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Impact Damage and Strain Rate Effects for Toughened Epoxy Composite Structures

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Abstract

Structural integrity of composite systems under dynamic impact loading is investigated herein. The GENOA virtual testing software environment is used to implement the effects of dynamic loading on fracture progression and damage tolerance. Combinations of graphite and glass fibers with a toughened epoxy matrix are investigated. The effect of a ceramic coating for the absorption of impact energy is also included. Impact and post impact simulations include verification and prediction of: (1) Load and Impact Energy, (2) Impact Damage Size, (3) Maximum Impact Peak Load, (4) Residual Strength, (5) Maximum Displacement, (6) Contribution of Failure Modes to Failure Mechanisms, (7) Prediction of Impact Load Versus Time, and (8) Damage, and Fracture Pattern. A computer model is utilized for the assessment of structural response, progressive fracture, and defect/damage tolerance characteristics. Results show the damage progression sequence and the changes in the structural response characteristics due to dynamic impact. The fundamental premise of computational simulation is that the complete evaluation of composite fracture requires an assessment of ply and subply level damage/fracture processes as the structure is subjected to loads. Simulation results for the graphite/epoxy composite were compared with the impact and tension failure test data, correlation and verification was obtained that included: (1) impact energy, (2) damage size (3) maximum impact peak load, (4) residual strength, (5) maximum displacement, and (6) failure mechanisms of the composite structure.

Introduction

Toughened epoxy composites are able to sustain large strains in matrix dominated deformation and display nonlinear stress-strain relationships. Additionally the stiffness and strength are significantly affected by temperature and strain rate. A computational capability is developed and validated for the analysis of impact loading damage propagation of toughened epoxy composite structural systems. The GENOA virtual testing software environment is used to implement the dynamic loading effects on fracture progression and damage tolerance. The software enhancement/verification introduces dynamic equations for analyses of large deformations, effects of loading rate, and stress wave propagation. The developed code is validated using test data time histories and projectile impact loading characteristics to verify the type, extent of damage and the associated energy absorption in composite structures (ref. 1).

This paper outlines the enhancement and validation of the GENOA (GENeralized Optimizer and Analyzer) FEA based progressive failure life prediction software under dynamic impact loading for advanced toughened epoxy composite structures. GENOA uses a multiscale building block verification strategy (fig. 1). This foundation focuses on hierarchical progressive failure analyses and verification at each step of the load deformation plot shown (fig. 2). Advanced material and component designs require evaluation of mechanical properties, effects of their uncertainties, and life assessment to meet the challenge of “order of magnitude” improvement on composite structural safety (refs. 2 and 3). Progressive fracture analysis (PFA) methodology considers the failure mechanisms by identifying the

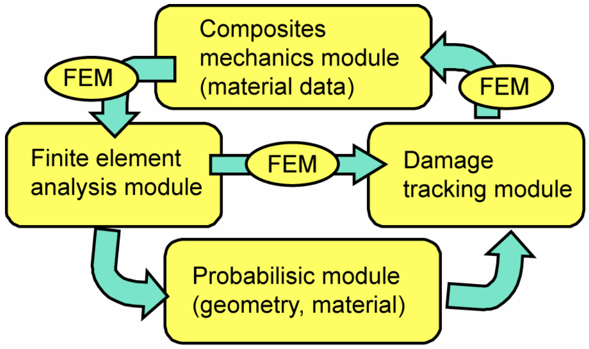


Figure 1.—A Schematic diagram of the principal elements of the GENOA PFA software.

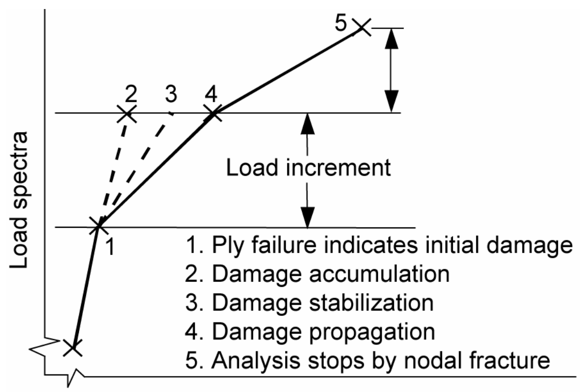


Figure 2.—Damage tracking is expressed in terms of load spectrum, and displacement relationship.

TABLE I.—CONCEPT AND FUNCTIONALITY OF GENOA-PFA

Concept/Methodology	Functionality
Updated/total lagrangian	Geometrical non-linearity
Material property degradation at fiber/matrix, lamina level	Material non-linearity
Adaptive meshing	Singularity conditioning
P element-mixed iterative FEM	Minimize residual error conditioning
Fourteen failure mechanism	Flexibility for damage growth (3D) space
Percent contribution of failure modes to fracture	Identify fracture for each mode
Strain energy release rates due to damage—local and global	Damage and fracture monitoring
Stochastic evaluation	Random damage propagation, sensitivity

basic cause of which structure failures occur, grow and/or coalesce to critical dimensions such that the structure no longer has an adequate safety margin to avoid catastrophic global fracture (ref. 4).

The concept and functionality of GENOA's Progressive Failure Analysis (PFA) is outlined in table I (ref. 4). At each individual load step, in-plane and through-the-thickness stresses obtained through composite micro-stress analysis are assessed according to distinct failure criteria outlined in table II (ref. 5).

GENOA's computational simulation approach for prediction of structural fracture in monolithic or composite materials formally quantifies: (a) all active fracture modes, (b) the type(s) of flaws initiating

TABLE II.—FAILURE CRITERIA CONSIDERED IN GENOA

Mode of Failure	Description
Longitudinal tensile	Fiber tensile strength, fiber volume ratio
Longitudinal compressive	(1) Rule of mixtures based delaminations, (2) Fiber microbuckling, and (3) fiber crushing
Transverse tensile	Matrix modulus, matrix tensile strength,
Transverse compressive	Matrix compressive strength, matrix modulus, and fiber volume ratio.
Normal tensile	Plies are separating due to normal tension
Normal compressive	Due to very high surface pressure i.e., crushing of laminate
In-plane shear	Failure in plane shear relative to laminate
Transverse normal shear	Shear failure acting on transverse cross oriented in a normal direction of the ply
Longitudinal normal shear	Shear failure on longitudinal cross section that oriented in a normal direction of ply
Modified distortion energy	Combined stress failure criteria used for isotropic materials
Relative rotation criterion	Considers failure if the adjacent plies rotate excessively with one another

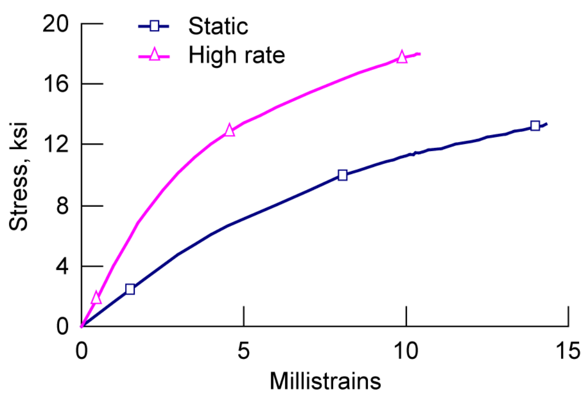


Figure 3.—Tensile response of a representative (45°) toughened polymer matrix composite for quasi-static (4.75×10^{-5}/sec) and high (405/s) strain rates.

active fracture modes, and (c) the coalescing and propagation of fractures to critical dimensions for imminent structural fracture (failure). The approach to determining the durability and damage tolerance (D&DT) in the framework of structural fracture damage is characterized by five sequential stages of damage/crack development: (1) initiation, (2) growth, (3) accumulation (i.e., coalescence of propagating flaws), (4) stable propagation (to a critical amount), and (5) unstable or very rapid propagation (beyond the critical amount) to collapse.

Simulation of Nonlinear Behavior

For toughened epoxy composites the nonlinear stress-strain relationship may be approximated in the form of a Ramberg-Osgood relationship. The general Ramberg-Osgood relationship is written in equation (1) for each material axis of the ply:

$$\varepsilon = a\left(\frac{S}{E}\right)\left(\frac{\sigma}{S}\right)^{n} \tag{1}$$

Where ε is the strain, σ is the stress, S is the reference “yield” stress, E is the initial modulus of elasticity, and a and n are additional material parameters that define the nonlinear stress-strain relationship. For toughened epoxy composites, equation (1) can be specialized via regression analysis. The specific parameters are identified as a = 1.603 and n = 1.3684 based on characteristic test data on toughened epoxy composites. The results are plotted as shown in figure 3.

Multi-Factor Interaction Method

In equation (1), the parameters E and S depend on the strain rate R. The strain rate dependency and the temperature dependency of the stress-strain relationship can be represented in terms of a multi factor interaction equation (MFIE) as follows:

$$\frac{P}{P_o}=\left(\frac{t_{gw}-t}{t_{gw}-t_o}\right)^{0.5}\left[1+\frac{R}{R_r}\left(\frac{P_r}{P_o}-1\right)\right]^{RE} \tag{2}$$

Where P is a material property such as E or S, t_{gw} is the wet glass transition temperature, t_o is the reference (room) temperature, t is the service temperature, R is the strain rate, R_r is the reference strain rate, P_r is the value of the subject property at the reference strain rate of R_r. Using the values associated with figure 3, $R_o = 4.75\times10^{-5}$/sec, $R_r = 405$/s, $E_o = 1702$ ksi, $E_r = 3788$ ksi, $S_o = 13.33$ ksi, $S_r = 18.86$ ksi, we obtain the following MFIE for rate effects on modulus E and strength S:

$$\frac{E}{1702}=\left(\frac{t_{gw}-t}{t_{gw}-t_o}\right)^{0.5}\left[1+\frac{R}{405}\left(\frac{3788}{1702}-1\right)\right]^{1.0} \tag{3}$$

and

$$\frac{S}{13.33}=\left(\frac{t_{gw}-t}{t_{gw}-t_o}\right)^{0.5}\left[1+\frac{R}{405}\left(\frac{18.86}{13.33}-1\right)\right]^{1.0} \tag{4}$$

Therefore, for a given strain rate, e.g. R=100/s at room temperature $t=t_o$ we obtain E and S as:

$$E=1702\left[1+\frac{100}{405}\left(\frac{3788}{1702}-1\right)\right]^{1.0} = 2217 \text{ ksi} \tag{5}$$

$$S=13.33\left[1+\frac{100}{405}\left(\frac{18.86}{13.33}-1\right)\right]^{1.0} = 14.70 \text{ ksi} \tag{6}$$

Therefore, the associated stress-strain diagram at the strain rate of 100 is evaluated from equation (1) as:

$$\varepsilon=1.603\left(\frac{1}{2217}\right)14.70^{-0.3684}\,\sigma^{1.3684} \tag{7}$$

The stress-strain diagram defined by equation (7) is depicted in figure 4.

It is noted that the above equations are derived based on coefficients that are validated using test data at several high strain rates on the IM7–8552 toughened epoxy composite material. The full 3–D dynamic equations of motion are integrated within the damage propagation simulation. Within each load increment during impact damage simulation, the direct integration of the dynamic finite element equations is carried out with adaptive mesh refinement as needed. After each dynamic load increment and after the imposition of structural damage, nodal displacements, velocities, and accelerations are used to continue the

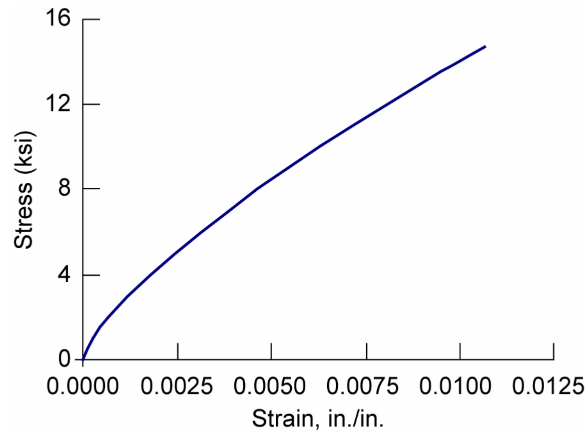


Figure 4.—Tensile stress-strain relationship for (45°) toughened polymer matrix composite for (100/s) strain rate.

TABLE III.—COMPARISON OF TEST AND SIMULATION RESULTS FOR COMPOSITE MONOCOQUE (WOVEN G30-500/R6376) SPECIMEN

Type	Test	Simulation
Impact energy	7.58 ft-lb	7.58 ft-lb
Impact damage size	0.6×0.7 in.	0.6×0.7 in.
Max impact peak load	897 lb	835 lb (Total Lagrangian/pseudo-static) 1025 lb (dynamic))
Tension after impact residual strength at 864 lb	80,590 psi	81,457 psi
Maximum displacement	0.20 in.	0.197 in.
Failure mechanism	Transverse tensile	Transverse tensile

simulation in the subsequent dynamic load increment with the appropriate initial conditions. The updated Lagrangian approach is used to account for the true damage states during the application of dynamic loading. Stress wave propagation effects are correctly accounted for via explicit time integration of the dynamic finite element equations. The 3–D dynamic simulation of damage propagation is validated by comparing the simulation results with the existing toughened epoxy composite impact test data. Simulation results are presented in the form of residual strength, impact damage vs. load and time, and fracture pattern. The validation under impact loading includes: (1) damaged foot print area, (2) fragmentation foot print, (3) impact velocity versus time, (4) acceleration versus time, (5) force versus time, (6) damage versus time, (7) penetration depth, and (8) local structural displacements. In this context, the solution is similar to an explicit form. The total Lagrangian refers to the total displacement that is accumulated at the end of a converged load increment.

Results and Discussion

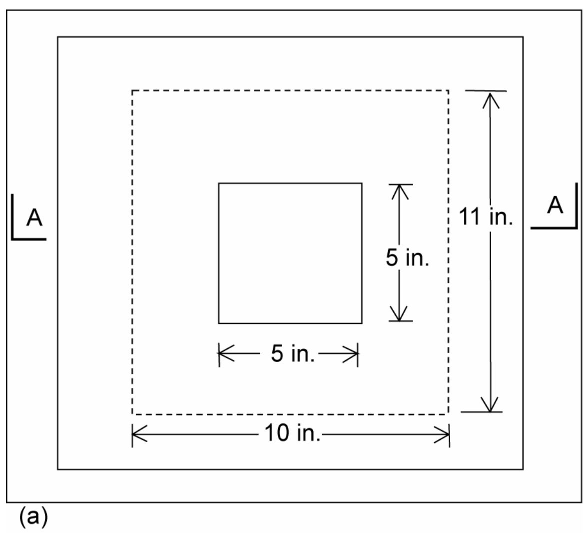
GENOA progressive failure analysis software was utilized to simulate and verify a composite test specimen, under impact and residual tensile strength after Impact. Table III compares the simulation versus test results.

Description of Composite Test Specimen

A woven G30-500/R6376 panel (45/-45/0/90/0/90/0/90/0/90/-45/45) with a woven fabric layer ply thickness of 0.014 in. was experimentally impacted by a steel ball drop and was subsequently tested in tension. The properties of fiber and matrix are in reference 1. The post impact evaluation showed the presence of minimal damage on the skin at the impact sides (ref. 7). However, some damage was evident on the back side of the panel.

Description of the Panels and Test Procedure

The 10-in.-wide by 11-in.-long panel (fig. 5(a)) was sandwiched between two supporting plates during impact (fig. 5(b)). The impacting device with 1-in.-diameter impactor had a weight of 53.75 lb and impact velocity of 3.01 ft/sec. The impacting energy was 7.58 ft-lb. The panel was made with six layers of G30-500/R3676 fabric (in which the fiber volume was 60 percent) with the ply lay-up of (45,–45), 4×(0,90), (45,–45). Each fabric ply was 0.014 in. thick and the total thickness of the panel was 0.084 in.



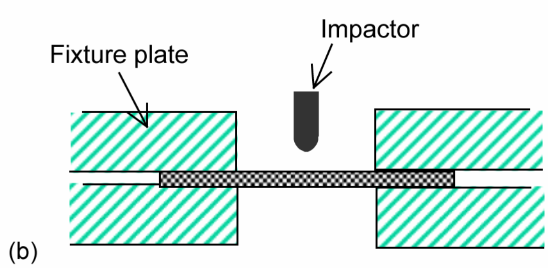


Figure 5(a).—Schematic of impacting panels.
(b) Impacting test fixture.

Comparison Between Test and Simulation of Equivalent Property Generation

GENOA Composite Constituent Analyzer predicted the equivalent mechanical properties using the lamination theory (ref. 4) utilizing: (1) cure temperature, (2) ply orientation, (3) ply thickness, (4) moisture, (5) defects, and (6) volume fraction. It can predict the equivalent constituent properties including: (1) composite modulus, (2) thermal expansion, (3) moisture expansion coefficients, (4) heat conductivity, (5) laminate Strength, (6) Poisson's ratio, (7) moisture diffusivity, (8) ply stress, and (9) ply strength. Composite Constituent Analyzer provides important design information (e.g., margin of safety) needed to optimize composite material systems, and facilitates designers in understanding fiber and matrix stress distributions in a composite system under load. Table IV shows the comparison between test and simulation of equivalent properties of G30-500/R6376 ply with 0/90 lay-up.

TABLE IV.—COMPARISON OF TEST AND SIMULATION OF EQUIVALENT PROPERTIES OF G30-500/R6376 PLY WITH 0/90 LAY-UP

Property	Test Data	Predicted by GENOA
Tensile modulus, msi	10.0	9.70
Compression modulus, msi	9.50	9.70
Shear modules, msi	0.75	0.72
Tensile strength, ksi	129.0	130.5
Compressive strength, ksi	103.0	100.0
Shear strength, ksi	12.4	13.8

Impact Simulation Methodology

The impact module in GENOA-PFA (ref. 5) was used to simulate the impacting process and the damage it caused. Figure 6 shows the comparison between simulation and test under the impact loading. As shown in figure 6, three types of PFA simulations were performed to represent the test: (1) updated Lagrangian where incremental loading is applied on the structure, (2) total Lagrangian, and (3) pseudo dynamic solutions.

Impact Loading Simulation

The impact module in GENOA-PFA was used to simulate the impacting procedure and the damage it caused. No impact damage occurred on the G30-500/R6376 impacted surface. But there was evidence of damage at the opposite side of the impact location.

Impact Simulation

The finite element model utilized nodal based analysis and through the thickness shell elements were used to simulate the test panel. There were 1855 nodes and 1768 elements. The panel was sandwiched between two support plates as shown in figure 4. Each support plate had a 5×5 in.^{2} opening in the center. All edges were modeled as fixed, and all the nodes between the two supporting plates were constrained in the out of plane direction. The velocity of the impactor was 36.212 in./sec and the mass of the impactor was 53.75 lb. The impact energy was 7.58 ft-lb.

The simulation was started with an initial velocity of 36.12 in./sec that decreased with the time as the kinetic energy was transformed to strain and damage energies. When the ball velocity decreased to 20.15 in./sec after 0.0029 sec of the impact, the bottom plies in the area of 0.5 by 0.5 in. under the impactor started to damage due to transverse tensile failures. The contact force at time was 513 lb. Figure 7 shows the damaged node locations.

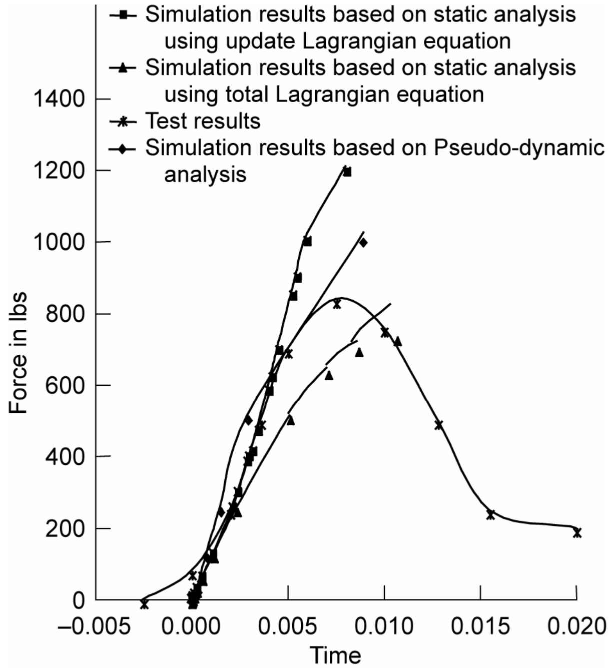


Figure 6.—Comparison of test and simulation under impact loading (impacting force changes with time (impact velocity: 3.01 ft/sec)).

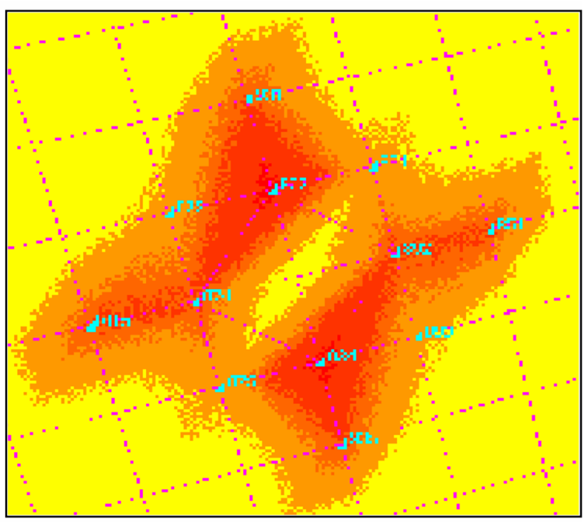


Figure 7.—Transverse tensile damage initiation (0.5×0.5 in.).

With further decreases in the impact ball velocity, the damage propagated from the middle of the panel to increasingly more nodes enlarging the damage area. After the impact ball came to rest the damage extended to the area of 1.2 by 1.2 in. Figure 8 shows the damage extent after impact. All the damage modes are due to transverse tensile (table V). This implied the damage due to impact was limited in the matrix cracking. No fiber breakage was found in the simulation. Figures 9 and 10 show the velocity and deflection in the middle point versus the time, respectively. The progressive damage patterns at loads 864, 914, and 1210 lb are shown in figures 11 to 13.

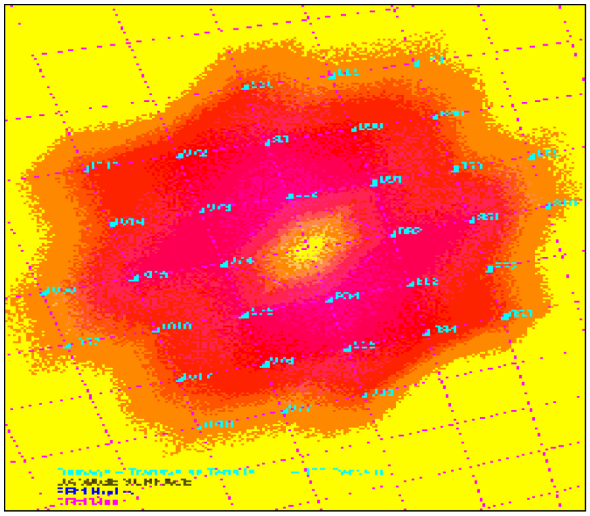


Figure 8.—Transverse tensile damage pattern (1.2×1.2 in.) after impact.

TABLE V.—PSEUDO STATIC LOADING TO SIMULATE IMPACTING PROBLEM (UPDATED LAGRANGIAN)

Number of damaged nodes	Load (lb)	Damage description
6	399	Damage at the very bottom ply due to transverse tensile failure
22	864	Damage at the four bottom plies due to transverse tensile failure
26	914	Damage at the four bottom plies due to transverse tensile failure
	1210	Broke the specimen at the loading point

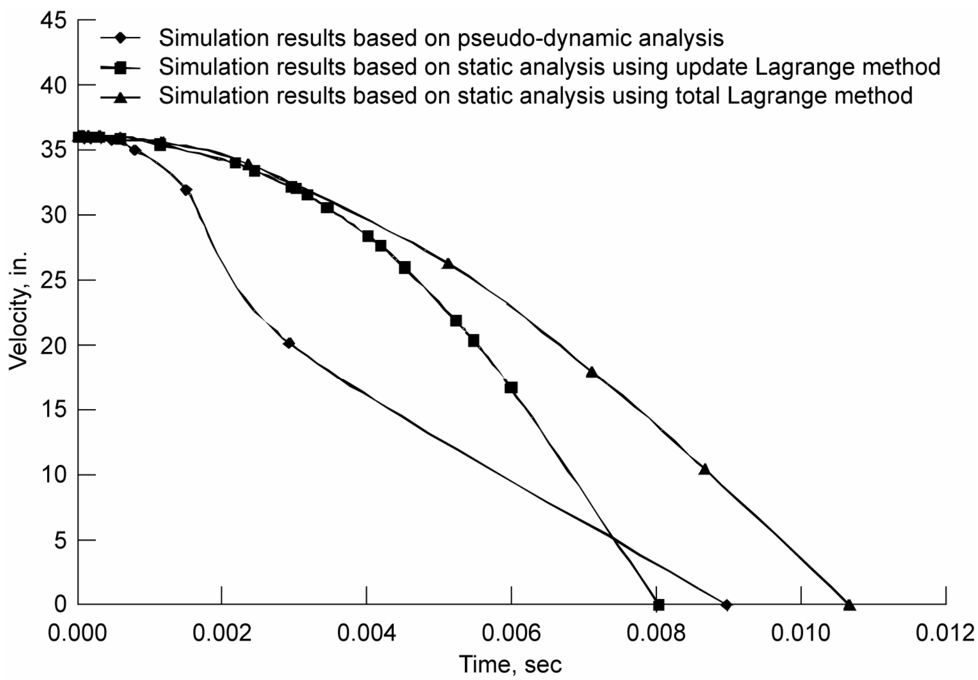


Figure 9.—Velocity of the impactor ball change with the time impact velocity: 3.01 ft/sec.

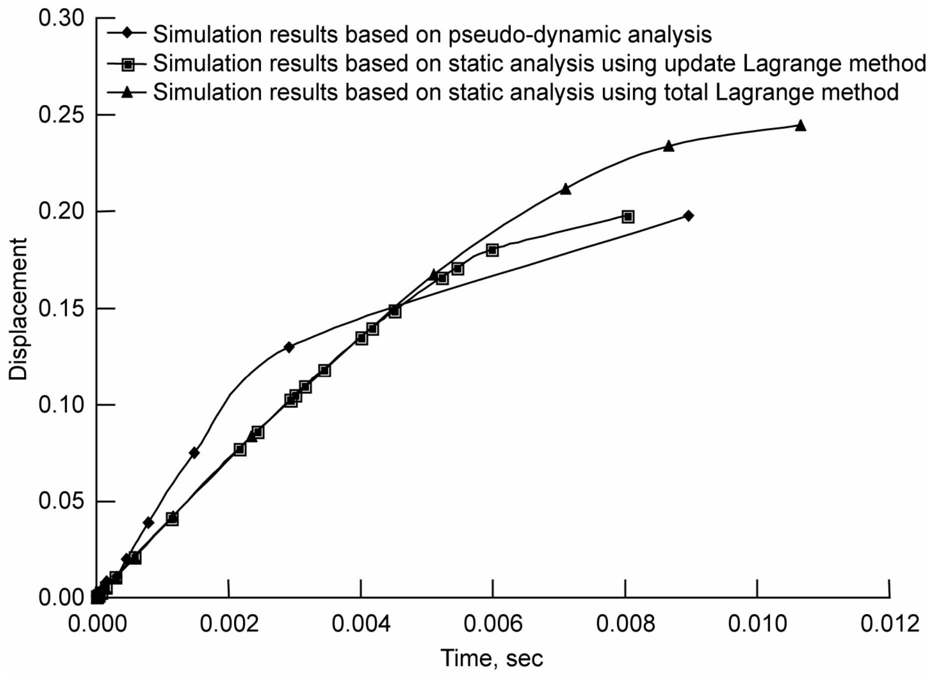


Figure 10.—Deflection of the mid point of the impacted panel changed with the time impact velocity: 3.01 ft/sec.

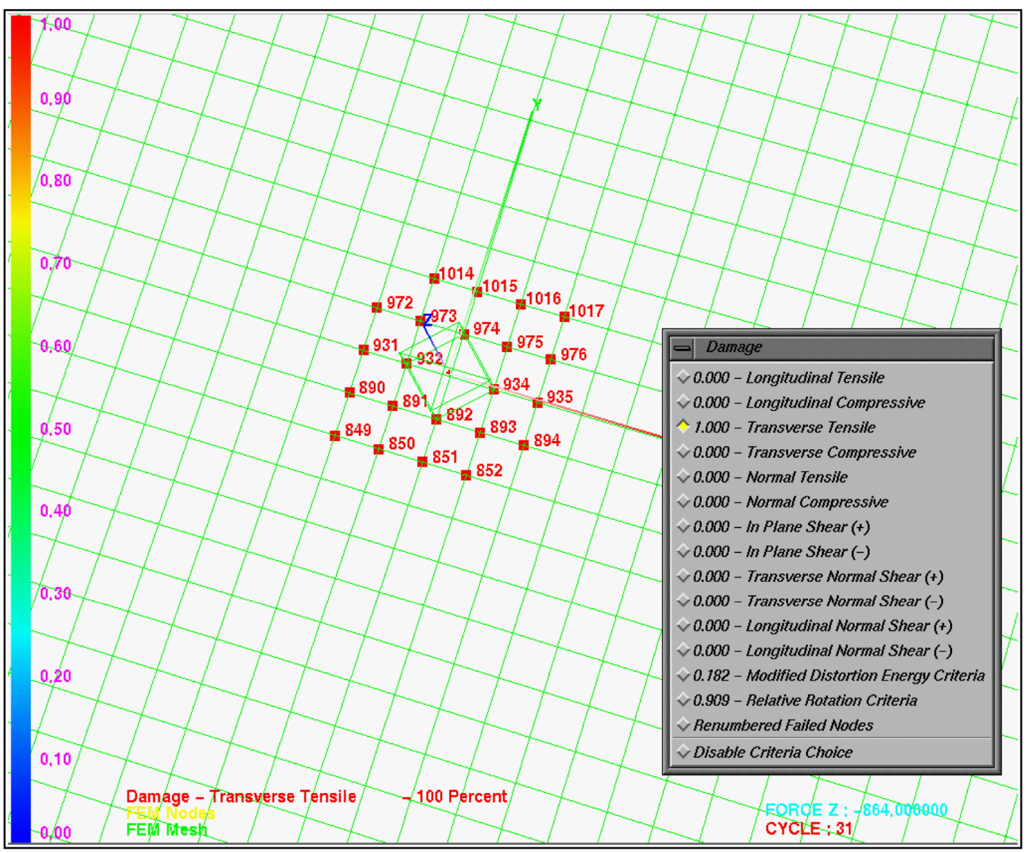


Figure 11.—Transverse tensile damage pattern at loading of 864 lb.

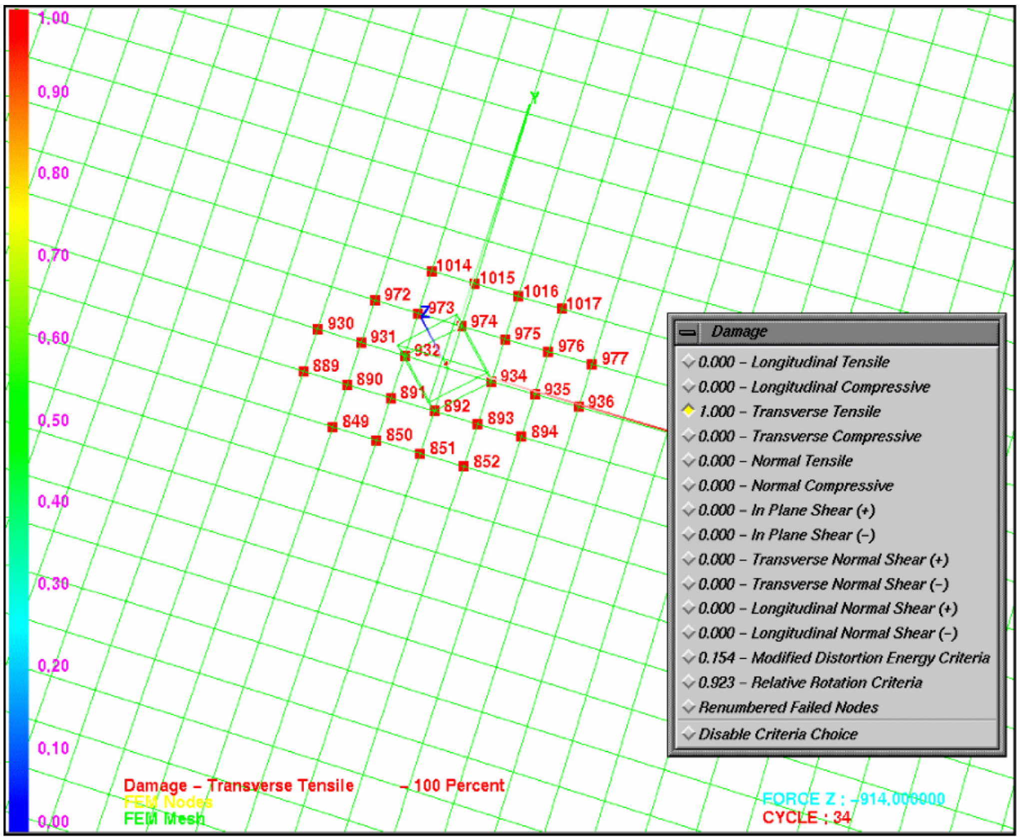


Figure 12.—Transverse tensile damage pattern at loading of 914 lb.

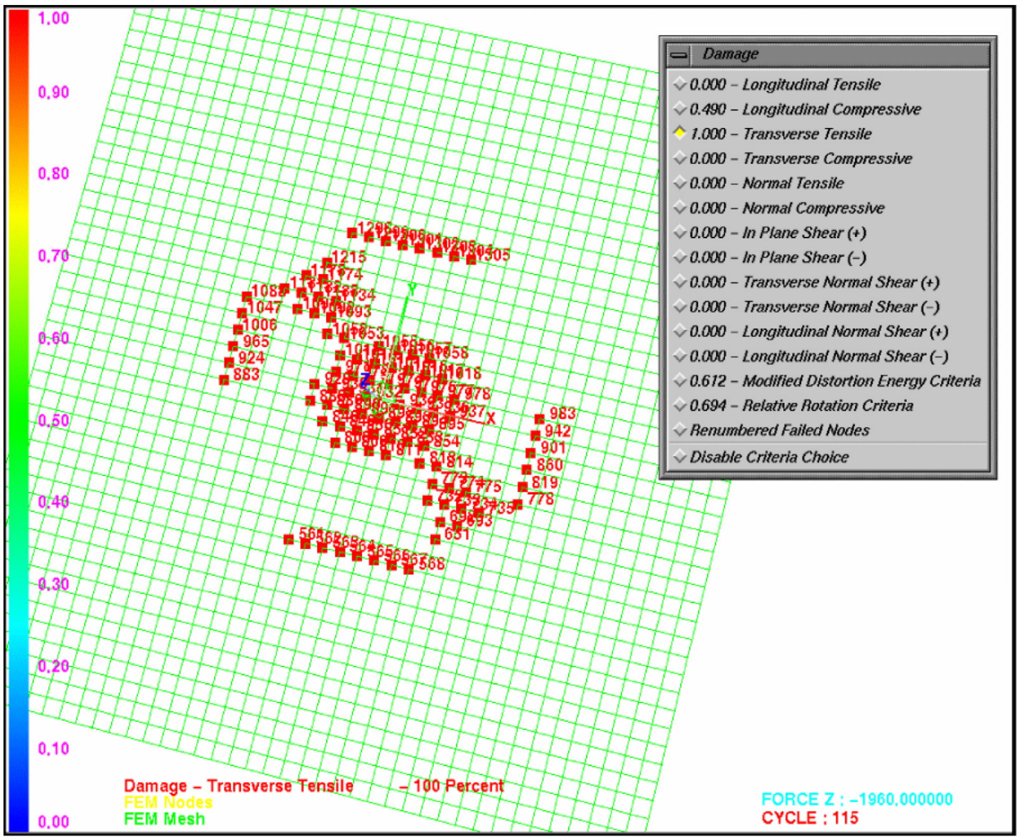


Figure 13.—Damage pattern (transversese tensile, distortion energy) at loading of 1210 lb.

Impact Test and simulation Comparison (impact velocity: 3.01 ft/sec)

The comparison between the test and simulation results is shown in table 6.

TABLE VI.—TEST AND SIMULATION COMPARISON

	Test	Total Lagrangian	Updated Lagrangian	Pseudo dynamic
Peak load, lb	897	835	1210	1025
Maximum deflection, in.	0.20	0.24	0.1977	0.198

Specimen size: 10-in.-wide by 11-in.-long panel
Ply configuration: (45,–45),4×(0,90),(45,–45)

Impact Test Results

The Impact test results of the monocoque composite panel are shown in table 6. The measured damage size for the test 1 and 2 were 0.6 by 0.7 and 1.2 by 1.2 in., respectively. Results of dynamic impact loadings are summarized in table 7.

TABLE VII.—IMPACT RECORDED TEST DATA OF 25 FT-LBS IMPACTED BALL ON A COMPOSITE MONOCOQUE WOVEN G30-500/R6376 PANEL (45/-45/0/90/0/90/0/90/0/90/-45/45) PANEL

Test number	1	2	3
Impact velocity, ft/sec	3.01	4.87	3.16
Impact energy, ft-lb	7.58	19.79	8.35
Max load, lb	897.6	916.14	858.64
Total time, msec	19.75	22.92	19.77
Energy to max load, ft-lb	7.03	14.05	6.65
Total energy, ft-lb	5.60	18.96	6.94
Deflection at max load, in.	0.20	0.30	0.19

Tension After Impact Residual Strength

Tension after impact residual strength assessed the damage it caused, damage propagation, and residual strength of the panel. GENOA PFA module was used to simulate Tension after impact damage propagation of the damaged panel due to the impact loading of 864 and 914 lb. Figures 14(a) and 14(b) show the damage pattern comparison between the experimental and simulation results.

After impact simulation, a pure tension simulation was conducted. Boundary conditions for the tension simulation were: (1) the left edge was completely fixed, (2) the right edge was fixed in the out of plane direction, (3) duplicated nodes were applied to the right edge to provide for equal displacement in the y direction (in plane), and the tension load was applied to the right edge. Since some of the bottom plies were already damaged due to the impact, these damages were considered as initial damage for the tension simulation.

GENOA-PFA was used to simulate the damaged panel under pure tension loading case. The impact load prior to testing in tension was 864 lb. The comparison between the simulation and test results are shown in table 8. Figure 14 shows damage pattern prior to Tension after impact (TAI), and figure 15 shows the percent damage versus load during the impact.

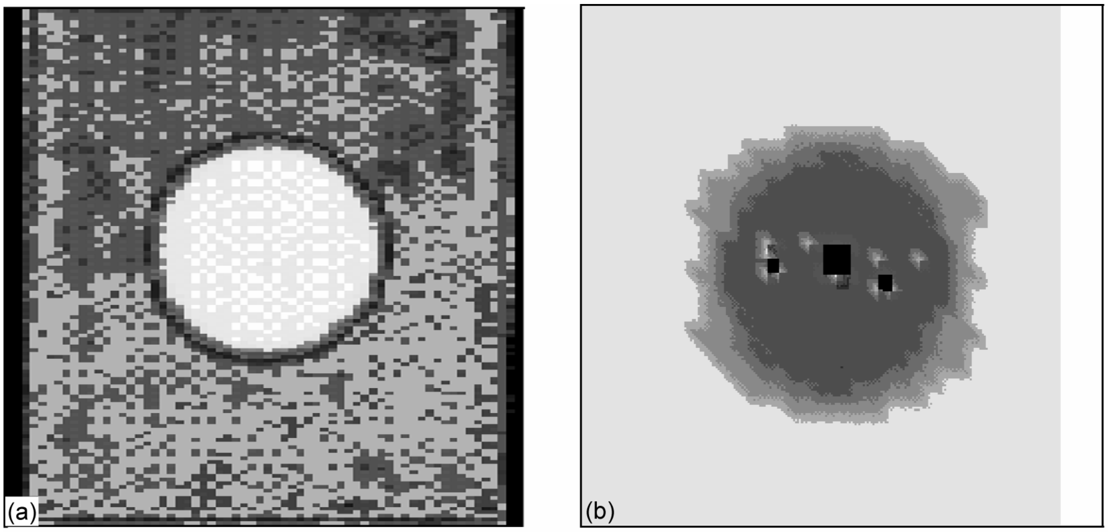


Figure 14.—Fracture and simulated patterns in test. (a) Experimental pattern (1.2×1.2 in.). (b) Simulated fracture pattern (1.2×1.2 in.).

TABLE VIII.—TEST VERSUS SIMULATION OF UNDAMAGED TENSILE SPECIMEN

Test	Ultimate load simulation
30,300 lb	29,700 lb

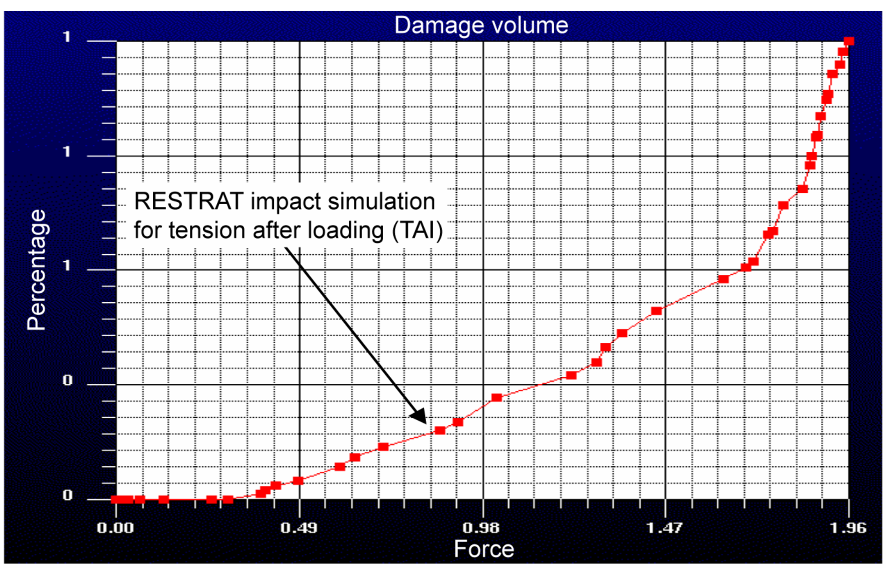


Figure 15.—Percent damage versus load (864 lb) prior to tension after impact (TAI).

Static Tension Simulation of Undamaged Panel

GENOA-PFA was used to simulate the undamaged 0.084-in.-thick woven G30-500/R6376 panel (5.5 by 3.8 in.) with the ply configuration (45/-45/0/90/0/90/0/90/ 0/90/-45/45). The predicted strength was 93,045 psi (29700/(0.084 by 3.8). Table 8 shows the comparison of the test versus the simulation.

Impact of Ballistic Resistant Composite Armor

In this example we consider a glass fiber/epoxy composite panel designed for high velocity impact resistance. After we have the FEM model (fig. 16), we execute the impact PFA program (under impact loading). Table 9 summarizes the composite structure and impact parameters. Table 10 describes the damage initiation and propagation stages under impact loading. Figure 17 depicts the damage propagation stage and figure 18 shows the state of damage at the ultimate impact loading, immediately before failure.

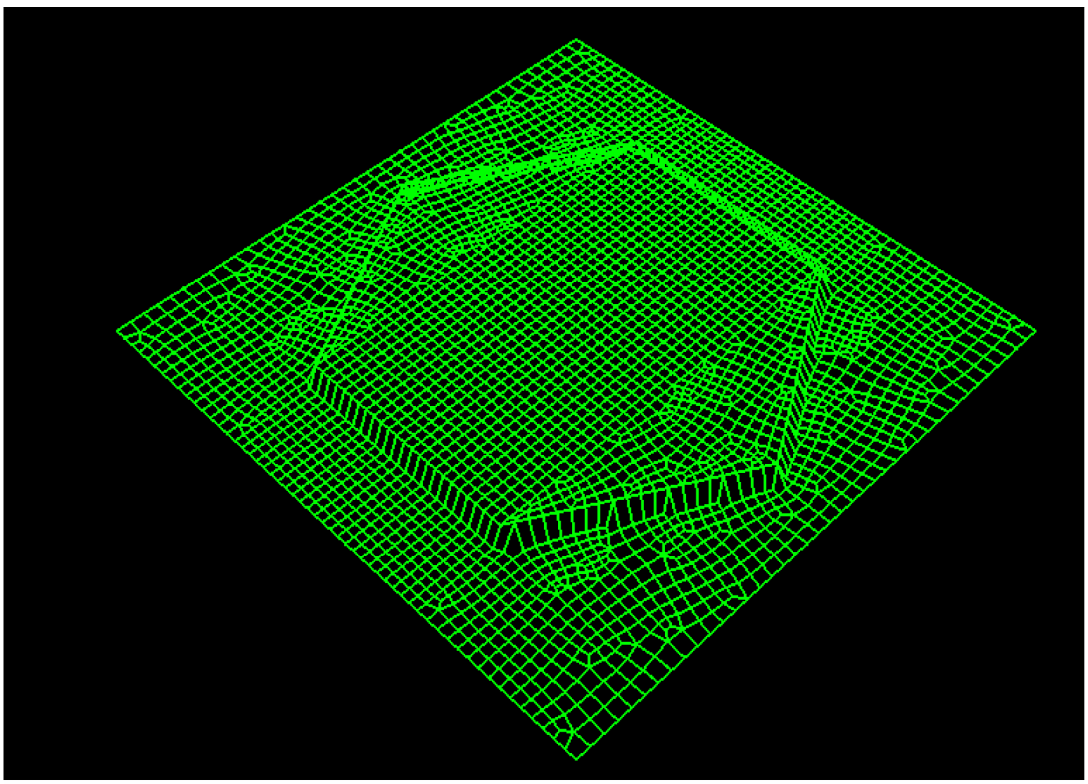


Figure 16.—FEM model of the panel with a ceramic tile on it (GENOA 3.2).

TABLE IX.—SIMULATION OF FIBERGLASS SPECIMEN UNDER IMPACT LOADING

Simulation ID	Material	Panel layup	Test type	Test temp	Length, in.	Width, in.	Thick, in.	Projectile, lb	Velocity, ft/sec
Fiberglass1 no stitch	E-glass	$[45/0/-45/90]_{13}$	impact	70.0	10.0	10.00	0.689	0.264	2650

TABLE X.—SIMULATION RESULTS OF FIBERGLASS SPECIMEN UNDER IMPACT LOADING

Simulation ID	Damage initiator, lb	Damage propagation, lb	Ultimate loading, lb	Damage description
Fiberglass1 no stitch	1024	2048	5536	Damage was initiated at the center of the panel, then spread to neighbor region. There is no fracture failure after running 900 cycles. The damage mode is longitudinal compressive failure.

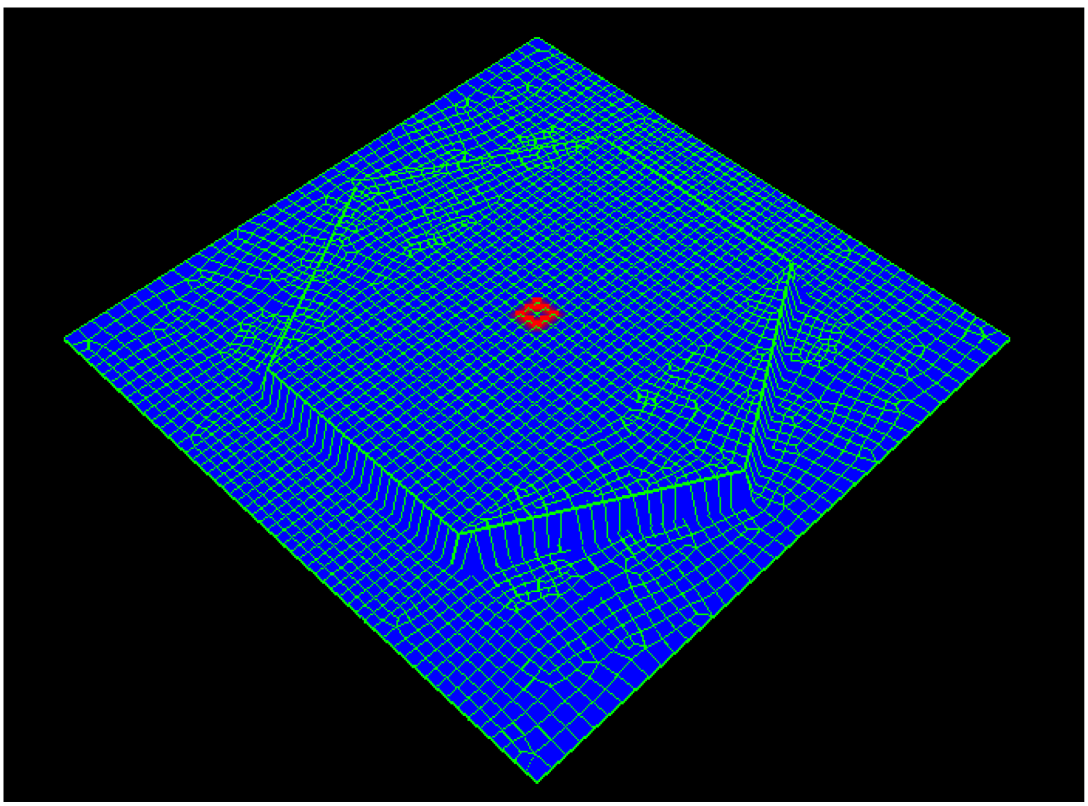


Figure 17.—Initial damage at the center of the panel.

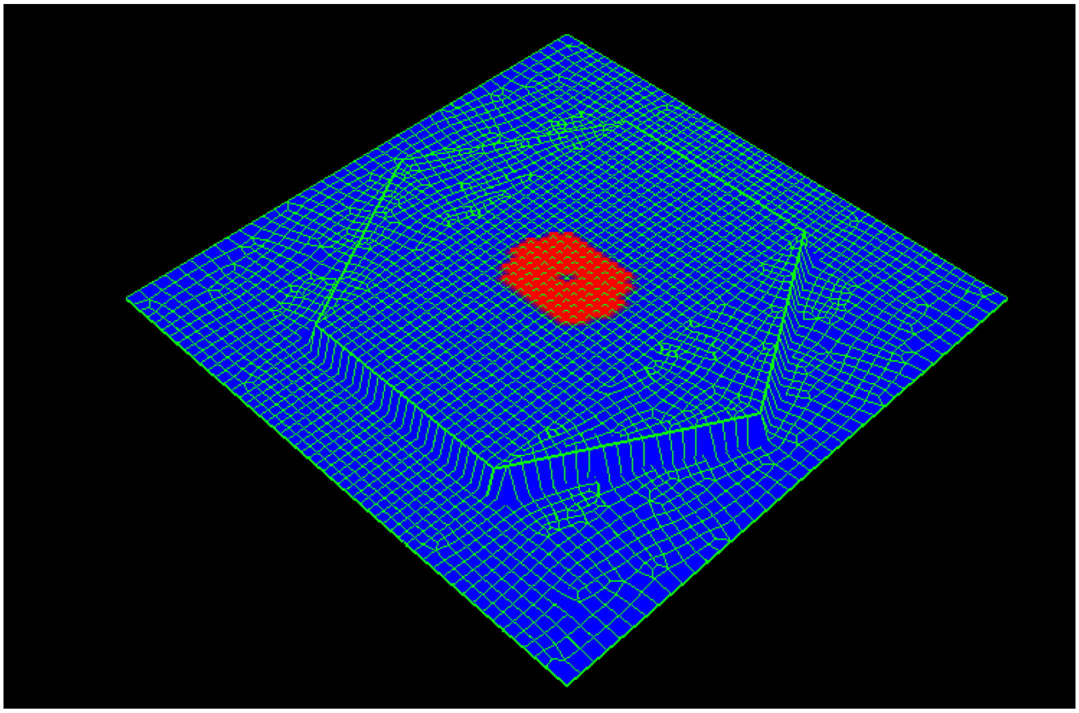


Figure 18.—Damage propagation from the center of the panel.

Summary and Conclusions

Impact loading of composite panels was simulated. Composite ply damage produced by impact was quantified. Damage tolerance was evaluated by conducting a progressive fracture simulation of residual strength. Results of some simulations were validated by comparison with test data. On the basis of the results obtained from the investigated composite specimen and from the general perspective of the available computational simulation method, the following conclusions are drawn:

1. Computational simulation can be used to track the details of damage initiation, growth, residual strength, and fracture for composites subjected to impact.
2. Success of the simulation process requires evaluation and tracking of constituent fiber and matrix level damage processes.
3. Impact loading may or may not produce visible damage on the impacted face.
4. The damage patterns as well as ultimate strength of the specimen subjected to impact were accurately predicted.
5. Computational simulation, with the use of established composite mechanics and finite element modules, can be used to predict the influence of initial damage, as well as loading and material properties on the response of composites.

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13. ABSTRACT ***(Maximum 200 words)***
Structural integrity of composite systems under dynamic impact loading is investigated herein. The GENOA virtual testing software environment is used to implement the effects of dynamic loading on fracture progression and damage tolerance. Combinations of graphite and glass fibers with a toughened epoxy matrix are investigated. The effect of a ceramic coating for the absorption of impact energy is also included. Impact and post impact simulations include verification and prediction of (1) Load and Impact Energy, (2) Impact Damage Size, (3) Maximum Impact Peak Load, (4) Residual Strength, (5) Maximum Displacement, (6) Contribution of Failure Modes to Failure Mechanisms, (7) Prediction of Impact Load Versus Time, and (8) Damage, and Fracture Pattern. A computer model is utilized for the assessment of structural response, progressive fracture, and defect/damage tolerance characteristics. Results show the damage progression sequence and the changes in the structural response characteristics due to dynamic impact. The fundamental premise of computational simulation is that the complete evaluation of composite fracture requires an assessment of ply and subply level damage/fracture processes as the structure is subjected to loads. Simulation results for the graphite/epoxy composite were compared with the impact and tension failure test data, correlation and verification was obtained that included: (1) impact energy, (2) damage size, (3) maximum impact peak load, (4) residual strength, (5) maximum displacement, and (6) failure mechanisms of the composite structure.

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