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Abstract

The response to high velocity impact of a composite blade is probabilistically evaluated. The evaluation is focused on quantifying probabilistically the effects of uncertainties (scatter) in the variables that describe the impact, the blade make-up, (geometry and material), the blade response (displacements, strains, stresses, frequencies), the blade residual strength after impact, and the blade damage tolerance. The results of probabilistic evaluations results are in terms of probability cumulative distribution functions and probabilistic sensitivities. Results show that the blade has relatively low damage tolerance at 0.999 probability of structural failure and substantial at 0.01 probability.

Introduction

A computational simulation method is presented for non-deterministic impact evaluation of a fan composite blade of an aircraft engine of a subsonic mission. The objective of the present investigation is to present methods/codes for simulating computationally the process of assessing the structural performance of an impacted fan composite blade in the presence of uncertainties in blade fabrication, material properties, loading, and impact condition. An in-house computer code called EST/BEST (Engine Structures Technology Benefits ESTimator) is used to carryout the non-deterministic assessment of an impacted fan blade.

Recent research activities at NASA Glenn Research Center have focused on developing multi-scale, multi-level, and multi-disciplinary analysis and design methods. Multi-scale refers to formal methods which describe complex material behavior; multi-level refers to integration of participating disciplines to describe a structural response at the scale of interest; multi-disciplinary refers to open-ended for various existing and yet to be developed disciplines. For example, these include but are not limited to: multi-factor models for material behavior, multi-scale composite mechanics, general purpose structural analysis, progressive structural fracture for evaluating durability and integrity, noise and acoustic fatigue, emission requirements, hot fluid mechanics, heat-transfer and probabilistic simulations. Many of these, as well as others, are encompassed in the integrated computer code EST/BEST. The discipline modules integrated in EST/BEST include: engine cycle (thermodynamics), engine weights, internal fluid mechanics, cost, mission and coupled structural/thermal, various composite property simulators and probabilistic methods to evaluate uncertainty effects (scatter ranges) in all the design parameters on the structural response of interest. The focus of this investigation is on evaluating the effects of the uncertainties on specified response(s). It is assumed that suitable deterministic analyses are available to predict the specified response(s). It is further assumed that the reader has working knowledge in computational structural mechanics, composite mechanics and some knowledge in probabilistic mechanics. The major reason being the complexity of the subject would require a treatise to make this report self contained. The references cited subsequently provide background material on each discipline employed in this investigation. It is also important to keep in mind that the report demonstrates the capability but not any specific blade design.

Approach

The EST/BEST computer program, shown in figure 1, is used to carryout the investigative study presented in this paper. As can be observed in that figure component as well as system evaluations are performed within a single framework of soft-coupled modules. The modules included are integrated computer codes with multiple functional capabilities. The ones that were used for the results to be presented later are (1) NNEPWATE (refs. 1 and 2) for engine cycle analysis for defining operating requirements; (2) Flow and blade design codes for predicting a representative shape (ref. 3); (3) Engine Component Structural and Fluid Modeling for finite element generation (ref. 4); (4) Material Library - for composite mechanics simulation (refs. 5 to 7); (5) BLASIM for impact assessment (ref. 8); (6) NESSUS for probabilistic evaluation (ref. 9), and (7) CODSTRAN for progressive structural fracture (ref. 10).

Blade Model Description

The module for blade design in the EST/BEST software system is used to predict the required blade shape. The blade design requirements, as estimated by the engine cycle analysis, are rotor speed of 2200 rpm and overall pressure ratio of 1.3. The fan rotor is made up of 32 blades. The blade is 43.8 inches long while the axial chords at the tip and the hub are 13.5 and 7.0 in., respectively. The blade maximum thickness to chord ratio is 0.03 at the tip and 0.085 at the hub. The blade setting angle varied from tip to hub from 65 to 18°.

Once the blade is configured by fluid flow analyses for aerodynamic efficiency, the COSMO module in EST/BEST is used to generate the finite element model needed for structural and impact analyses. The blade is made from graphite epoxy composite with symmetric lay-up and consisting of shell and core plies oriented as follows: $[45,-45,0,0,45,0]_s$ – the outer ±45 plies are the shell plies; the others are the core plies. The composite fiber volume and void volume ratios are 0.65 and 0.05, respectively. Core plies are used to fill the blade where the blade thickness is greater than the thickness of four-plies. The blade is modeled with 55 nodes and 40 triangular plate finite elements. The element has six degrees of freedom at each node (three translations and three rotations).

Impact Modeling and Analysis

The impact is evaluated by using the BLASIM module in EST/BEST (ref. 11). The projectile that impacts the blade has a density similar to that of ice and is modeled as a spherical object. The projectile impacts the leading edge of the blade with the forward velocity of a general aviation plane (about 265 mph). The impact angle is a function of both the projectile velocity and the rotor speed. Depending on the diameter of the projectile and the blade spacing, only a portion of the projectile may impact the blade. Also, only the normal component of the impact force to the local chord is considered to cause the most damage locally and at the root.

For computing the leading edge strain due to impact, the projectile impact is considered as a transient distributed load on a specified region of the blade. Since the damage caused by the impact is highly localized, only a portion of the blade around the impact region (i.e., a specified local patch (mesh refinement) along the span and half of the blade along the chord) is modeled. The region around the impact location is assumed to be highly stressed and undergoes large deflection. The stiffness of these elements is modified to reflect material damage as predicted by the dominant stress in a combined stress failure criterion. Modal integration techniques are employed to obtain the undamped transient response of the local impact region utilizing the first five modes of the damaged blade. These are also used subsequently to calculate the corresponding global blade response.

The root damage analysis is evaluated by assuming that the projectile impact is an impulse load. A combined ply stress failure criterion based on modified distortion energy is used to evaluate root and/or local damage. If the failure function reaches the value of 1.0, then it is assumed that failure is imminent while a value of less than 1.0 indicates no local damage.

Deterministic Impact Analysis

BLASIM is used to perform the blade impact response. The impact projectile is assumed to impact the blade region along the leading edge of the blade between 50 and 90 percent of the blade span. A one-inch projectile radius impacts the leading edge of the blade with a velocity of 388 ft./sec. The projectile velocity is typical for takeoff conditions of a subsonic aircraft. The deterministic impact analysis shows that the leading edge strain at the impact location is about 3 percent while the combined failure stress criterion function is 0.38 compared to 1.0 for failure. The first three natural frequencies of the blade are also evaluated before and after impact. The blade geometry is updated to account for local large deformations. Results from the deterministic evaluation are presented for local large deformation, for local strain and for blade local damage as described subsequently.

The local large deformation results for leading in-plane displacement are shown in figure 2 as a contour plot due to impact at the 70 percent span. As it can be observed, the large deformation is confined to a span location between 45 and 65 percent of the span reaching 1.5 in. magnitude in 0.39 msec, which is the end of the contact time. Note that this large local deformation occurred because of the relatively high chord-wise stiffness of the blade.

The corresponding leading edge strains are shown in Figure 3 for three different impact span locations: about 60, 70 and 80 percent of the blade length. It is observed that: (1) the strains vary nonlinearly with time; (2) they level off at near the end of the contact time about 0.39 msec; and (3) they vary approximately as the square of the impact location as they reach their maximum values.

CODSTRAN (ref. 10) was used to evaluate the locally damaged blade. The results are shown in figure 4, as a computer generated plot at the end of the impact. This is a deterministic evaluation that corresponds to 50 percent probability level. It is observed that the leading edge is damaged from the 60 percent span to the blade tip with a loss of the outer 40 percent of the leading edge. The CODSTRAN results also showed that: (1) the fracture strength of the original blade is about 52 percent higher than the operating speed, and (2) that of the impacted blade is only 4 percent higher. Coincidentally, the 52 percent corresponds to the typical 1.5 safety factor used in aircraft design.

The significance of including the deterministic results is to emphasize that deterministic evaluation precedes probabilistic evaluation. Probabilistic evaluations described here are perturbations about deterministic states that describe the physics of the situation—blade impact in the present case. Recall that structural probabilistic simulations are used to evaluate/assess the effects of uncertainties (scatter ranges) in the primitive variables that describe/define the physical system—the composite blade in this case.

Probabilistic (Nondeterministic) Impact Analysis

Nondeterministic impact analysis has been carried out on the fan composite blade. The objective here is to assess structural performance of the blade under impact conditions in the presence of uncertainties in primitive variables such as blade fabrication, material properties, loading, and impact condition. For this evaluation, the uncertainties are considered as a scatter range (herein defined as percent variation from the mean) expressed by some assumed percentage from the mean. The primitive variables that are perturbed along with their mean values, assumed coefficients of variation (COV) and assumed distribution inputs to FPI are in table I. The assumed COV and distributions are considered representative and are used here to illustrate the simulation procedure. The probabilistic evaluations were performed by using a first order probability method, which is known to be accurate near the mean and approximate away from the mean.

The probabilistic analysis is carried out using the FPI module in NESSUS. The evaluation includes the leading edge strain and root damage due to impact, and the first three natural frequencies before and after impact. Also, the sensitivities of the response parameters (leading edge strain, root damage, and pre-and-post impact frequencies) due to the scatter in primitive variables are assessed.

Leading edge strain probabilistic results are shown in figure 5 in terms of cumulative distribution function. The primitive variables used are included in the figure. It is observed that the probabilistic leading edge strain at the impact location varies from about –2 percent at low probabilities of structural fracture, to about +8 percent at high probabilities. This means that uncertainties (scatter ranges) in the primitive variables can cause local impact strains, –2 percent at near zero probabilities and 8 percent at near unity probabilities. It is noted that the –2 percent strain is unrealistic because the methodology used is approximate at best near the tails. More accurate methods, such as the Advance Mean Value, have to be used to obtain better results near the tails. The corresponding probabilistic sensitivity factors are shown in Figure 6 in terms of relative magnitudes—the sum of their squares equals unity. Factors with large magnitudes affect the results in the cumulative distribution (shown in fig. 5) the most. It is observed that impact location has the greatest effect, projectile radius has moderate effect, other impact variables (projectile velocity, rotor speed and density) have lesser effect. The conclusion from these results is that the magnitude of the leading edge strain under the impact is dominated by the impact primitive variables and can be resisted most effectively by fiber modulus and fiber volume ratio. The blade thickness is represented by the ply thickness and has negligible effect, as mentioned previously.

Blade root-fracture probabilistic results in terms of cumulative distribution function for the highest stressed ply, determined by using the combined-stress failure-criterion in CODSTRAN, are shown in figure 7. The fracture cut-off line is also shown. The dominant stress for that fracture is ply transverse tension in the –45° ply. It is observed that the scatter can be from –1 to +1 (+1 denotes laminate fracture). The probability for –1 is near zero whereas that for +1 is less than 0.9. It can be inferred that the impact conditions evaluated will induce laminate transply cracking in the –45° ply near the root at about 10 percent of the time.

The corresponding probabilistic sensitivity factors are shown in figure 8. It is observed that projectile primitive variables have major effects—projectile radius dominates, density, rotor speed and location have moderate effects. Projectile velocity has lesser effect. Material primitive variables—matrix strength has moderate effect; other material variables have negligible effects. Fabrication variables—void volume ratio and outer ply orientation have lesser effects. The other remaining variables have negligible effects. The important conclusion is that the sensitivities are very dependent on the function evaluated. Note—the impact location dominates local strain; projectile radius dominates laminate root fracture; fiber modulus dominates local strain; matrix strength dominates for laminate root fracture initiated by transply cracking.

Cumulative distribution functions of natural frequencies before and after impact damage are shown as follows: (1) figure 9 depicts the impact effects on the first frequency (dotted line, before impact; solid line after impact). The first frequency is not affected by the impact damage since it is predominately a cantilever bending mode. (2) The corresponding sensitivities are shown in figure 10. Note that (a) the rotor speed dominates, (b) fiber volume ratio and fiber modulus have moderate effects, (c) the impact primitive and other material processing variables have negligible effects. It may be inferred that in-service monitoring of first frequency will not detect local leading edge impact damage, since there is negligible change in the frequency before and after impact.

Comparable results for the second frequency are shown in figure 11 (frequency) and figure 12 (sensitivities). Important observations in figure 11 are: (1) Leading edge damage causes about 10 cycles per second frequency loss, and (2) The two cumulative distribution functions are parallel—indicating that the primitive variables affecting the second frequency are the same before and after impact. Important observations in figure 12 are: (1) fiber volume ratio and fiber modulus dominate; (2) impact location and rotor speed have moderate effects; (3) the remaining primitive variables have negligible effects; and (4) the effects for the dominant variables are the same before and after impact which is consistent with the observation of parallel curves in figure 11. The impact location has effects only after impact. It may be concluded that second frequency sensitivity monitoring will indicate local leading edge impact damage; however, it will not differentiate dominant primitive variables effects.

Those for the third frequency are shown in figure 13 for frequency and scatter range and in figure 14 for sensitivities. The scatter range for these frequencies is about 25 percent which is the same as that for the second frequency. These results are very similar to those for the second frequency except that the decrease is 20 cycles per second after impact and that the impact location has greater effect than in the second. Conclusion—third frequency in service monitoring is more sensitive to local leading edge impact damage. However, this would require more extensive instrumentation to accurately monitor it.

Progressive Fracture Analysis

The CODSTRAN module in EST/BEST has been used to evaluate the progressive structural damage and fracture of a fan composite blade subjected to impact conditions. The local fracture, local strain and respective blade deformations resulting from the NESSUS probabilistic impact analysis at 0.01, 0.5 and 0.999 probabilities were used as inputs to CODSTRAN. CODSTRAN then was executed once for each probability level by continually increasing the equivalent impact load until the end of the impact. Results obtained from this simulation include damage volume, damage displacements, damage strains and blade fracture behavior. These results are described below.

The cumulative damage volume is plotted in figure 15 for three probabilities of 0.01, 0.5 and 0.999 versus the 0.5 probability impact load. As can be observed, there are substantial differences in the curves for the different probabilities including major nonlinear behavior for the 0.5 probability and relatively little damage for the 0.999 probability curve. Corresponding displacements at the impact location are plotted in figure 16. The resultant displacements are almost linear to fracture. The 0.999 probability curve fractures at a relatively low impact load but reaches the same displacement magnitude as the 0.50 probability. The 0.01 probability curve fails at about the same impact load as the 0.50 probability but at about one-half the displacement.

The corresponding local strains under the impact in the top ply along the fibers for the three probabilities are plotted in figure 17(a). Note final damages are indicated with X. Note also that the strains are monotonically increasing functions with impact load with the 0.999 strain curve being almost linear to fracture reaching a strain of about 1.4 percent. The 0.50 probability curve is almost linear up to 15 kips and then becomes nonlinear to fracture. The 0.01 probability curve is linear to fracture.

Corresponding top ply strains in the fiber direction are plotted in figure 17(b). Note the substantial nonlinearity of the 0.5 probability curve. Blade fracture computer diagrams are shown in figure 18 for the non-impacted and the impacted blade. These results were obtained by: (1) using the values of the primitive variables of the most probable points (0.01, 0.5 and 0.999, table II); (2) the blade geometry was updated to account for the conditions in (1) above; and (3) an equivalent impact load was incrementally increased in CODSTRAN until the blade sustained the greatest amount of damage. It is noted that the magnitude of the impact load at the greatest damage was close to that predicted by BLASIM (ref. 8) for the 0.5 probability case. The observations from the results in figure 18 is that the impact load caused severe damage to the blade for all three probability levels but did not break the blade.

Evaluation of Primitive Variables Magnitudes for Achieving Specified Probabilities

A very important aspect of probabilistic simulations is the use of the sensitivity factors to identify/quantify the values of the respective primitive variables for specified probabilities of the response. This means that for any response probability there is a corresponding most probable set of values for the respective primitive variables. If those magnitudes exceed the scatter in one or more primitive variables, assumed or expected from experience, then a decision has to be made: (1) accept the exceedence if it is physically admissible, or (2) select a different probability for which all the primitive variable values are within the expected scatter. For the blade impact investigated herein, the primitive variable values were evaluated at all three, 0.999, 0.50 and 0.01 probability levels for the local strain due to impact. The results are summarized in table I. It is important to observe the impact location values for 0.01 and 0.999 probabilities are 46.17 and 67.03 in. compared to the expected scatter of 50.7 and 59.5 in., respectively. Obviously, these impact locations are –16 and 22 percent from the mean, which are more than twice the expected scatter range. Therefore, the 0.01 and 0.999 probabilities of impact occurrence can only be admissible if we expand the scatter range for the impact location to –16 and +22 percent. This by far is a very important observation and highlights the inclusive effectiveness of probabilistic evaluations not only for blade impact but also for structural reliability in general. Another important aspect is checks on the assumed variations and distributions in the primitive variables. The checks can be made by assuming different values and re-run the evaluations. Then compare corresponding cumulative distributions and sensitivity factors. If these are approximately the same, the results are insensitive to the assumed COV and distribution types. The method described may, therefore, be considered as “self corrective.”

Concluding Remarks

The salient concluding remarks from an investigation to probabilistically evaluate blade impact damage are summarized in groups below high, medium and low, respectively: (1) Impact parameters affecting impact-location-strain include: high-location and projectile radius; medium, projectile velocity and projectile density; low-blade rotational speed. (2) Composite resistance to local-impact-strain includes: high-fiber volume ratio and fiber modulus; medium-outer ply angle; low-fiber strength. (3) Impact parameters affecting local-impact-stress include: high-projectile radius, projectile density, projectile rotor speed and impact location; medium-projectile velocity. (4) Composite blade resistance parameters to local-impact-stress include: high-matrix strength; medium-void volume ratio and outer ply angle; low-fiber volume ratio, ply thickness, fiber modulus, fiber strength. (5) Parameters that affect global blade response include: high-local blade damage, limited to leading edge, no blade global fracture during impact. (6) Loss in frequency due to impact is negligible in the first frequency, 5 percent in second and 10 percent in third. (7) Parameters affecting frequency sensitivities include: (a) first—rotor speed, fiber modulus, fiber volume ration; (b) second—fiber modulus, fiber volume, ratio, impact location, rotor speed; (c) third—fiber volume ration, fiber modulus, impact location, rotor speed. (8) Local damages sustained at specified probabilities of structural fracture are: least amount of damage at 0.999 probability; moderate amount of damage at 0.50 probability; maximum amount of damage at 0.01 probability. Alternatively, the 0.01 probability design is the most damage tolerant as would be intuitively expected. However, these damages did not break the blade.

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TABLE I.—PRIMITIVE VARIABLES

Primitive Variables	Mean value	Coefficient of variation (±%)	Distribution
Projectile Radius, in.	1.0	0.15	Normal
Projectile Density, lb/in.^{3}	0.0325	0.20	Normal
Projectile Velocity, mph	230	0.15	Normal
Impact Location, in.	55.1	0.08	Normal
Rotor Speed, rpm	2200	0.10	Normal
Fiber Volume Ratio	0.65	0.10	Normal
Void Volume Ratio	0.05	0.15	LogNormal
Outer Ply Angle	45°	0.10	Normal
Fiber Modulus, psi	$31.0\times10^{+6}$	0.10	Normal
Matrix Modulus, psi	$0.50\times10^{+6}$	0.05	Normal
Fiber Tensile Strength, psi	$0.40\times10^{+6}$	0.10	LogNormal
Matrix Tensile Strength, psi	$0.40\times10^{+6}$	0.05	LogNormal

TABLE II.—MOST PROBABLE DESIGN AT 0.01, 0.50, AND 0.999 PROBABILITIES
[Impact Analysis of a Fan Composite Blade—Engine of a Subsonic Mission.]

Primitive Variable	Prob. = 0.01	Prob. = 0.50	Coefficient of variation (±%)	Prob. = 0.999
Projectile Radius, in.	0.89	1.0	15	1.151
Projectile Density, lb/in.^{3}	0.0304	0.0325	20	0.0352
Projectile Velocity, mph	214	230	15	251
Impact Location, in.	46.17	55.1	8	67.03
Rotor Speed, rpm	2127	2200	10	2297
Fiber Volume Ratio	0.676	0.65	10	0.615
Void Volume Ratio	0.0493	0.05	15	0.0495
Ply Thickness, in.	0.00501	0.005	5	0.00498
Outer Ply Angle	45.46°	45	10	44.39
Fiber Modulus, psi	$32.05\times10^{+8}$	$31.0\times10^{+6}$	10	$29.60\times10^{+8}$
Matrix Modulus, psi	$0.500\times10^{+6}$	$0.50\times10^{+6}$	5	$0.499\times10^{+6}$

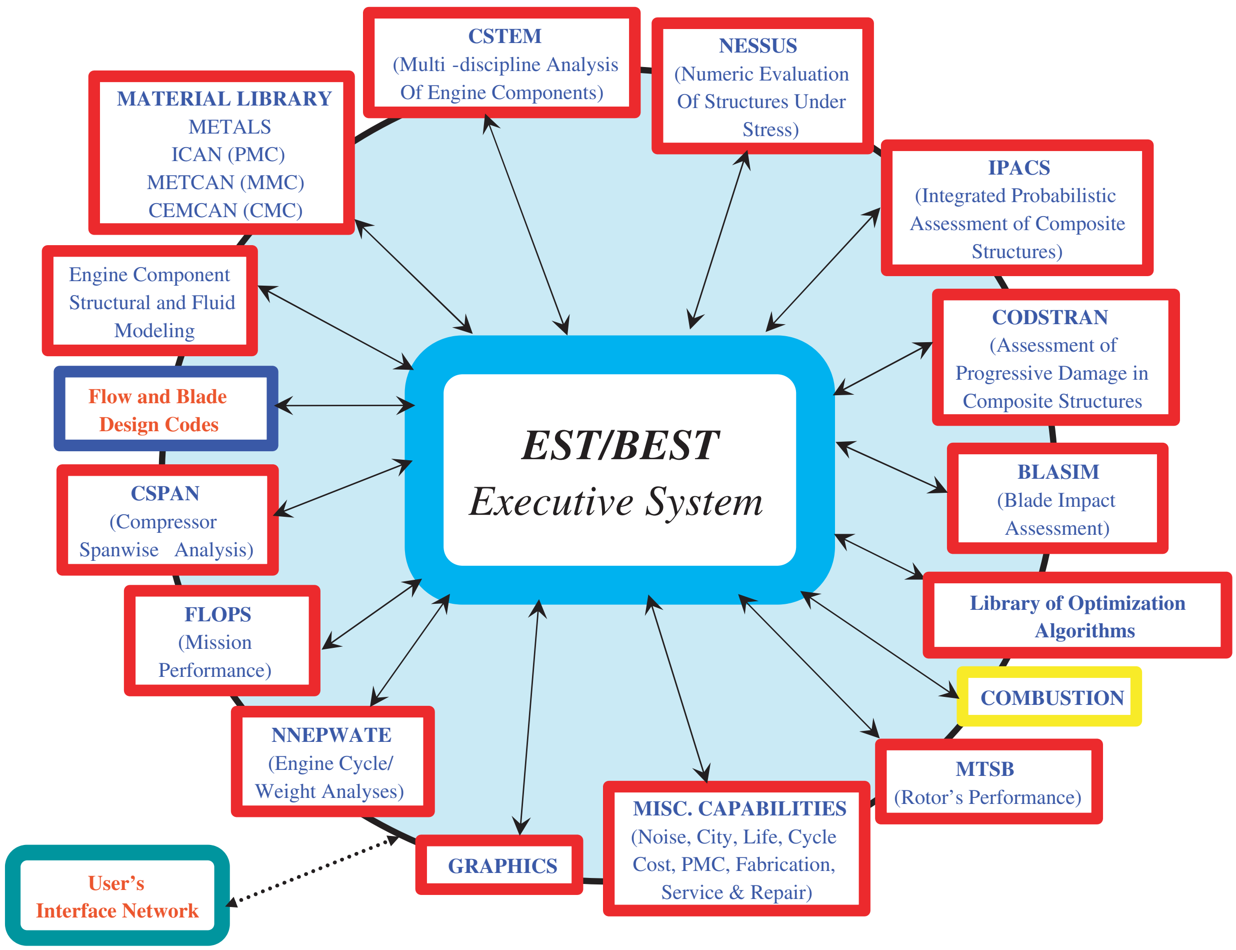

Figure 1.—EST/BEST Engine Structures Technology Benefit Estimator.

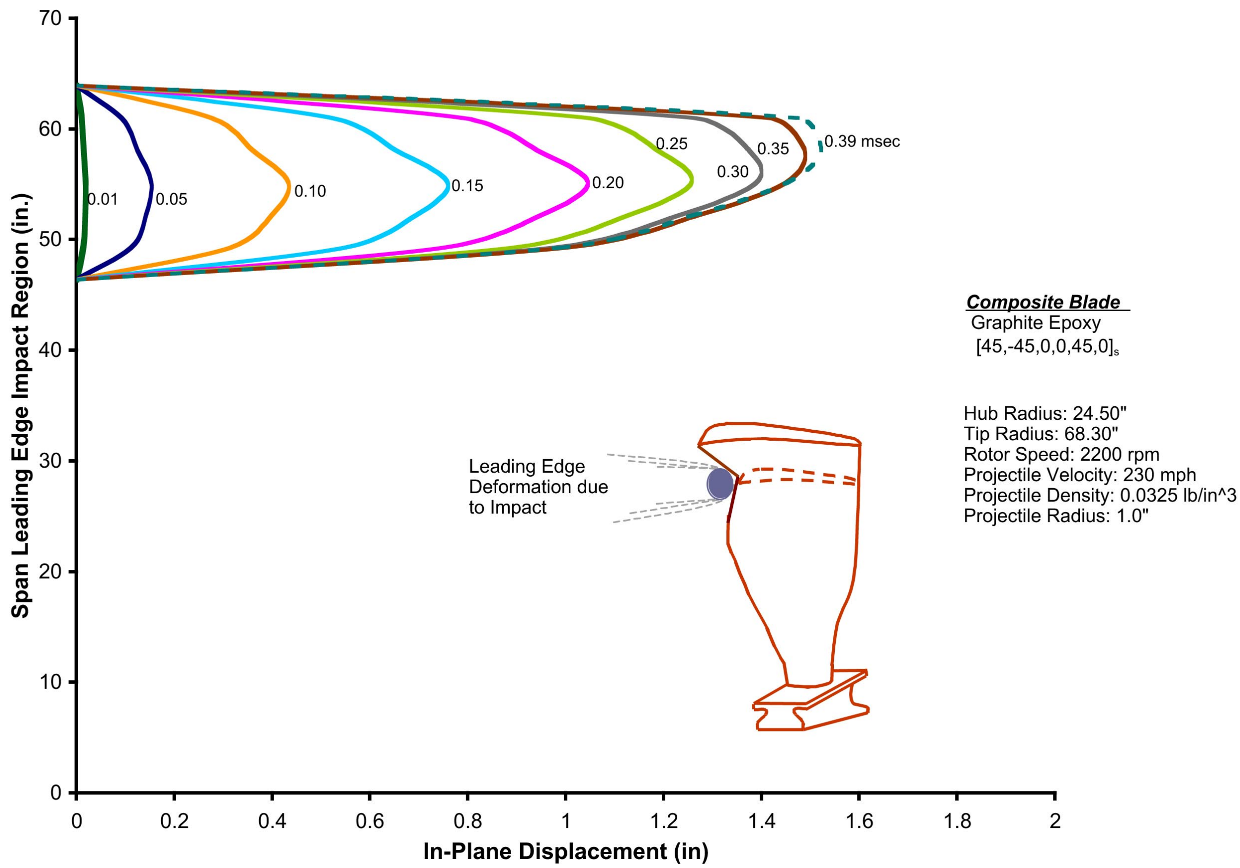

Figure 2.—Local blade leading edge displacement due to impact (fan stage 1 composite blade - engine of a subsonic mission).

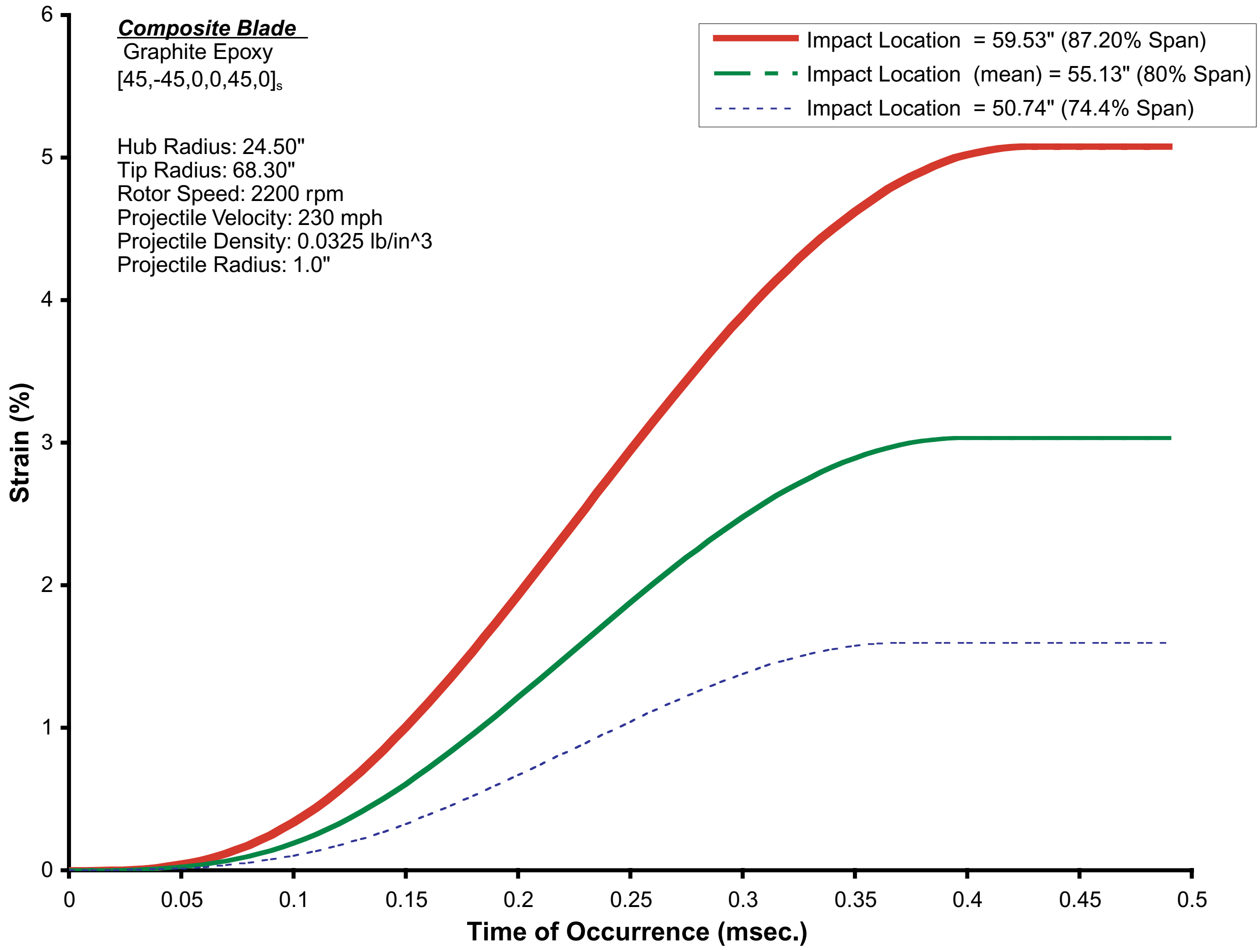

Figure 3.—Blade leading edge maximum strain due to impact as a function of projectile impact location (fan stage 1 composite blade - engine of a subsonic mission).

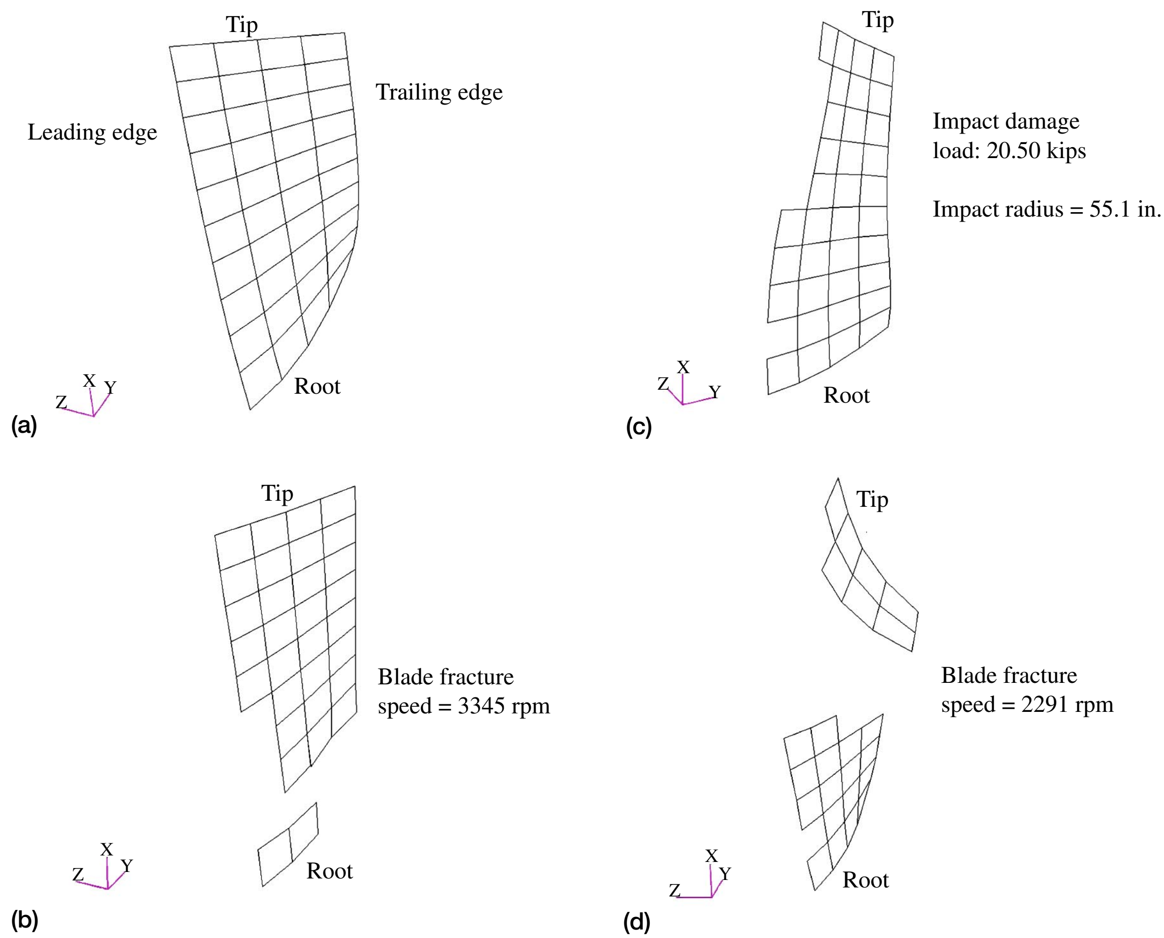

Figure 4.—Blade progressive fracture evaluation as predicted by CODSTRAN (with and without impact). (a) Blade operating at 2200 rpm (without impact). (b) Blade failure due to increased rotor speed (without impact). (c) Maximum blade damage due to impact. (d) Blade failure of impacted blade due to increased rotor speed.

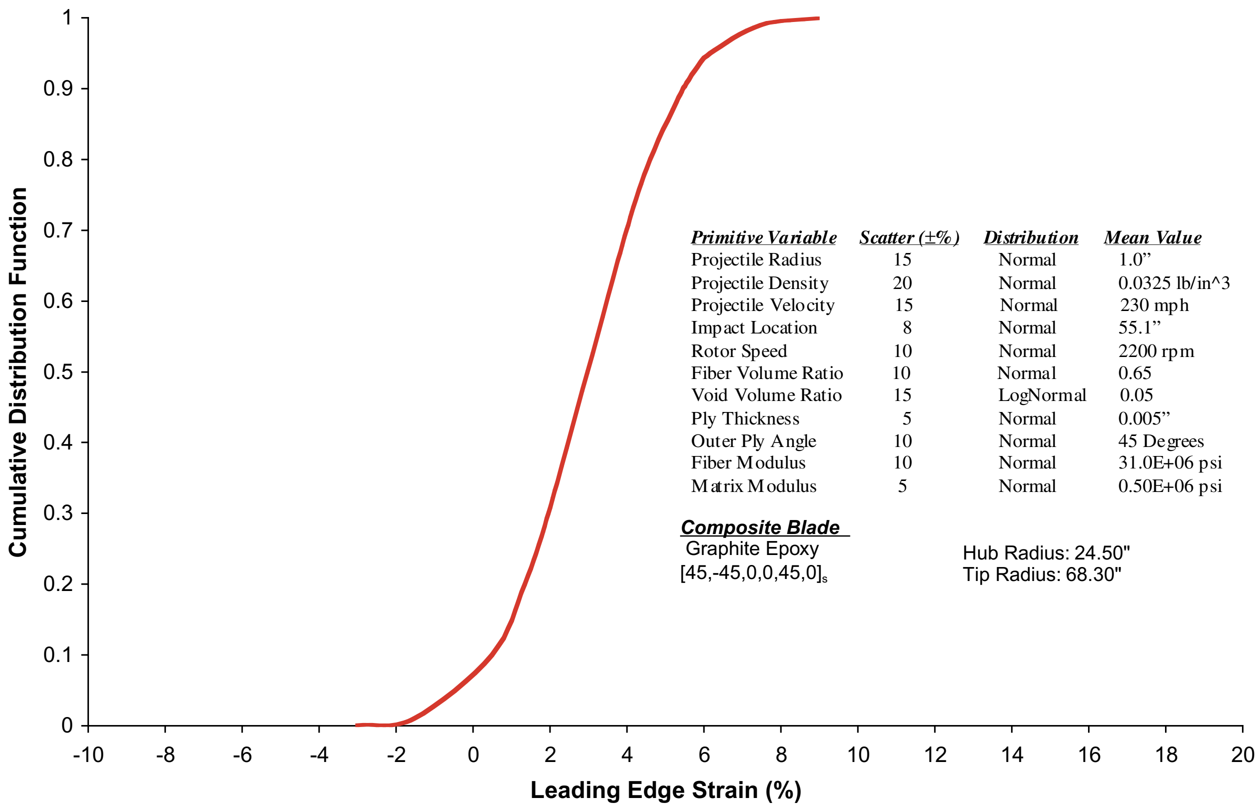

Figure 5.—Probabilistic evaluation of leading edge maximum strain due to impact (fan stage 1 composite blade - engine of a subsonic mission).

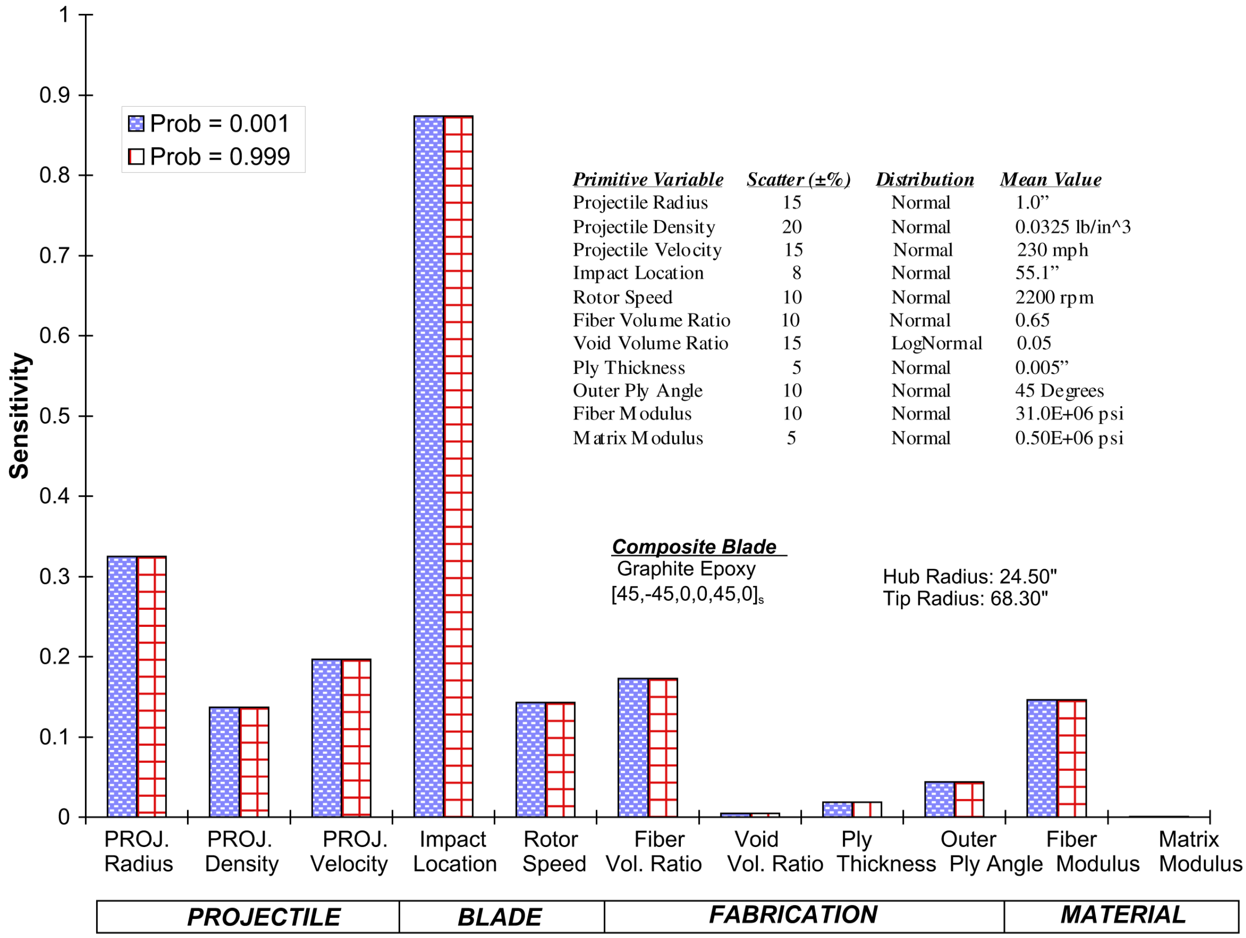

Figure 6.—Sensitivity of leading edge strain due to impact (fan stage 1 composite blade - engine of a subsonic mission).

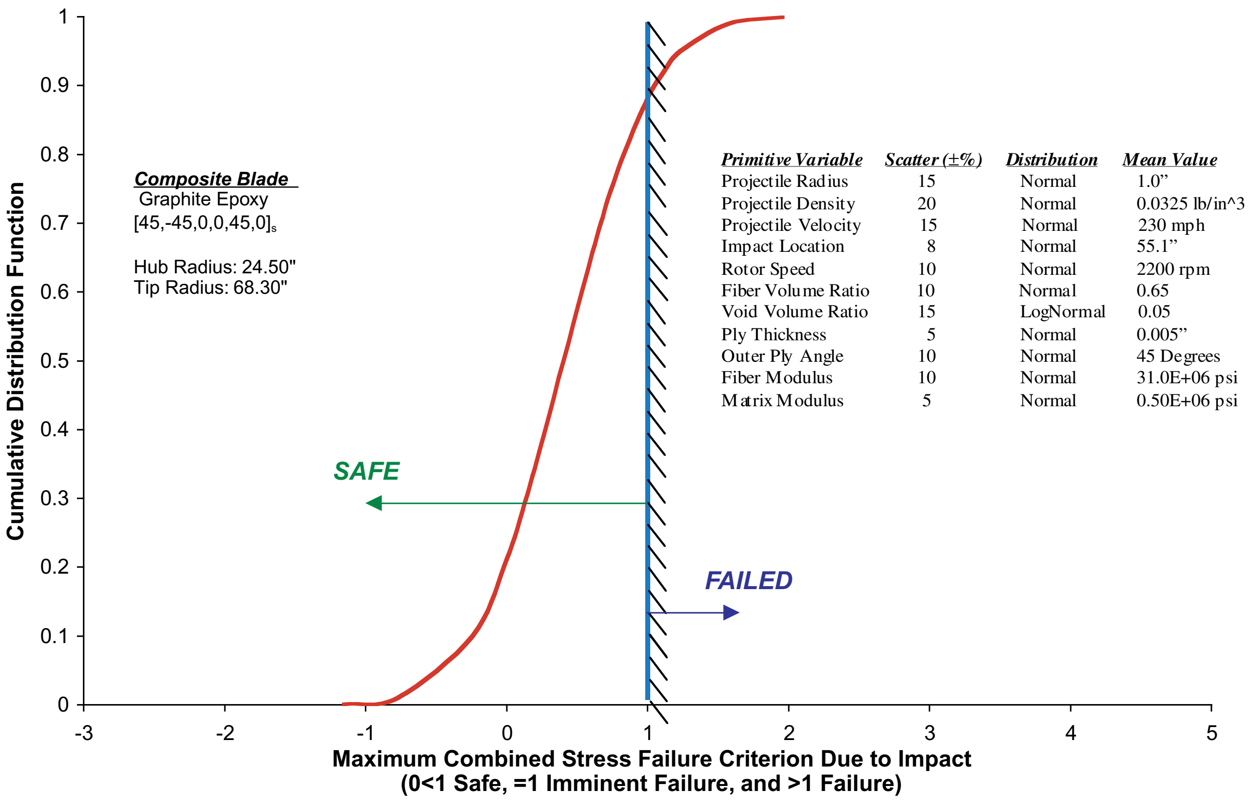

Figure 7.—Probabilistic evaluation of combined stress failure criterion ply 10 (–45°) at the blade root (fan stage 1 composite blade - engine of a subsonic mission).

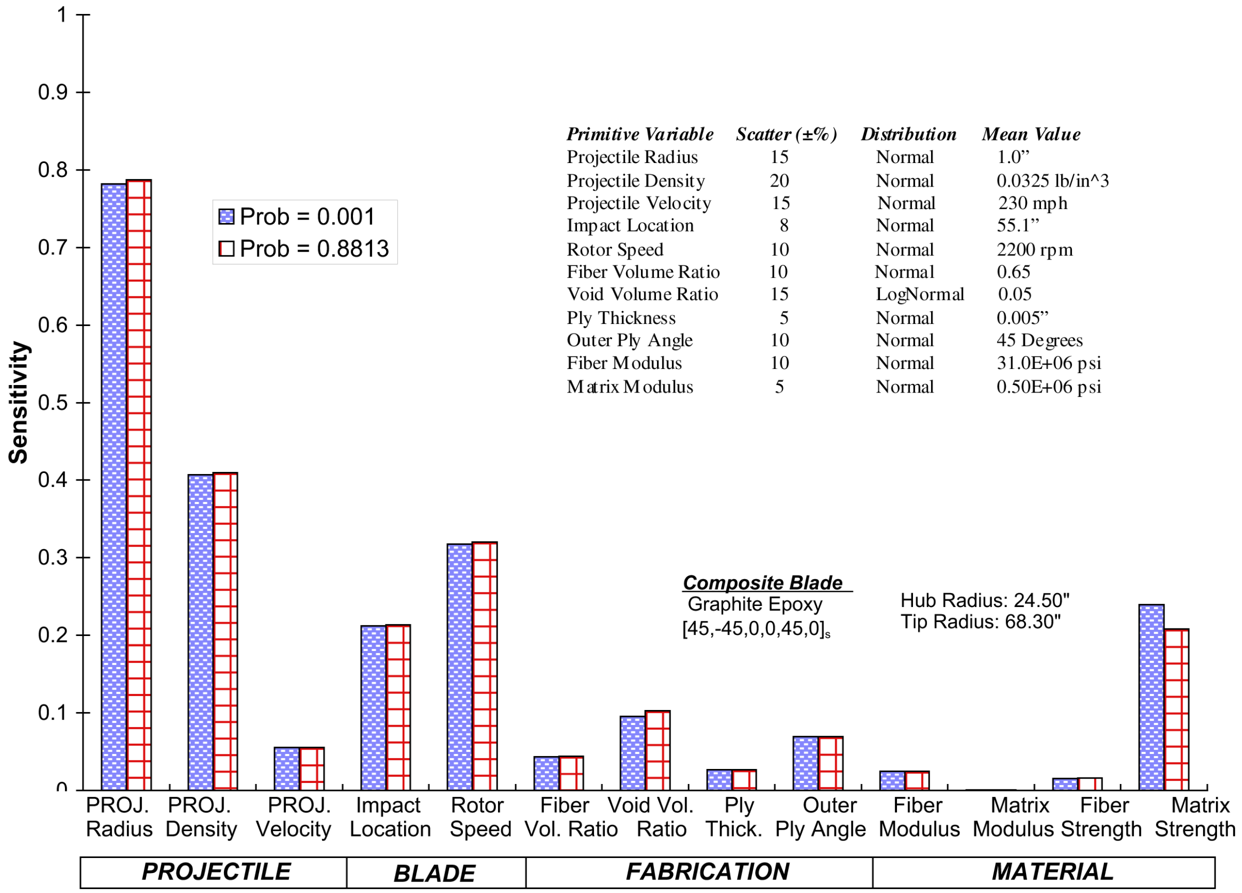

Figure 8.—Sensitivity of combined failure stress criterion ply 10 (–45°) at the blade root due to impact (fan stage 1 composite blade - engine of a subsonic mission).

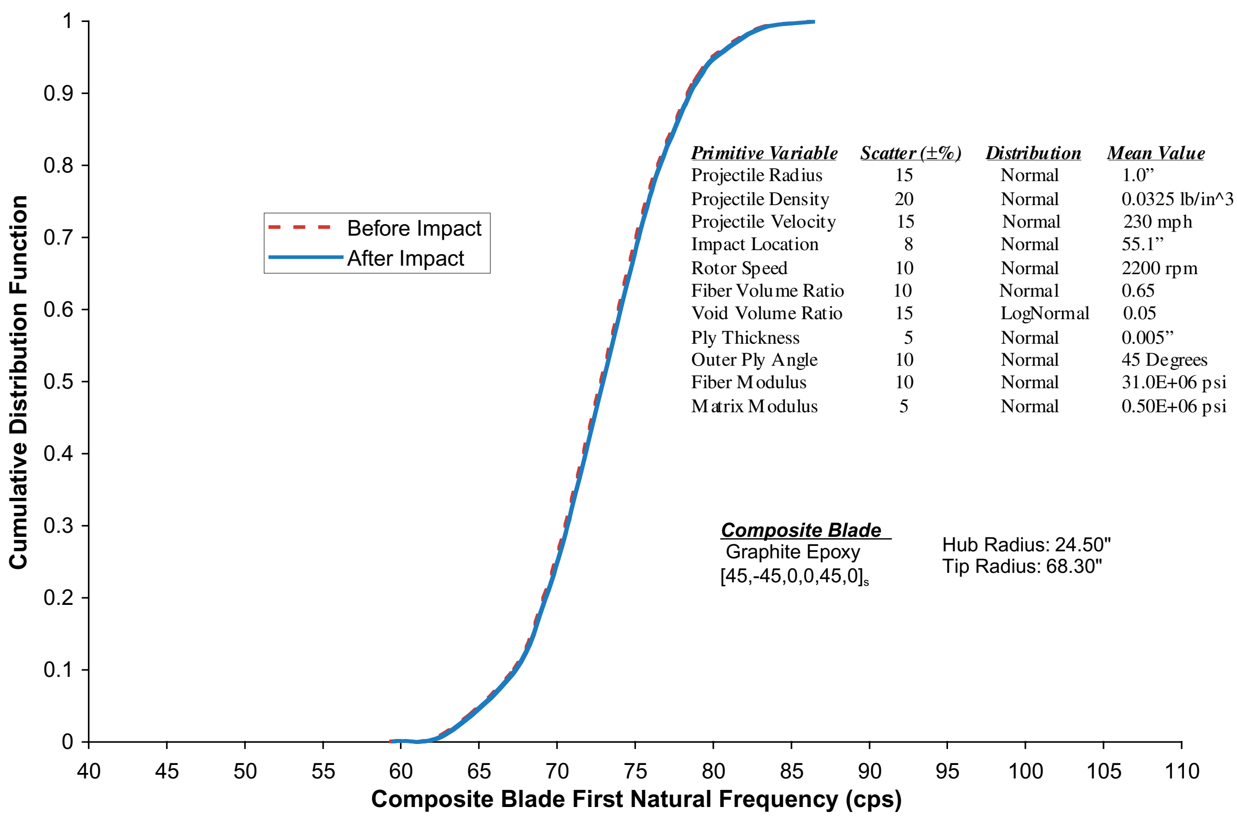

Figure 9.—Probabilistic evaluation of blade first natural frequency before and after impact (fan stage 1 composite blade - engine of a subsonic mission).

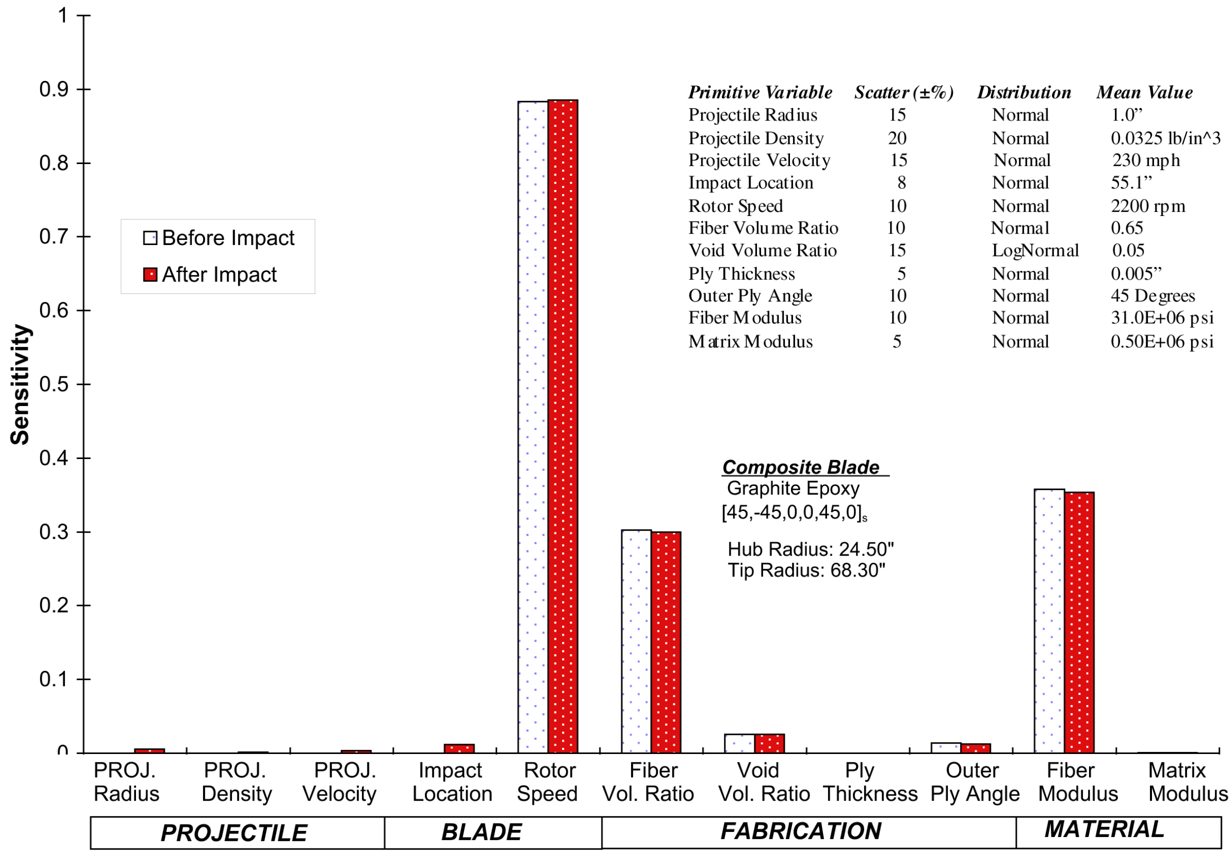

Figure 10.—Sensitivity of blade first natural frequency at 0.001 probability (fan stage 1 composite blade - engine of a subsonic mission).

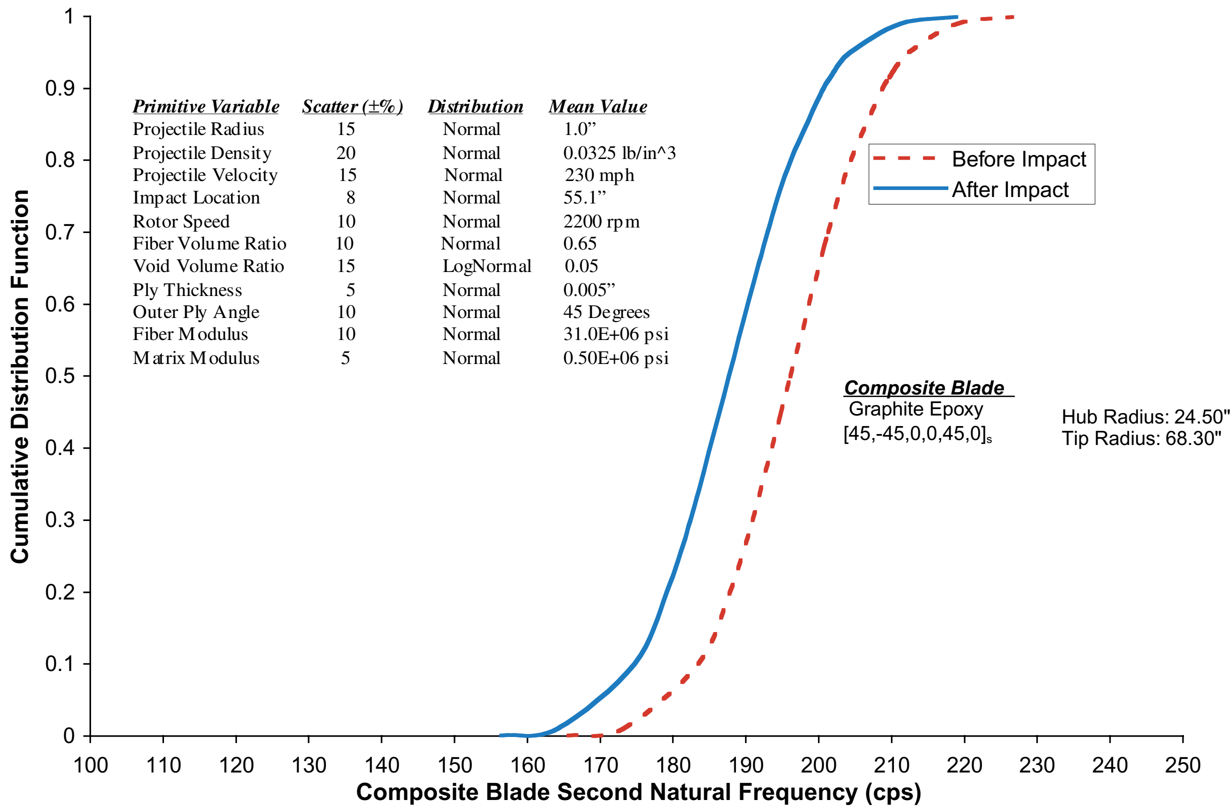

Figure 11.—Probabilistic evaluation of blade second natural frequency before and after impact (fan stage 1 composite blade - engine of a subsonic mission).

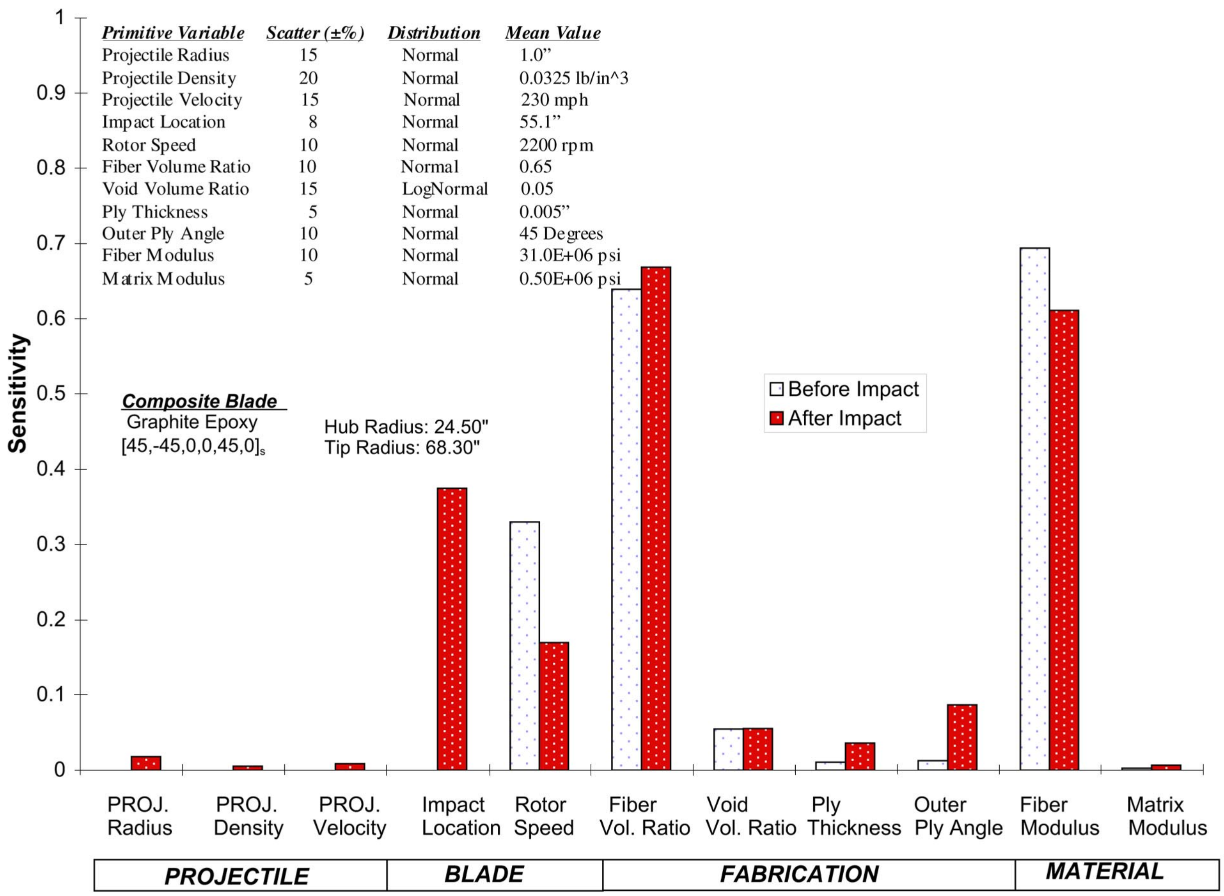

Figure 12.—Sensitivity of blade second natural frequency at 0.001 probability (fan stage 1 composite blade - engine of a subsonic mission).

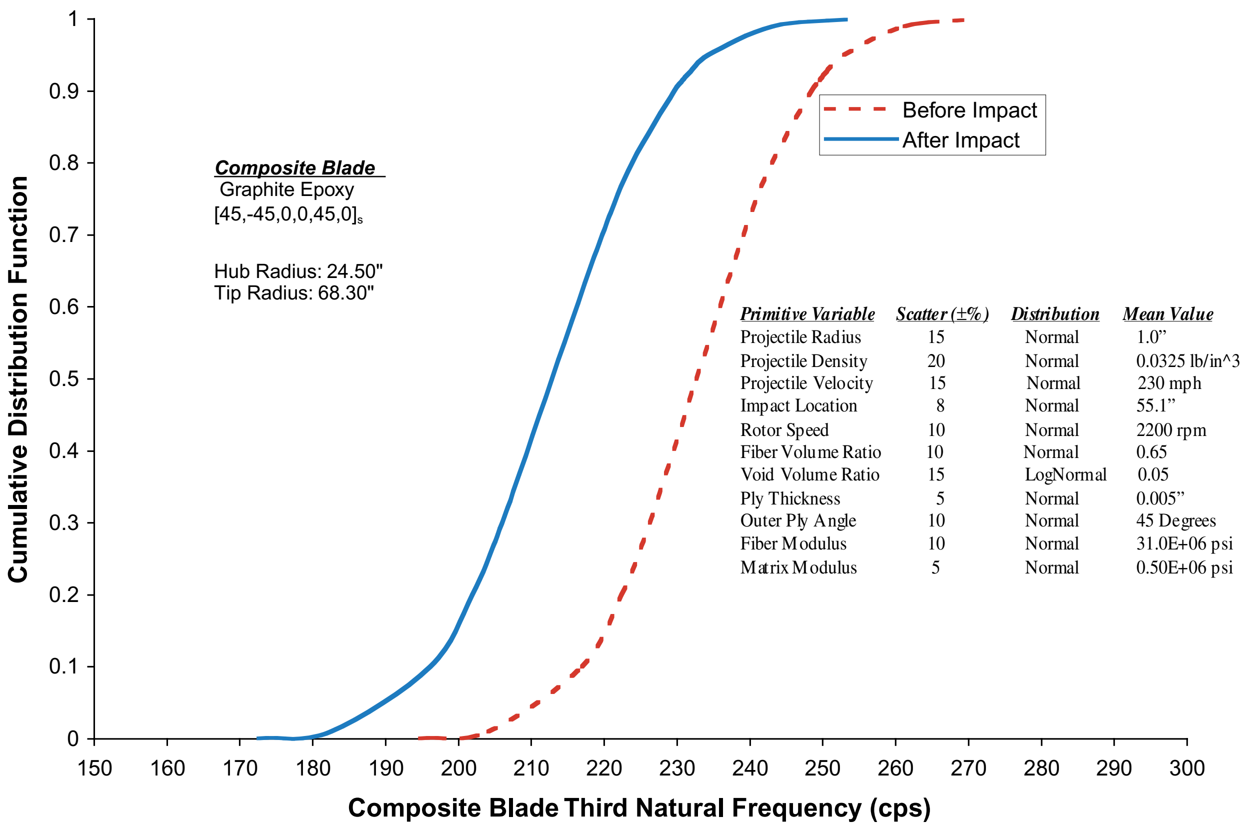

Figure 13.—Probabilistic evaluation of blade third natural frequency before and after impact (fan stage 1 composite blade - engine of a subsonic mission).

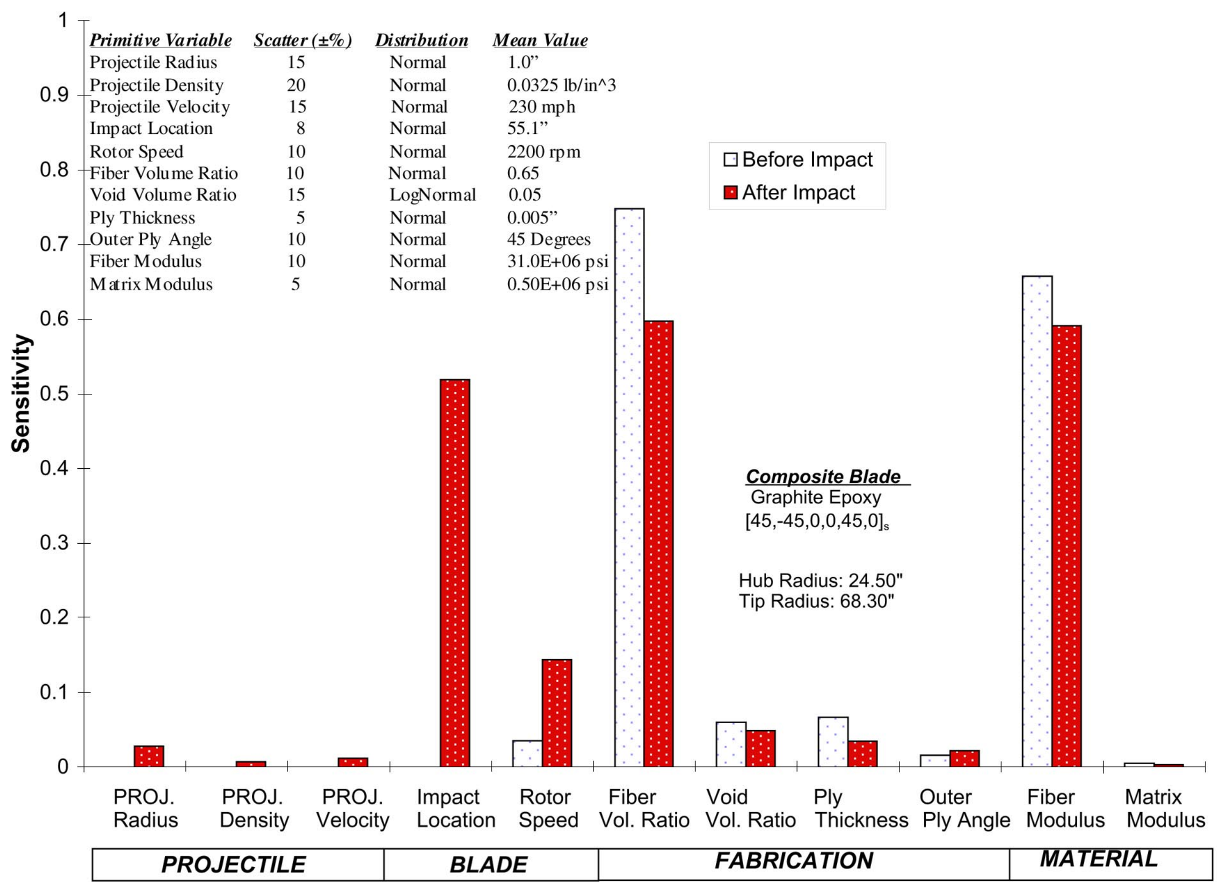

Figure 14.—Sensitivity of blade third natural frequency at 0.001 probability (fan stage 1 composite blade - engine of a subsonic mission).

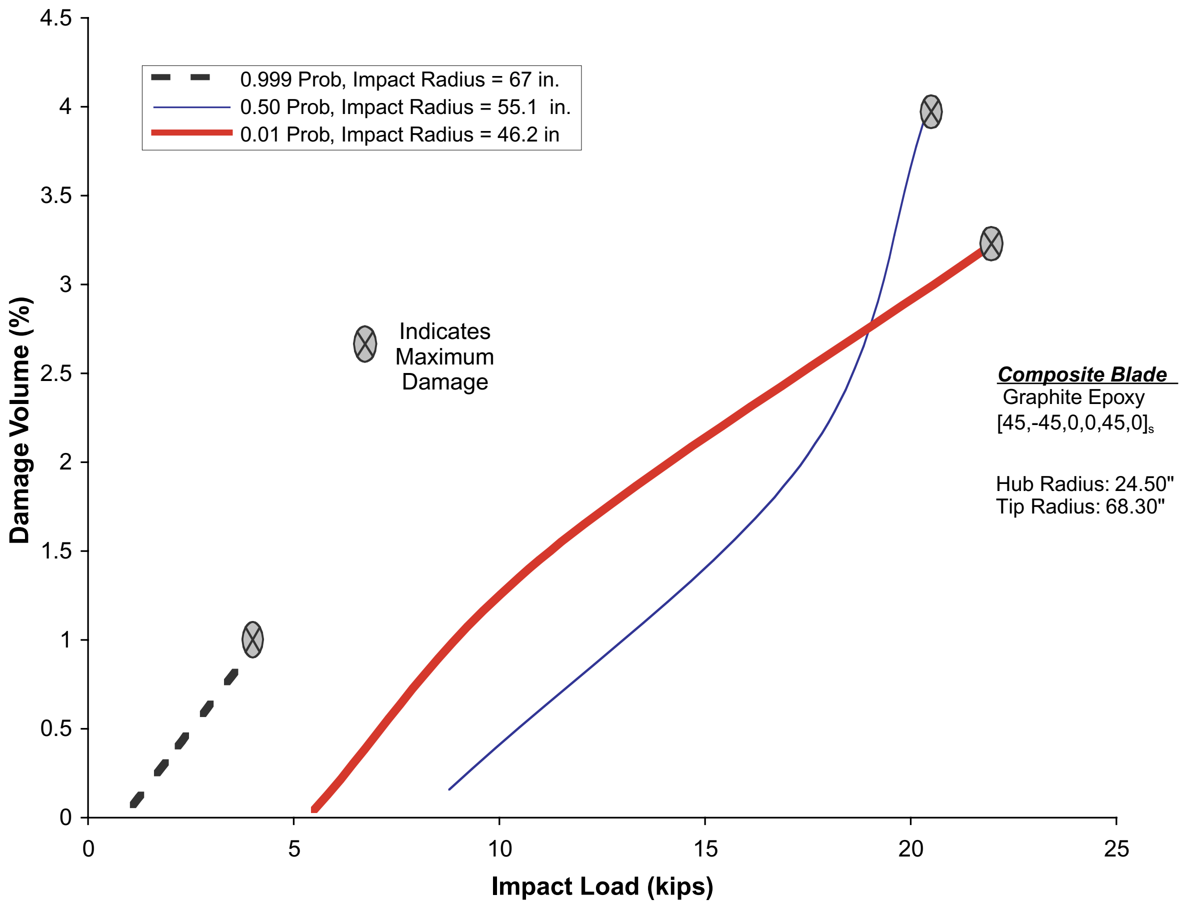

Figure 15.—Damage volume due to incremental impact load. Progressive fracture evaluation predicted by CODSTRAN at three most probable points.

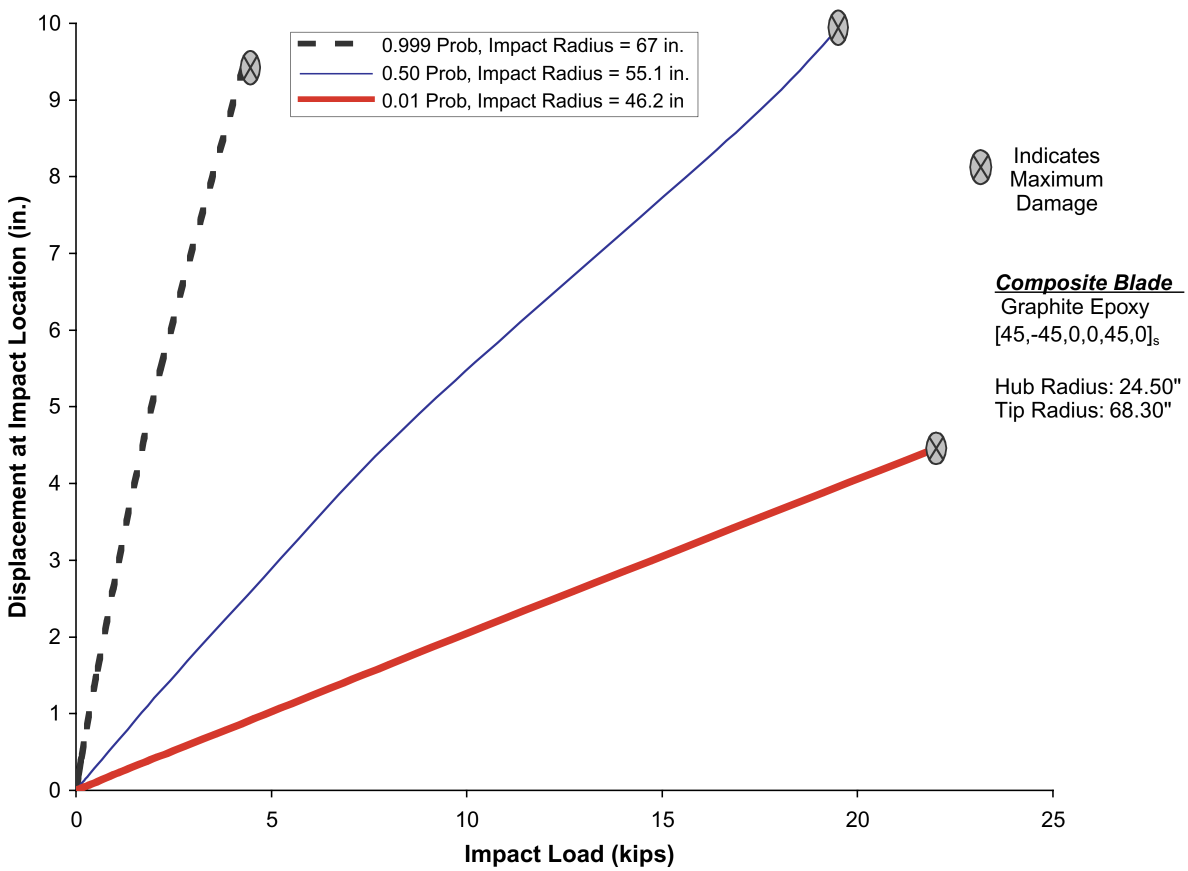

Figure 16.—Resultant displacement in chordwise and flapwise direction due to incremental impact load. Progressive fracture evaluation predicted by CODSTRAN at three most probable points.

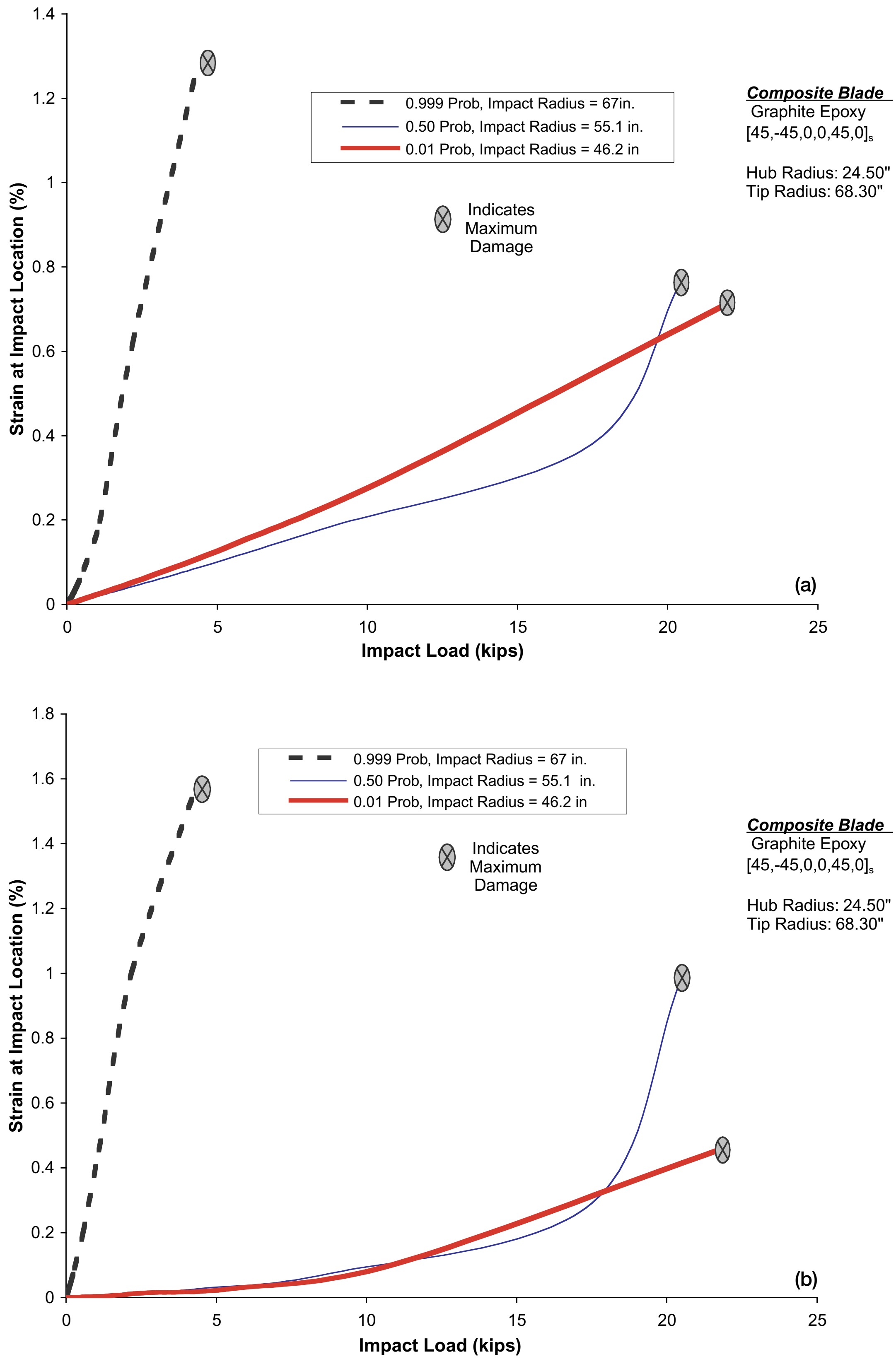

Figure 17.—Progressive fracture evaluation predicted by CODSTRAN at three most probable points. (a) Top ply strain in the fiber direction due to incremental impact load. (b) Top ply strain in the transverse direction due to incremental impact load.

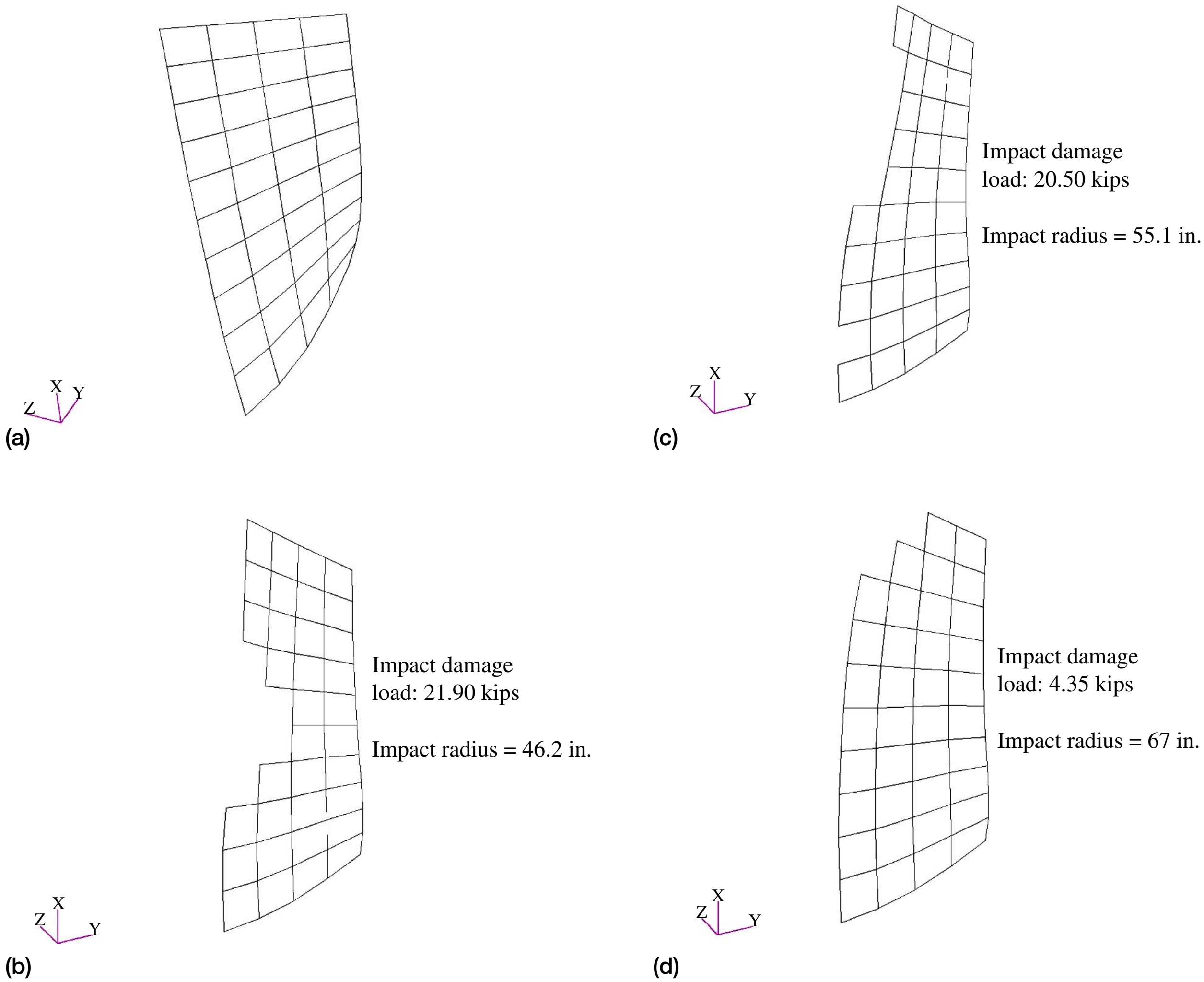

Figure 18.—Maximum blade damage resulting from incremental impact load. Progressive fracture evaluation predicted by CODSTRAN at three most probable points. (a) Blade operating at 2200 rpm (without impact). (b) Blade damage due to impact (at 0.01 probability). (c) Blade damage due to impact (at 0.50 probability). (d) Blade damage due to impact (at 0.999 probability).

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

The response to high velocity impact of a composite blade is probabilistically evaluated. The evaluation is focused on quantifying probabilistically the effects of uncertainties (scatter) in the variables that describe the impact, the blade make-up (geometry and material), the blade response (displacements, strains, stresses, frequencies), the blade residual strength after impact, and the blade damage tolerance. The results of probabilistic evaluations results are in terms of probability cumulative distribution functions and probabilistic sensitivities. Results show that the blade has relatively low damage tolerance at 0.999 probability of structural failure and substantial at 0.01 probability.

14. SUBJECT TERMS
Damage tolerance; Computational simulation; Structural performance; Grahite fibers; Polymer matrix; Computer codes; Reliability; Senitivities; Residual strength; Uncertainties; Scatter bounds

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