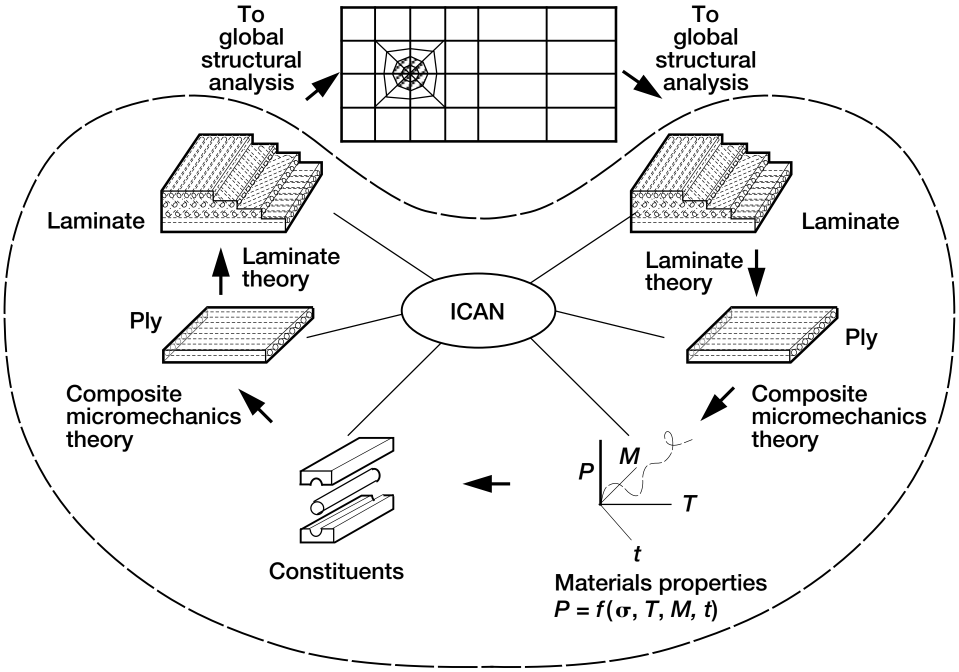


Figure 1.—Composite Durability Structural Analysis code (CODSTRAN) schematic (P = constituent material property; M = moisture; T = temperature; t = time; σ = stress).

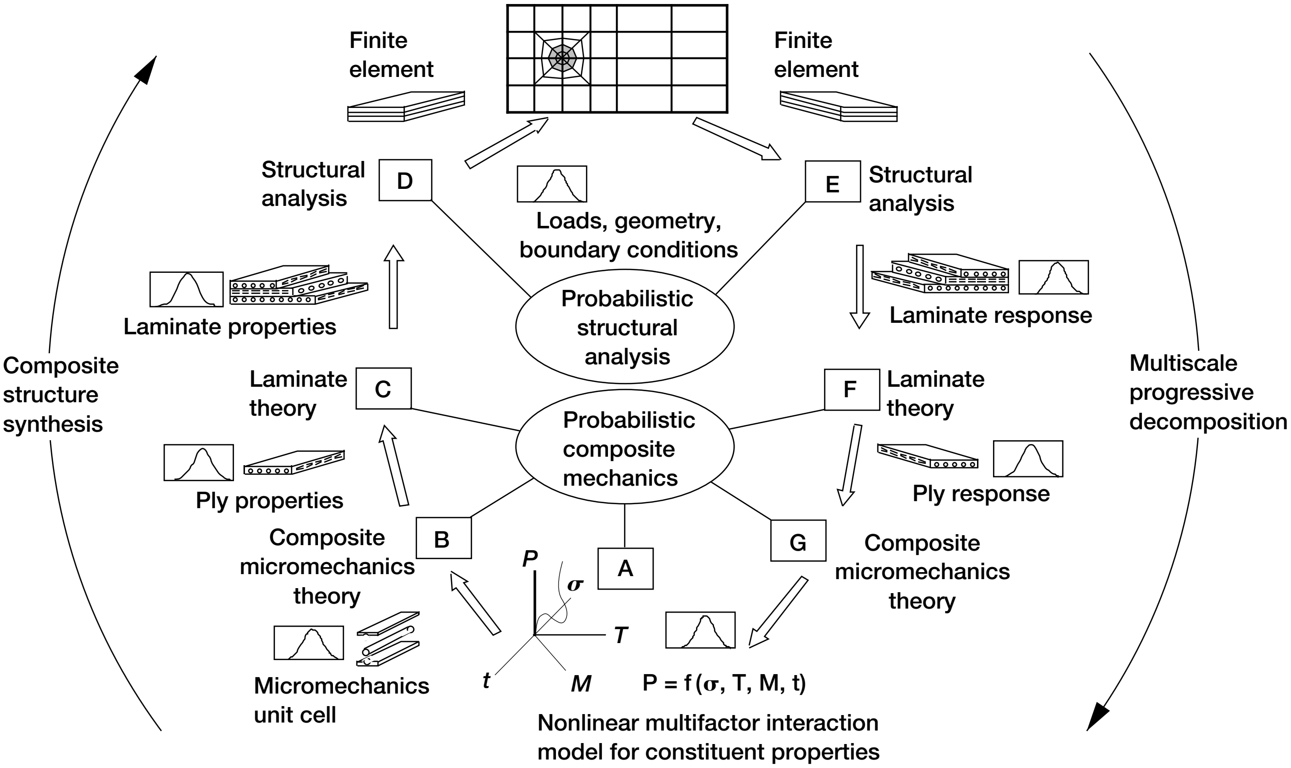


Figure 2.—Integrated Probabilistic Assessment of Composite Structures (IPACS) (P = constituent material property; M = moisture; T = temperature; t = time; σ = stress).

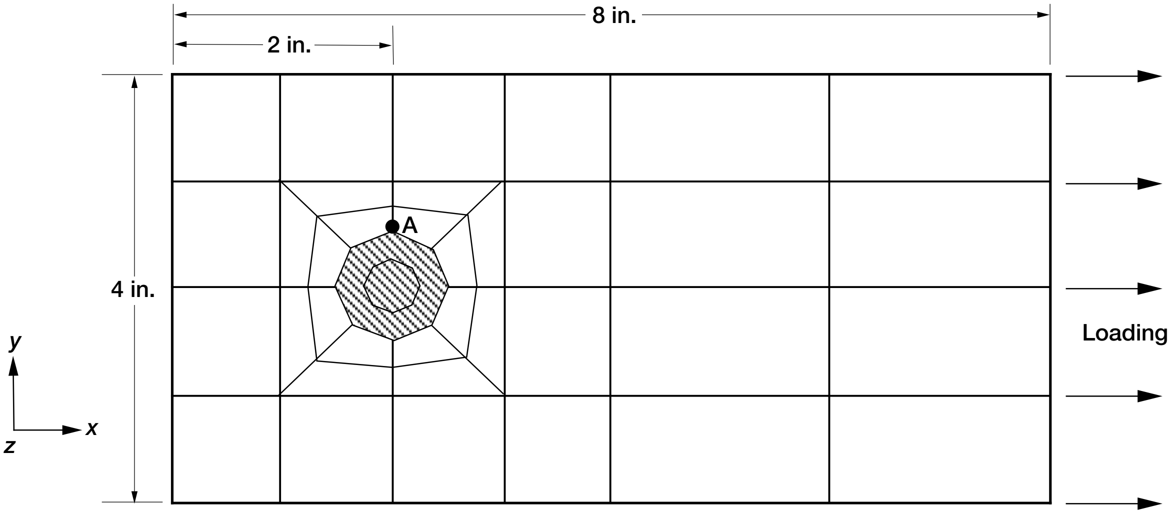


Figure 3.—Bolted joint composite panel and finite-element model. Damage initiates at point A.

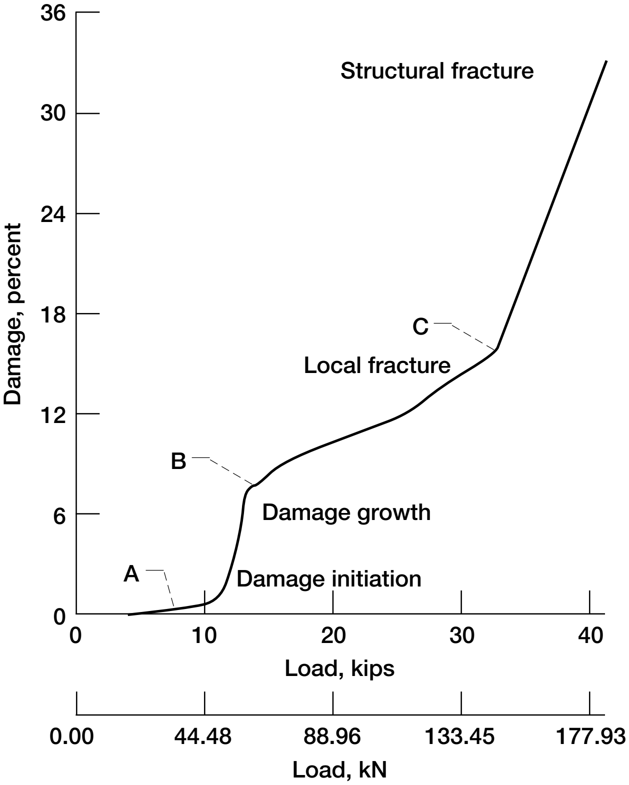


Figure 4.—Damage progression in bolted laminate.

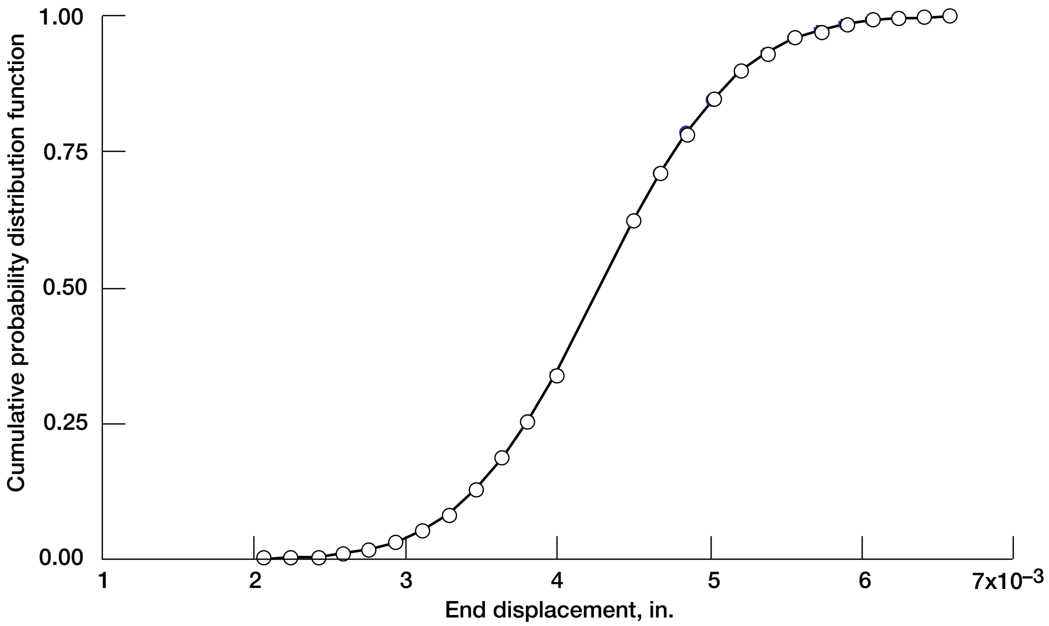


Figure 5.—Cumulative probability distribution function of bolted-laminate end displacement before damage initiation.

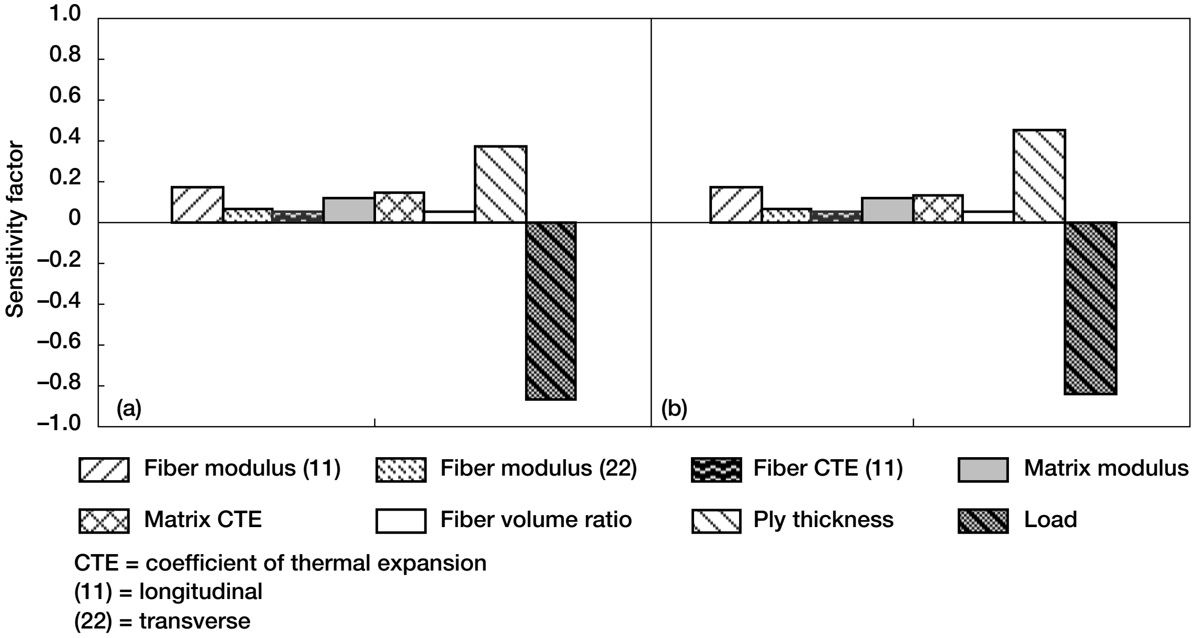


Figure 6.—Sensitivity of bolted-laminate end displacement to uncertainties in design variables before damage initiation. (a) Probability = 0.001. (b) Probability = 0.999.

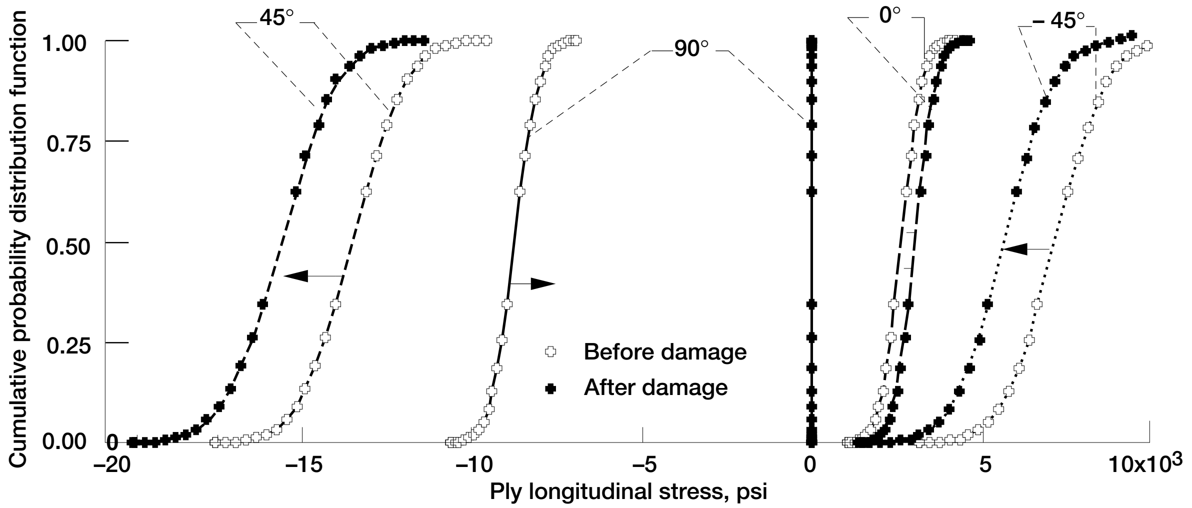


Figure 7.—Ply longitudinal stress before and after damage (damage initiated at 90° ply).

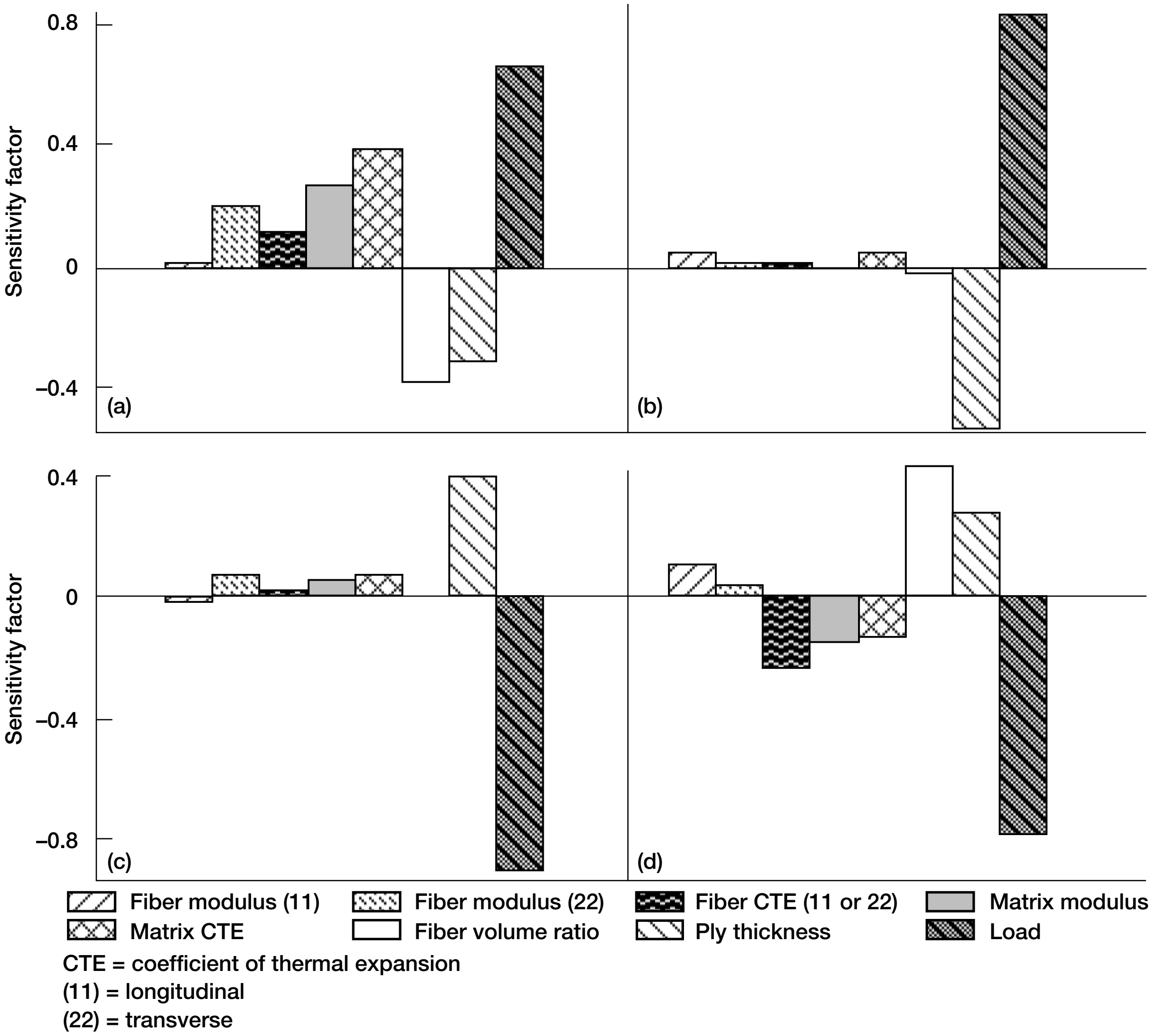


Figure 8.—Sensitivity factors for 0.001 cumulative probability of ply longitudinal stresses before damage initiation. (a) In 90° ply. (b) In 45° ply. (c) In –45° ply. (d) In 0° ply.

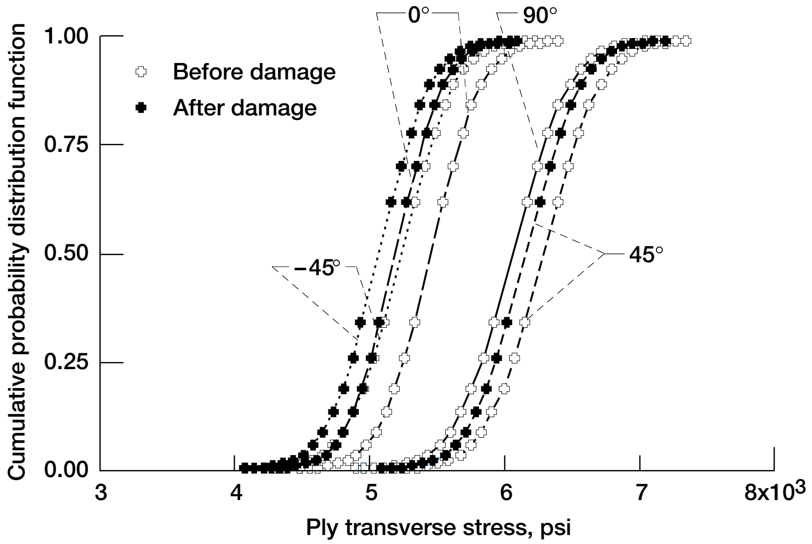


Figure 9.—Ply transverse stress before and after damage (damage initiated at 90° ply).

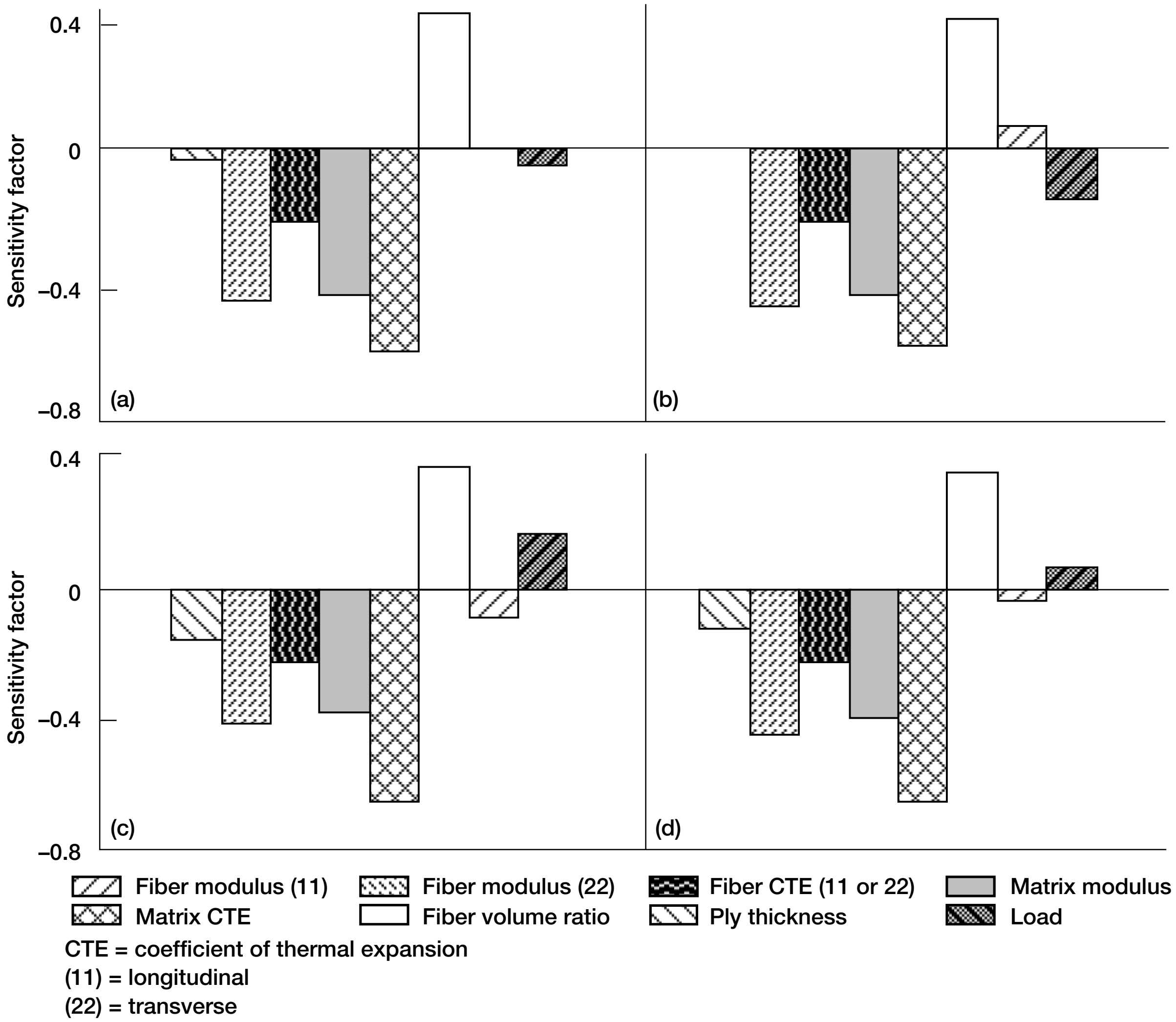


Figure 10—Sensitivity factors for 0.001 cumulative probability of ply transverse stresses before damage initiation. (a) In 90° ply. (b) In 45° ply. (c) In −45° ply. (d) In 0° ply.

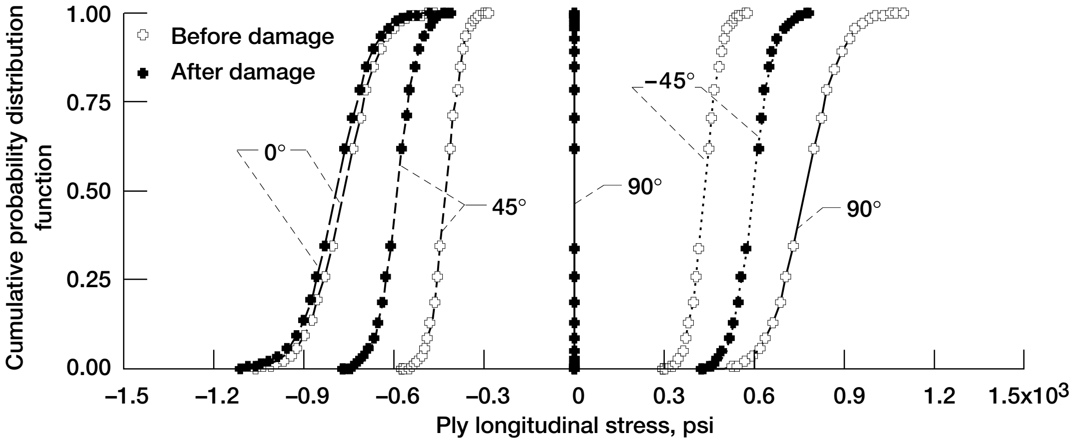
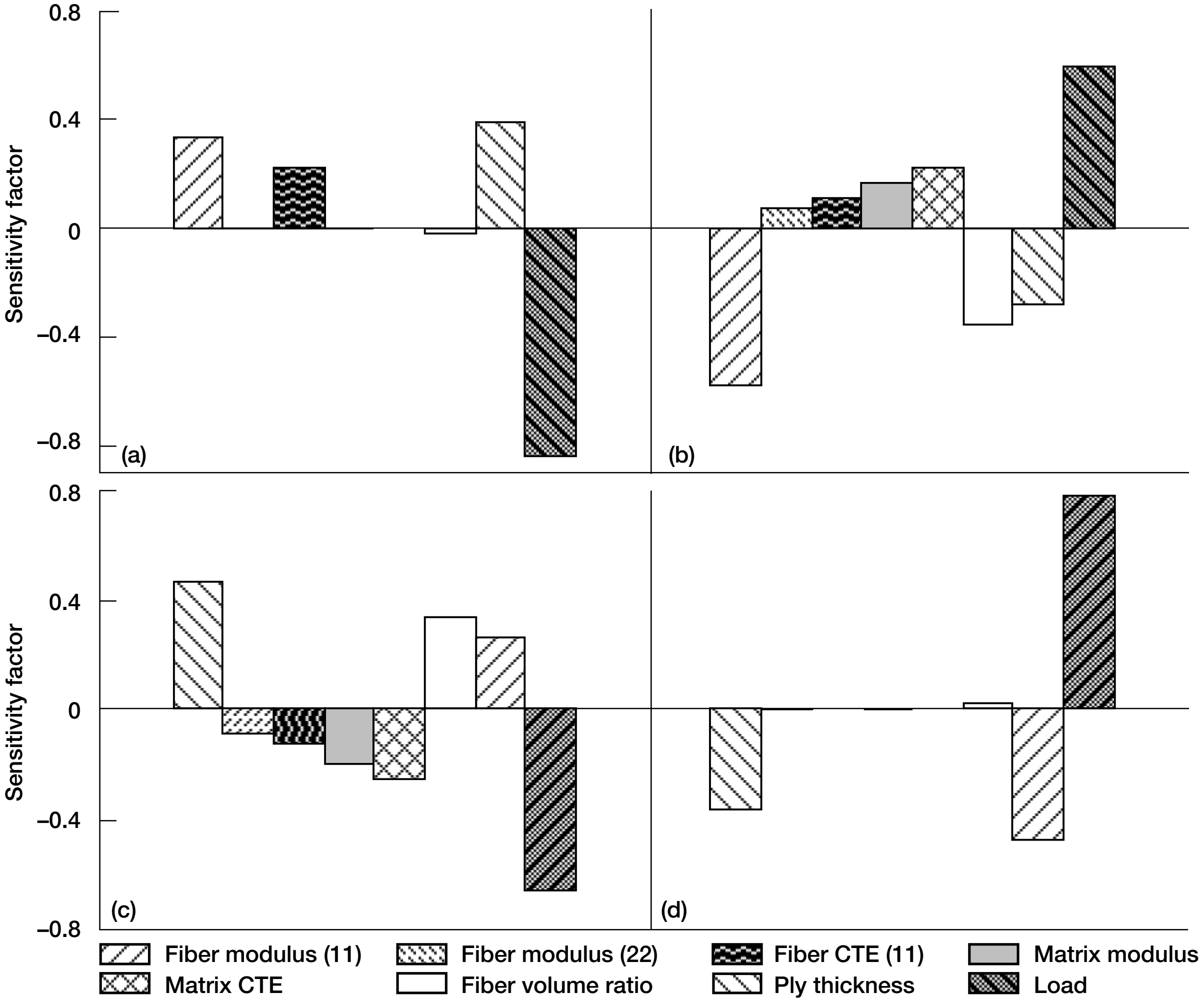


Figure 11.—Ply shear stress before and after damage (damage initiated at 90° ply).



CTE = coefficient of thermal expansion
(11) = longitudinal
(22) = transverse

Figure 12.—Sensitivity factors for 0.001 cumulative probability of ply shear stresses before damage initiation. (a) In 90° ply. (b) In 45° ply. (c) In −45° ply. (d) In 0° ply.

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13. ABSTRACT ***(Maximum 200 words)***

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