ABSTRACT

A combined experimental and 3-D dynamic nonlinear finite element approach was adopted to study composite beams subject to drop-weight or ballistic impact. The composite specimens, made of S2 glass-reinforced toughened epoxy (44% fiber volume fraction, cured at 350°F), had 24 layers (approximately 6.35 mm) with various stacking sequences. They were damaged by impacts using either an Instron-Dynatup 8520 instrumented drop-weight impact tester (low-velocity impact) or an in-house high-speed gas gun (ballistic impact). For both types of tests, the time-histories of dynamic strains induced during impact were recorded using strain gages mounted on the front and back of the composite beam specimen. For drop-weight impact tests, the time history of impact force was also recorded; whereas for ballistic impact tests, only the impact velocity was calculated from the recorded change in voltage outputs, which resulted from the traversing of the impactor through two optical paths formed by two sets of diode laser-amplified photo diode pairs.

The commercially available 3-D dynamic nonlinear finite element software, LS-DYNA, incorporated with a proposed nonlinear anisotropic damage model, was then used to simulate the experimental results. Good agreement between experimental and FEM results can be seen from comparisons of dynamic strain and impact force histories and damage patterns. Once the proposed nonlinear anisotropic damage model was verified by experimental results, further finite element simulations were conducted to predict the ballistic limit velocity ($V_{50}$) for penetration prevention.

INTRODUCTION

Because of their high specific strength and stiffness, composite materials have been adopted for various beam-type load-bearing structures for several decades [1]. Recently these high strength, high stiffness and low density composites had found beam-type structural applications under high loading rates, such as driveshafts of automobiles, rotor blades of helicopters, intake fan blades of jet engines, or even an entire composite wing of a space craft [2-4]. The damage tolerance of a composite used for this class of applications depends greatly on the impact-resistance capability of the material. When designing a composite beam, we often treat it as a 1-D linearly-elastic member and pay attention only to the axial stress/strain induced by the flexural deformation. However, once a composite beam is damaged, no matter what the source of defect is (e.g., delamination, matrix cracking, fiber breakage, fiber-matrix debonding, etc.), the 1-D nature, in general, is no
longer preserved and the damaged structural member should be treated in the more complicated 3-D manner, including nonlinear elasticity and anisotropy induced by damage [4-5]. Furthermore, in order to achieve significant reduction in cost and weight, advanced technologies such as stitching, braiding and knitting had recently been employed to form 3-D composites [6-8]. Hence the study of structural behaviors of composite beams requires rigorous analyses based on the more realistic 3-D nonlinear anisotropic constitutive laws. In this study, a combined experimental and 3-D dynamic nonlinear finite element approach was adopted to study composite beams subject to drop-weight or ballistic impact.

EXPERIMENTAL PROCEDURES

Composite panels made of toughened epoxy (i.e., cured at 350°F) reinforced by uni-directional S2 glass fibers (44% fiber volume fraction) were first machined into simple strip or dog-bone beam specimens. The panels had 24 layers (approximately 6.35 mm) of laminae, which were stacked with different lay-up configurations:

1) uni-directional: \[ 0^\circ \]
2) cross-ply: \[ 0^\circ / 90^\circ, 0^\circ / 90^\circ \] or \[ 90^\circ / 0^\circ \]
3) quasi-isotropic: \[ 0^\circ / 45^\circ / 90^\circ / -45^\circ \] or \[ 90^\circ / 45^\circ / 0^\circ / -45^\circ \]

The first part of the experimental program involved low-velocity impact tests, which were conducted using an Instron-Dynatup 8250 pneumatic-assisted, instrumented drop-weight impact tester equipped with a pneumatic break to avoid multiple strikes. As shown in Fig. 1, a 6.35mm thick dog bone specimen of 254 mm in length, 25.4 mm in width at both ends and tapered down to 12.7 mm in the mid-section was clamped circumferentially in the specimen fixture of the drop-weight impact tester along a circle of a diameter of 76.2 mm measured from the center of the specimen. In addition, two strain gages were mounted on the front and back faces of the specimen, respectively, at a distance of 12.7 mm away from center.

The specimens, as shown in Fig. 2, were then impacted by a Charpy-type straight-line impactor with different impact velocities, \( V_0 \). Table 1 lists the specimen stacking sequences and the impact velocities of a 5.1 kg hemi-spherical drop-weight tup for five drop-weight tests. For each drop-weight test, the impact velocity and the time-histories of impact force and strains were recorded. It should be pointed out that because of the high levels of strains generated during the drop-weight impact event, only one out of the five tests the strain gage mounted on the tension side survived (i.e., SG-2 on the bottom face in Fig. 1). On the other hand, we always recorded successfully the strain histories in SG-1, which was mounted on the top face in Fig. 1.

The second part of the experimental program concerned about ballistic impact tests, which were conducted using an in-house high pressure gas gun. As shown in Fig. 3, high pressure helium, once released by a fast acting solenoid valve, provides the impact force needed to accelerate a 22-caliber copper bullet through the gun barrel to the desired speed. Near the muzzle of the gun barrel, two sets of diode laser-amplified photo diode pairs form two optical paths separated by 101.6 mm. The
voltage changes caused by the traversing of the projectile through the two optical paths were recorded for estimating the projectile speed.

The projectile then impinged onto a 24-layer composite strip specimen with dimensions shown in Fig. 4. The specimen, which was also mounted with strain gages, was clamped in a length of 50.8 mm at both ends. Thus, the ballistic impact test resembles a clamped-clamped beam under dynamic three-point bending. As shown in Fig. 4, the composite beam specimen was impacted by a 22-caliber copper projectile at the center. Two strain gages, marked as SG-1 and SG-2, respectively, were mounted on the impact side of the specimen. One of the strain gages was 25.4 mm and the other was 38.1 mm away from center. During the impact test, the projectile sometimes could not hit directly at the center. A strain gage can not survive the impact if the impingement is too close to it. Having one strain gage on each side allowed us to obtain at least one good strain measurement. Table 2 summarizes the specimen lay-up configurations and the impact velocities of three ballistic impact tests.

![Figure 4. A typical composite beam specimen mounted with two strain-gages on the ballistic impact side.](image)

<table>
<thead>
<tr>
<th>Test</th>
<th>Lay-up sequence</th>
<th>Impact velocity, (V_0) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>([0/90]_{2s})</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>([0/90]_{3s})</td>
<td>298</td>
</tr>
<tr>
<td>3</td>
<td>([0/45/90/\sim45]_4)</td>
<td>442</td>
</tr>
</tbody>
</table>

**Table 2. Parameters of ballistic impact tests.**
(projectile: 22-caliber copper bullet)

**EXPERIMENTAL RESULTS AND DISCUSSION**

**(A) DROP-WEIGHT IMPACT TESTS**

Various factors (such as lay-up configuration, laminate thickness, constituent properties, temperature, impact velocity and energy, etc) can affect the impact response and damage patterns. For instance, for the 1st and 2nd drop-weight tests (cross-ply beams of different stacking sequences), the tup was first placed at the highest point of the impact tester, then dropped by free-fall. The velocity obtained was around 3.98 m/s. Figure 5 depicts the time histories of impact force and dynamic strain for Drop Test 1. As shown in the figure, peak impact force: 5.5 KN and maximum dynamic strain: 2,100 µε occurred around 1.0 and 1.4 ms, respectively. By observing the ultrasonic C-scans and optical microfractographs, as shown in Figs 6 and 7, respectively, the 3.98 m/s drop-weight impact velocity did not create any delamination in the \([0/90]_{3s}\) specimen.

![Figure 5. Impact force and strain histories of Drop Test 1: \([0/90]_{3s}\) cross-ply S2 glass-toughened epoxy composite beam impacted at 3.98 m/s by a 5.1 kg hemi-spherical drop-weight.](image)

**Figure 6.** Ultrasonic C-scans of the cross-ply specimen before and after impact in Drop Test 1.

**Figure 7.** Post-mortem optical microfractographs of the cross-ply specimen used in Drop Test 1.
Figure 8 shows the recorded time histories of impact force and dynamic strains for Drop Test 2. The peak impact force and maximum dynamic strain were 5.0 KN and 1,000 µε, and occurred around 1.5 and 1.7 ms, respectively. Figure 9 displays the corresponding post-impact optical microfractographs, which clearly shows slight delamination. As indicated by these figures, for two otherwise identical cross-ply beams, e.g., \([0°/90°]_{ls}\) vs \([90°/0°]_{ls}\), different stacking sequences provide small difference in impact resistance.

In order to reach higher drop-weight impact velocities, the pneumatic assistance option of the impact tester was activated for the remaining three Drop Tests; thus, as listed in Table 1, the impact velocities for Drop Tests 3 to 5 are 10.21, 10.72 and 10.83 m/s, respectively. These drop-weight tests with higher impact velocities caused more delamination and further damage. Figures 10 to 15 show their corresponding time-histories of impact forces and dynamic strains as well as optical microfractographs.
As depicted in Figs 12 and 13, the quasi-isotropic \([90\, /45\, /0\, /-45\,]_S\) specimen was the weakest and could only resist an impact force of 3.6 KN. During the drop-weight impact test, the specimen was broken completely at the impact site. By observing Figs 14 and 15, the uni-directional \([0\,]_S\) specimen could sustain a higher load of 3.9 KN; but also failed completely at the impact site. On the other hand, when impacted at 10.21 m/s, the \([90\, /0\,]_S\) cross-ply specimen, even though suffered delamination in several layers; did not sever fully, as shown in Fig. 11. The cross-ply specimen sustained an impact force up to 5.8 KN, as indicated in Fig. 10. Thus, one may conclude that the cross-ply configurations: either \([0\, /90\,]_S\) or \([90\, /0\,]_S\) were stronger than other configurations when all other impact parameters being the same.

(B) BALLISTIC IMPACT TESTS

Figures 16 to 18 show the dynamic strain histories, post-impact optical microfractographs and the deformed 22-caliber copper projectile for the three ballistic impact tests described in Table 2. As shown in Fig. 16, no delamination was observed for Ballistic Test 1: \([0\, /90\,]_S\) cross-ply impacted at 120 m/s. Only the top layer of the composite was slightly damaged and the deformation of the projectile was not severe.

For the Ballistic Test 2: \([0\, /90\,]_S\) cross-ply impacted at 298 m/s, the 22-caliber copper projectile penetrated into the ninth layer of the composite. As shown in Fig. 17, higher dynamic strains were produced; more delamination formed; and the projectile deformed more significantly.
Figure 16. Strain histories and the post-mortem specimen and after-impact projectile of Ballistic Test 1: $[0°/90°]_2S$ cross-ply S2 glass-toughened epoxy composite beam impacted at 120 m/s by a 22 caliber copper projectile.

Figure 17. Strain histories and the post-mortem specimen and after-impact projectile of Ballistic Test 2: $[0°/90°]_2S$ cross-ply S2 glass-toughened epoxy composite beam impacted at 298 m/s by a 22 caliber copper projectile.

Figure 18. Strain histories and the post-mortem specimen and after-impact projectile of Ballistic Test 3: $[0°/45°/90°/−45°]_3S$ quasi-isotropic S2 glass-toughened epoxy composite beam impacted at 442 m/s by a 22 caliber copper projectile.

Figure 19. Stress-strain curves characterizing the damage-induced nonlinear anisotropic behaviors of the S2 glass/toughened epoxy. The slopes of these curves represent $E_1$: lamina Young’s modulus along the fiber (longitudinal) direction, $E_2 = E_3$: lamina Young’s moduli along the transverse directions, and $G_{12} = G_{13}$: lamina in-plane shear moduli, respectively. The initial slopes of these curves are: 40, 13 and 10 GPa, respectively. In addition, the density $\rho$ of the composite is: 2 g/cm$^3$. These curves were then entered as User-Defined Material into LS-DYNA, which is a commercially available general-purpose finite element code for analysis of 3-D large deformation dynamic response of structures based on explicit-time integration scheme [11].

DYNAMIC FINITE ELEMENT SIMULATIONS

(A) PROPOSED NONLINEAR ANISOTROPIC MODEL

The afore-mentioned experimental results were used to validate a damage-induced nonlinear anisotropic constitutive law developed previously by this research group [9-10]. Figure 19 shows the stress-strain curves characterizing the damage-induced nonlinear anisotropic behaviors of the S2 glass/toughened epoxy. The slopes of these curves represent $E_1$: lamina Young’s modulus along the fiber (longitudinal) direction, $E_2 = E_3$: lamina Young’s moduli along the transverse directions, and $G_{12} = G_{13}$: lamina in-plane shear moduli, respectively. The initial slopes of these curves are: 40, 13 and 10 GPa, respectively. In addition, the density $\rho$ of the composite is: 2 g/cm$^3$. These curves were then entered as User-Defined Material into LS-DYNA, which is a commercially available general-purpose finite element code for analysis of 3-D large deformation dynamic response of structures based on explicit-time integration scheme [11].

Figure 20 shows the LS-DYNA finite element meshes simulating (a) drop-weight impact onto a $[90°/0°]_{2s}$ cross-ply composite beam, (b) ballistic impact into a $[0°/90°]_{2s}$ cross-ply composite beam.
composite beam and (c) ballistic impact into a $[0/45/90/-45]_{3s}$ quasi-isotropic composite beam. Low velocity drop-weight impact problems were modeled using orthotropic elastic material model (MAT 002) of LS-DYNA, which is valid for describing the elastic-orthotropic behaviors of solids, shells and thick shells without consideration for failure [11]. The Charpy-type straight-line impactor was modeled as a rigid body in the FEM simulations for drop-weight impact tests.

![Figure 19. Nonlinear longitudinal, transverse and in-plane shear stress-strain curves with their slopes representing Young’s and shear moduli.](image)

(a) $E_1$  (b) $E_2 = E_3$  (b) $G_{12} = G_{13}$

On the other hand, ballistic impact problems were modeled by plastic kinematic material (MAT 03) for the 22-caliber copper bullet and the Chang-Chang composite damage model (MAT 22) for the composite. The Chang-Chang model is an orthotropic material where optional brittle failure for composites can be defined [12-13]. Three failure criteria are possible in this model:

1. **Matrix cracking failure:**
   $$\left(\frac{\sigma_2}{S_2}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1$$
   where $\sigma_2$ and $S_2$ are the tensile stress and the associated tensile strength in the transverse direction whereas $\tau_{12}$ and $S_{12}$ are the in-plane shear stress and the associated shear strength between fibers and the matrix. Once this type of failure occurs, the material constants $E_2$ (Young’s modulus in the transverse direction), $G_{12}$ (in-plane shear modulus in the 1-2 plane), $\nu_{12}$ and $\nu_{21}$ (Poisson’s ratios in the 1-2 plane) are set to zero.

2. **Fiber breakage:**
   $$\left(\frac{\sigma_1}{S_1}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1$$
   where $\sigma_1$ and $S_1$ are the tensile stress and the associated tensile strength in the longitudinal direction whereas $\tau_{12}$ and $S_{12}$ are again the in-plane shear stress and the associated shear strength between fibers and the matrix. After fiber breakage, $E_1$ (Young’s modulus in the longitudinal direction), $E_2$, $G_{12}$, $\nu_{12}$ and $\nu_{21}$ are all set to zero.

3. **Compression failure:**
   $$\frac{\sigma_2^2}{2S_{12}} + \left(\frac{C_2}{2S_{12}}\right)^2 - 1 \geq 0$$
   where $C_2$ is the transverse compressive strength. When this type of failure occurs, the material constants $E_2$, $\nu_{12}$ and $\nu_{21}$ are all set to zero.

Note that if the index 2 in any of the above criteria is replaced by index 3, the rules applies also to failures in the transverse 3-direction and the 1-3 plane.

The criterion for delamination between the composite layers is governed by the criterion:
$$\max(0, \sigma_n) + \left(\frac{\sigma_s}{NFLS}\right)^2 \geq 1,$$ where $\sigma_n$ and $\sigma_s$ are normal and shear stresses acting on the layer interface, respectively, while $NFLS$ and $SFLS$ are normal and shear strengths of the layer interface, respectively. This criterion was incorporated into LS-DYNA through CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK.

Additionally, ERODING_SURFACE_TO_SURFACE contact model was used between the impactor and composite. This model allows elements to be eroded when certain failure criteria are met. In this study strain-based failure criterion was used for element erosion; that is, when $\varepsilon_{\text{erosion}} \geq \varepsilon_{\text{erosion}}$, element was eroded and removed from calculation. In summary, the following strength values were used: $S_1=0.988$ GPa, $S_2=S_3=0.044$ GPa, $S_{12}=S_{13}=0.13$ GPa, $C_2=0.285$ GPa, $NFLS\rightarrow\infty$, $SFLS=0.065$ GPa and $\varepsilon_{\text{erosion}}=18\%$.

**B) VERIFICATION OF FEM PREDICTIONS**

In this study FEM predictions with experimental results were compared mainly for impact force and dynamic strain histories.
and post-impact damage patterns. The FEM mesh in Fig. 20(a) was used to simulate Drop Test 2: cross-ply \([90/0]_{24S}\) composite beam impacted at 3.98 m/s by a 5.1 kg hemi-spherical drop-weight tup. Due to symmetry, only a quarter model was used with 256 elements for each layer for the 24-layer specimen. As shown in Fig. 21, the time histories of impact forces and dynamic strains between the experimental records and FEM results are in good agreement. The experimental curves of impact force and strain were smoother than the FEM results and exhibited time delays. This can be explained with the fact that experimental impact force and strain measurements were obtained through a load cell and strain gage amplifiers, where actual readings might have been filtered.

![Figure 21](image1.png)

(a) impact force

(b) dynamic strain

**Figure 21.** Comparison of impact force and dynamic strain histories for \([90/0]_{24S}\) cross-ply S2 glass-toughened epoxy composite beam impacted at 3.98 m/s by a 5.1 kg hemi-spherical drop-weight.

The FEM mesh in Fig. 20(b) was used to simulate Ballistic Tests 1 and 2: \([0/90]_{2S}\) cross-ply composite beam impacted at 120 and 298 m/s, respectively, by a 22-caliber copper projectile. Again, due to symmetry, only a quarter model was used. Because delamination mostly occurs at the interface where fiber orientations of the adjacent layers change and to save computational effort, instead of using 24 layers, only 8 layers with 600 elements for each layer were created. As shown in Fig. 22, the FEM predictions of strains are in good agreement with experimental results. Again perhaps due to the filtering in electronic circuitry, the experimental data were smoother and smaller than the FEM simulations.

![Figure 22](image2.png)

(a) Ballistic Test 1: \(V_0 = 120\) m/s

(b) Ballistic Test 2: \(V_0 = 298\) m/s

**Figure 22.** Comparison of FEM predictions and experimental results of strain histories of Ballistic Tests 1 and 2: \([0/90]_{2S}\) cross-ply composite beam impacted by a 22-caliber copper projectile.

For the 298 m/s case, the damage progression and beam-spanwise normal stress contours during impact are displayed in Fig. 23. Figure 24 shows the FEM prediction of time history of the projectile velocity. The result indicates that the projectile stuck to the composite specimen and the full impact duration completed in about 73 ms when the projectile velocity became zero literally.

The FEM mesh in Fig. 20(c) was used to simulate Ballistic Test 3: \([0/45/90/45]_3\) quasi-isotropic composite beam impacted at 442 m/s by a 22-caliber copper projectile. Full model was needed since the problem does not possess symmetry with respect to geometry and loading. Again only 8 layers with 1875 elements for each layer were chosen to save computational effort. Notice that fine mesh was created for the area where projectile impacted the composite while the remaining part was meshed coarsely. The FEM predictions and experimental results for the Ballistic Test 3 case are compared in Figs 25 and 26 for dynamic strain, damage patterns in both front and side views and the deformation of the projectile.
These two figures indicate that the FEM and experimental results are all in reasonably good agreement.

As shown in Fig. 26(d) the layers at the back tension side of the composite was delaminated extensively during the ballistic impact test. However, as depicted in Fig. 26(c), the FEM simulation showed less delamination. This may be attributed to the fact that during this ballistic impact test, the tip of the projectile was crashed into a mushroom shape, as shown in Fig. 26(f). The continuing penetration of the mushroom head into the back layers of the specimen may have gouged these layers; thus causing very severe damage. On the other hand, in order to maintain numerical stability, elements are eroded in LS-DYNA FEM computation when sufficient failure criteria were met; thus rendering the material elasticity to zero. Hence, the deformed projectile in FEM simulation, as shown in Fig. 26(e) caused less delamination.

As shown in Fig. 26(d) the layers at the back tension side of the composite was delaminated extensively during the ballistic impact test. However, as depicted in Fig. 26(c), the FEM simulation showed less delamination. This may be attributed to the fact that during this ballistic impact test, the tip of the projectile was crashed into a mushroom shape, as shown in Fig. 26(f). The continuing penetration of the mushroom head into the back layers of the specimen may have gouged these layers; thus causing very severe damage. On the other hand, in order to maintain numerical stability, elements are eroded in LS-DYNA FEM computation when sufficient failure criteria were met; thus rendering the material elasticity to zero. Hence, the deformed projectile in FEM simulation, as shown in Fig. 26(e) caused less delamination.

**Figure 23.** Damage progression and beam-spanwise stress counters of FEM simulation for Ballistic Test 2.

**Figure 24.** FEM prediction of projectile velocity for Ballistic Test 2.

**Figure 25.** Comparison of FEM predictions and experimental results of strain histories of Ballistic Test 3: quasi-isotropic composite beam impacted at 442 m/s by a 22-caliber copper projectile.

**Figure 26.** Comparisons of post impact damage patterns and projectile deformations of FEM and experimental results of Ballistic Test 3.

(C) **Ballistic Limit Velocity \( V_{50} \)**

Once the proposed damage-induced nonlinear anisotropic constitutive relation are verified by experimental results, the model can be employed in engineering design. For instance, we can use this model to predict the ballistic limit velocity \( V_{50} \) of armors made of this toughened composite. Here \( V_{50} \) is defined
as the velocity required for a projectile to reliably penetrate (i.e., at least 50%) a piece of armor. Consider composite beams made of \([0^°/90^°_s]_3\), S2 glass-toughened epoxy with three different thicknesses: 6, 13 and 25 mm. As shown in Fig. 27, our LS-DYNA based FEM analyses predict the corresponding ballistic limit velocities as 300, 500 and 950 m/s, respectively. Indeed, the simulations can be used to conclude that for this class of composite beams, the \(V_{50}\) vs thickness relation is almost linear, as illustrated in Fig. 28.

![Image](image_url)

**Figure 27.** FEM estimated ballistic limit velocities \((V_{50})\) for S2 glass/toughened epoxy composite beams with different thicknesses.

![Image](image_url)

**Figure 28.** The almost linear \(V_{50}\) vs thickness relation, as predicted by finite element simulations.

### CONCLUSIONS

S2 glass-toughened epoxy composite beams impacted at drop-weight (i.e., low) and ballistic (i.e., high) velocities were studied experimentally and numerically. Based on this study, the following conclusions can be drawn:

a) The cross-ply configurations: \([0^°/90^°_s]_3\), \([0^°/90^°_s]_3\) or \([90^°/0^°_s]_3\) have higher low impact resistance than the other configurations.

b) The time histories of impact force, dynamic strain, damage pattern and projectile deformation obtained from experiments and FEM simulations are in good agreement.

c) Delamination was the predominant damage mode for low-velocity drop-weight impact tests; whereas in addition to delamination, matrix failure, fiber breakage and projectile deformation were also observed in ballistic impact tests.

d) The ballistic limit velocity \(V_{50}\) depends almost linearly on the thickness of the composite beam.

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