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Experimental and Numerical Investigations on Damage and Delamination in Thick Plain Weave S-2 Glass Composites Under Quasi-Static Punch Shear Loading

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Center for Composite Materials, University of Delaware

Chian-Fong Yen
Material Sciences Corporation

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Bazle A. Gama,* Jia-Run Xiao,* Md. J. Haque,* Chian-Fong Yen,† and John W. Gillespie, Jr.*

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14. ABSTRACT
Quasi-static punch-shear tests are carried out on plain weave S-2 Glass/SC-15 epoxy composite thick laminates with a blunt impactor. Load-unload tests are carried out to capture different levels of damage mechanisms and the corresponding displacements at which they occur. Energies absorbed at different levels of damage are obtained from the load-unload curves. Two different support spans of 2.54-cm (1-in) and 10-cm diameter (4 in) with 22 layers (thickness 1.321 cm) of plain weave glass/epoxy plates are tested quasi-statically to identify interlaminar shear-dominated and tensile-shear combined modes of damage. After each test, the damaged plates are sectioned to visualize the extent of delamination and material damage. The punch shear tests are simulated using LS-DYNA composite material and delamination models. The modeling is carried out using a newly developed damage model, namely MAT 162, which has been incorporated into LS-DYNA. It uses damage mechanics principles for progressive damage and material degradation. The simulated results show excellent agreement with experimental results. It has been found that the dominant damage mechanisms are delamination and fiber breakage due to shear and tension. This study will be useful for characterizing and predicting damage and ballistic limits of thick-woven composites.

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1. Introduction

Thick-section composites are widely used as the backing plate in composite integral armor (CIA). The backing plate plays a crucial role in arresting the projectile by absorbing energy due to various interlaminar and intralaminar damage mechanisms, such as delamination, fiber breakage, and matrix cracking. Therefore, prediction of damage as well as energy absorption and ballistic limits are critical to determining the proper thickness of composite backing plates in CIA. It is assumed that the damage mechanisms in a high-velocity penetrating impact event are the same as those in a punch shear test (PST). The degree of damage and time-scale of occurrence may be different; however, the displacement level in which each damage mechanism initiates has been considered comparable for both static and dynamic events (*1*). The general approach adopted by researchers for predicting the damage in a ballistic event is to first conduct a PST to characterize the material and damage and the displacement levels at which they occur. In the next step, the impact event is simulated based on information from static tests to predict the residual velocities of projectiles and therefore, the ballistic limit.

Potti and Sun (*2*) characterized punch shear testing by simulating the load deflection curve up to the plug formation for carbon/epoxy quasi-isotropic composites. With their approach, they successfully predicted residual velocities of projectiles. Jeng et al. (*3*) characterized material damage for woven graphite-epoxy plates using a similar technique to Sun and Potti (*1*). For glass epoxy woven composites the sequence of damage mechanisms is different from quasi-isotropic carbon epoxy composites and hence, the load-deflection response is different as well. No other approaches for modeling damage during punch-shear testing have been found in the literature. Additional studies on punch shear experiments can be found in the published research (*4–6*).

Significant work has been done on modeling damage and delamination due to low-velocity impacts. Low-velocity impact tests are intended to characterize composites for nonpenetrating static and dynamic applications. The major damage mechanisms involved are delamination, fiber tensile failure, and matrix cracking. Williams and Vaziri (*7*) used damage mechanics principles along with matrix and fiber failure criteria to model damage for low-velocity impacts, in which they developed material subroutines for LS-DYNA. Load-deflection curves and the damage patterns compared well with experimental results. Yen and Caiazzo (*8*) implemented a damage model (MAT 162) by generalizing the layer failure model that exists in LS-DYNA (MAT 161). The damage mechanics approach (*9*) incorporates progressive damage and softening behavior after damage initiation. This model is implemented for single integration point brick elements only. Recent works for modeling delamination can be found in Borg et al. (*10*) and Zou et al. (*11*).

Most of the investigations previously mentioned considered thin composite plates. In the present report, the material and damage characterization involved in PSTs and simulations using LS-DYNA will be presented. In the present investigation, thick plates are tested and modeled. Therefore, delamination as well as damage must be simulated accurately to model the static or dynamic penetration problems. The modeling is carried out using two different approaches: (1) delamination and material damage are both modeled using MAT 162, and (2) MAT 162 is used for material damage only, while the delamination is modeled using the TIE-BREAK interface with fracture energy-based criterion for crack initiation, propagation, and arrest. The simulated results show reasonable agreement with the experimental results. It was found that the dominant damage mechanisms are delamination and fiber breakage due to shear and tension. This study will be useful for characterizing and predicting damage and ballistic limits of thick-woven composites.

2. Experimental Investigation and Observations

Quasi-static PST is conducted using a custom-made fixture. A PST fixture consists of a square support plate (50.8 mm thick) with a circular hole at the center, a relatively thin cover plate (12.7 mm thick) with a central hole similar to the support plate, and a cylindrical punch. A rectangular support is also used in addition to the support plate. Two sets of support plates and cover plates with a support span (SS) diameter (D_s) of 25.4 mm and 101.6 mm are fabricated. Composite plate specimens can be bolted on the PST fixture between the support plate and the cover plate. A cylindrical punch of diameter (D_P) 12.7 mm with a flat tip, is used. The combination of one punch and two support spans provides spans to punch ratios of 2.0 and 8.0 ($SPR = D_S/D_P$). An Instron 1332 loading frame with a 222-kN (50-kips) load cell is used in the quasi-static tests. Displacement-controlled tests are performed at a cross-head displacement rate of 2.54 mm/min. The load and cross-head displacement data are acquired using the Instron Series IX software.

Punch shear specimens of nominal dimension 17.8 × 17.8 cm are machined using a wet saw; eight holes are core drilled for bolting the specimens in the fixture. Mechanical properties of composites used in this study (fabricated from two-dimensional [2-D] woven fabric and SC15 resin) are provided in table 1 (*12*). Six different composite laminates are fabricated using 1, 2, 4, 6, 11, and 22 layers of plain weave S-2 Glass[*] fabric and are designated by 1L, 2L, 4L, 6L, 11L, and 22L, respectively. Specimens made from these laminates are tested under punch shear loading with *SPR* = 2.0 and 8.0, as shown in figure 1.

[*] S-2 Glass is a registered trademark of Owens Corning.

Table 1. Material properties of plain weave S-2 Glass/SC15 Composite laminates used in the computation.

MID	RO, kg/m^3	EA, GPa	EB, GPa	EC, GPa	PRBA	PRCA	PRCB
1	1.85E + 03	27.5	27.5	11.8	0.11	0.18	0.18
GAB, GPa	GBC, GPa	GCA, GPa	AOPT	—	—	—	—
2.9	2.14	2.14	2	—	—	—	—
XP	YP	ZP	A1	A2	A3	—	—
0	0	0	1	0	0	—	—
V1	V2	V3	D1	D2	D3	beta	—
0	0	0	0	1	0	0	—
SXT, MPa	SXC, MPa	SYT, MPa	SYC, MPa	SZT, MPa	SFC, MPa	SFS, MPa	SXY, MPa
604	291	604	291	472	800	500	58
SYZ, MPa	SZX, MPa	SFFC	AMODEL	PHIC	E_LIMT	S_DELM	—
58	58	0.3	2	20	1.3	1.5	—
OMGMAX	ECRSH	EEXPN	CERATE1	AM1	—	—	—
0.999	0.1	2	0	4	—	—	—
AM2	AM3	AM4	CERATE2	CERATE3	CERATE4	—	—
4	4	4	0	0	0	—	—

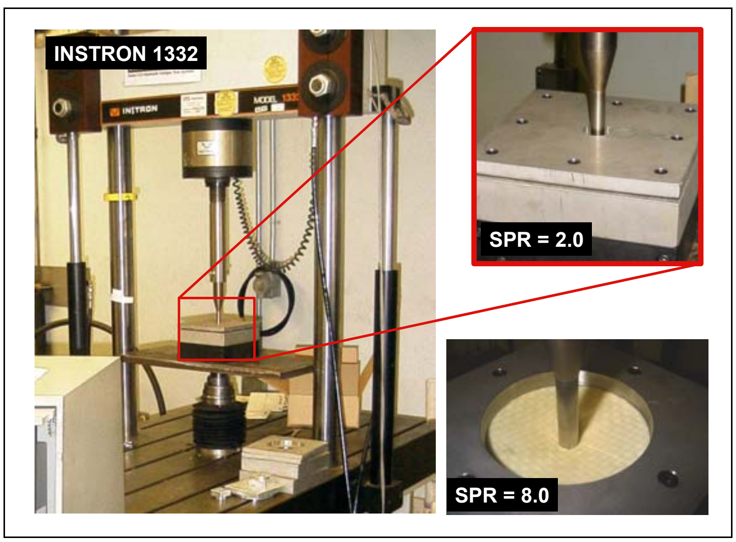


Figure 1. Experimental setup for quasi-static punch shear experiment.

In figure 2, the load displacement curves clearly show a bilinear behavior up to a maximum load for thick laminates and a linear behavior for thin laminates. A nondimensional parameter, $D_P D_S / H_C^2$, is useful in defining thin and thick laminates, where H_C is the thickness of composite laminates. Under quasi-static punch shear loading, a thin laminate is defined when $D_P D_S / H_C^2 > 100$, and a thick laminate is defined when $D_P D_S / H_C^2 < 100$. The difference between a thin and thick laminate can be identified by their load displacement behavior. Thin laminates show predominantly linear behavior up to failure (e.g., 1L and 2L in case of $SPR = 2.0$, and 1L, 2L, 4L, and 6L in case of $SPR = 8.0$); in this case, a thin laminate

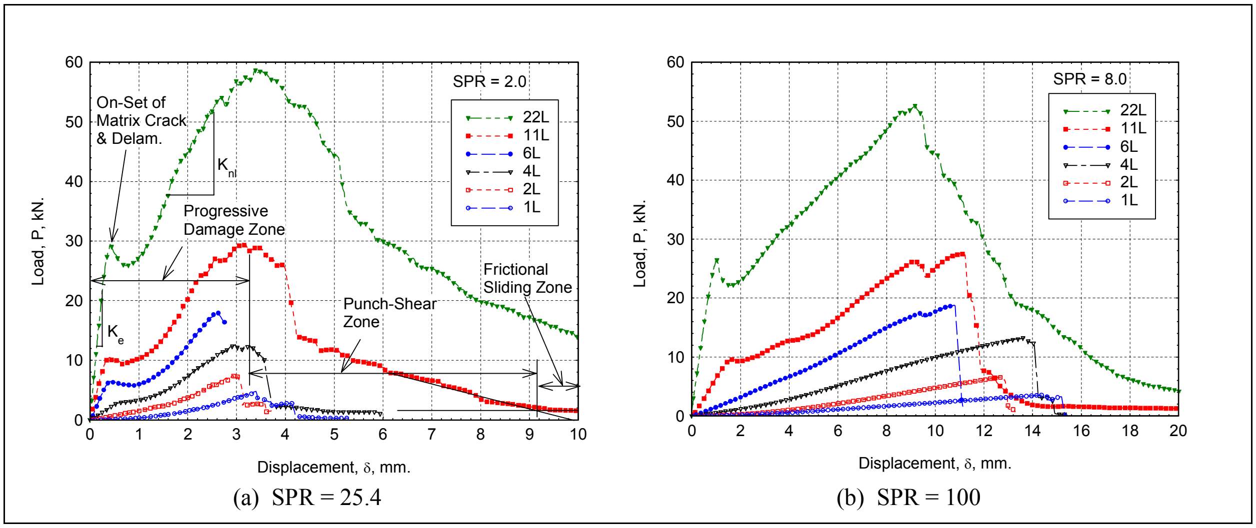


Figure 2. Punch shear behavior of 2-D baseline S-2 Glass/SC15 Composite laminates.

undergoes membrane tension before local punch shear. On the other hand, thick laminates show a linear behavior up to a point where the local matrix cracks, followed by the initiation of delamination through the thickness of the laminate that appears as a drop in load-deflection curve.

The initial stiffness of the specimen, K_e, can be defined by the initial slope of the load-displacement curve. Further loading up to the maximum load exhibits non-linear softening and corresponds to the progressive matrix cracking and propagation of delamination in the laminate (i.e., progressive damage). The stiffness in the progressive damage zone, K_{nl}, can be determined from the slope in the bilinear portion of the load-displacement curve. Local shear and crush of fibers accompanied by fiber bending and the progressive drop of the load in the punch shear zone represents tensile fracture during the complete punch shear process. The plateau level of the load corresponds to the frictional sliding of the punch through the laminate.

To model the punch shear behavior successfully, it is necessary to understand the evolution of the damage during the tests and how they are simulated in the material models. The sequence of damage modes are as follows: (1) delamination initiation, (2) delamination propagation, (3) fiber shear failure, and (4) fiber tensile failure. Delamination initiates due to high transverse shear localized around the punch, and propagates due to transverse shear loading. A drop in the load-deflection plot is observed. During delamination propagation, the plate carries the load and the contact force increases, but with a lower slope in the load-displacement curve that indicates a loss of flexural and shear stiffness due to delamination. After the delamination has extended to the full length of the plate and the plate has undergone large displacement, fiber failures begin to occur. This is characterized by a continuous drop in the load-displacement curve.

Due to the stress stiffening effect arising from large deflection, the bending deformation reduces, and the localized transverse shear stress begins to increase. At this time, either pure fiber-shear or combined fiber tensile/shear failure may occur. The localized transverse shear stress is highest just beneath and around the punch and decreases across the thickness. Also, the plate has a large tensile stress due to bending and stretching across the thickness. Both of the 25.4 cm and 100-mm-diameter plates showed similar behavior. Tensile failure of fibers can occur at the bottom of most layers during the time when the punch is progressing, and the upper layers have shear failure. For the 25.4-mm support span (figure 2a), the delamination initiated at a punch displacement of 0.75 mm, the start of the fiber shear failure ~3.81 mm, and the start of fiber tensile failure at 5.84 mm; and at 16 mm, the punch is about to exit. For the 100-mm support span (figure 2b), these figures are 1.27, 8.9, 12.7, and exit at 20 mm. As expected, the 100-mm span plate deforms more than the 25.4-mm span plate before the fiber shear failure initiates due to its lower bending rigidity than the 25.4-mm plate.

3. Numerical Modeling

Numerical modeling is accomplished using LS-DYNA with the newly implemented material model—MAT 162 and contact options. The material model is based on the progressive failure principle of Hashin (*13*) and the damage mechanics of Matzenmiller et al. (*9*) that incorporate features for controlling strain softening after failure. MAT 162 also accounts for strain rate effects in tension and shear. The equations for various failure modes are as follows:

$$\left(\frac{E_a.\varepsilon_a}{S_{AT}}\right)^2+\left(\frac{G_{ac}.\varepsilon_{ac}}{S_{AFS}}\right)^2-r_1^{\,2}=0 \text{ (fiber tensile/shear failure modes in a-direction),} \quad (1)$$

and

$$\left(\frac{E_b.\varepsilon_b}{S_{BT}}\right)^2+\left(\frac{G_{bc}.\varepsilon_{bc}}{S_{BFS}}\right)^2-r_2^{\,2}=0 \text{ (fiber tensile/shear failure modes in b-direction),} \quad (2)$$

where for the fabric model, *a*, *b*, and *c* denote the in-plane fill, in-plane warp, and out-of-plane directions, respectively. S_{AT} and S_{BT} are tensile strengths in the fill and warp directions, S_{AFS} and S_{BFS} are fiber shear failure strengths in a and b directions, ε_a and ε_b are tensile strains in a and b directions; ε_{ac} and ε_{bc} are shear strains in a-c and b-c planes, and r_1 and r_2 are damage thresholds.

$$\left(\frac{E_c.\varepsilon_c}{S_{FC}}\right)^2-r_3^{\,2}=0 \text{ (fiber crush failure mode),} \quad (3)$$

in which S_{FC} is fiber crush strength.

Delamination failure mode (through-thickness matrix failure) is governed by

$$S^2\left\{\left(\frac{E_c.\varepsilon_c}{S_{CT}}\right)^2+\left(\frac{G_{bc}.\varepsilon_{bc}}{S_{BC0}+S_{SR}}\right)^2+\left(\frac{G_{CA}.\varepsilon_{ca}}{S_{CA0}+S_{SR}}\right)^2\right\}-r_4^{\ 2}=0\,, \tag{4}$$

where S_{CT} is through-thickness tensile strength, and S_{BCO} and S_{CAO} are interlaminar shear strengths in a-c and b-c planes, respectively. *S* is the factor that takes into account the stress concentration and allows growth of delamination. The interlaminar shear strengths are considered to increase through-thickness compressive stress and decrease due to through-thickness tensile stress, according to the Mohr-Columb theory, which is given by

$$S_{SR}=-\varepsilon_c.E_c\tan\phi\,, \tag{5}$$

where ϕ is equivalent to angle for internal friction and ε_c equals the through-thickness strain, which is positive when tensile.

The property degradation model (Matzenmiller et al. [*9*]):

$$\varpi_i=1-e^{\frac{1}{m}(1-r_j^{\ m})}\,,\quad r_j\geq 1 \tag{6}$$

and

$$E_i=(1-\varpi_i)E_{i0}\,,\ G_i=(1-\varpi_i)G_{i0}\,, \tag{7}$$

where r_j = damage threshold, ϖ_i= damage variable, and *m* = strain softening parameter.

If the r_j values are kept constant and equal to 1.0, the model simplifies to MAT 161, which does not use the damage mechanics theory. However, in MAT 162, the damage threshold r_j is initially set to equal 1.0 to represent initial elastic deformations, but it increases as damage accumulates analogous to plasticity models. The modulii are degraded as the damage increases, according to equations 9 and 10. The damage variable ϖ varies from 0 to 1.0 as the r_j varies from 1 to infinity, according to the distribution of equation 6. The softening parameter *m* is varied to represent post-failure behavior.

4. Delamination Using MAT 162

When modeling delamination using MAT 162, the model does not require a physical interface, but needs a definition for the interface element layer. Once the matrix failure given by equation 4 is satisfied in any element in the predefined layer, the elements adjacent to it are identified for delamination growth. The subsequent stress components of those elements are multiplied by a user-defined factor—*S*—to account for stress concentration. The initial values of *S* are unity for all elements. *The S values are mesh sensitive*. After the delamination failure of an element has occurred, the in-plane load carrying capacity within the element is assumed to be elastic (no in-plane damage). The load carrying behavior in through the thickness direction is assumed to depend on the opening or closing of the matrix damage surface. For the tensile mode, $\varepsilon_z > 0$, the through-thickness stress components are softened and reduced to zero. For compressive mode, $\varepsilon_z < 0$, the damaged surface is considered to be closed, and ε_z is assumed to be elastic. In the mean time, the material may fail in fiber shear/tension given by equation 1 or 2. As the damage grows, the through-thickness tensile and shear modulii are reduced according to equation 7.

5. Delamination Using TIE-BREAK Interface

Delamination can also be modeled using the TIE-BREAK interface in LS-DYNA along with MAT 162. TIE-BREAK contact option 6 is used to model delamination by defining the physical interfaces. This option needs a crack-opening displacement and the critical failure stress to be specified that corresponds to the fracture energy in either mode I or mode II. The delamination propagates when the distance between the common nodes in the interface reaches a critical magnitude corresponding to the material fracture energy. This represents a more realistic way of modeling delamination propagation than the stress-based failure criteria. It should be noted that this option does not currently account for mixed-mode delamination. However, the delamination in the quasi-static punch shear test is predominantly mode II. The relationship between critical crack length and critical stress and fracture energy is presented in figure 3.

6. Element Erosion

The failed element is eroded to avoid increased solution time caused by thinning of the element or even generating a negative volume due to excessive deformations. A failed element is eroded if any of the following conditions are satisfied: (1) after fiber tensile failure, the tensile strain is greater than a specified value, (2) if compressive relative volume strain (ratio of current volume to initial volume) in a failed element is smaller than a specified value (e.g., 0.01), and (3) if tensile volume strain in a failed element is greater than a specified value (e.g., 10).

The goal of the punch shear simulation is to match the overall load-deflection curve and therefore enable the partioning of absorbed energy for each damage mode to be calculated. Due to the lack of a comprehensive materials database, this approach has required some tuning of the material and fracture properties of the material models used. The damage modes are related to the experimental load-unload tests that identifies the displacement associated with the initiation of various damage modes. Once the material is characterized through punch-shear simulation,

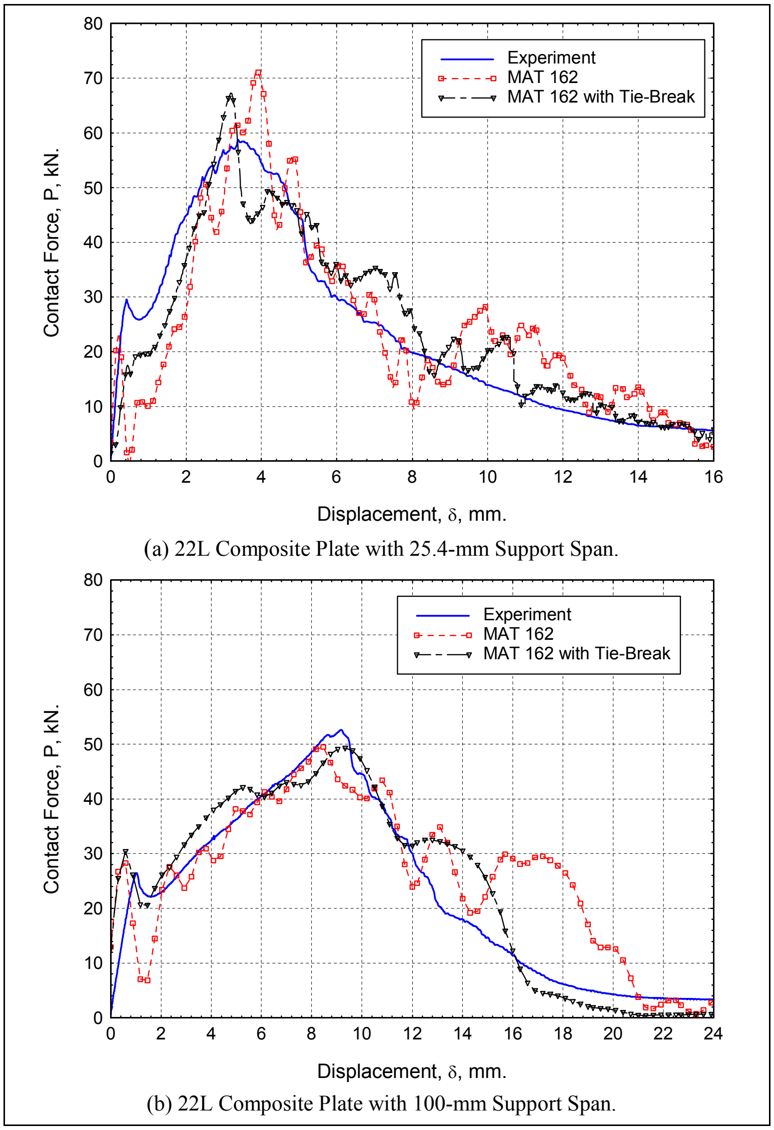
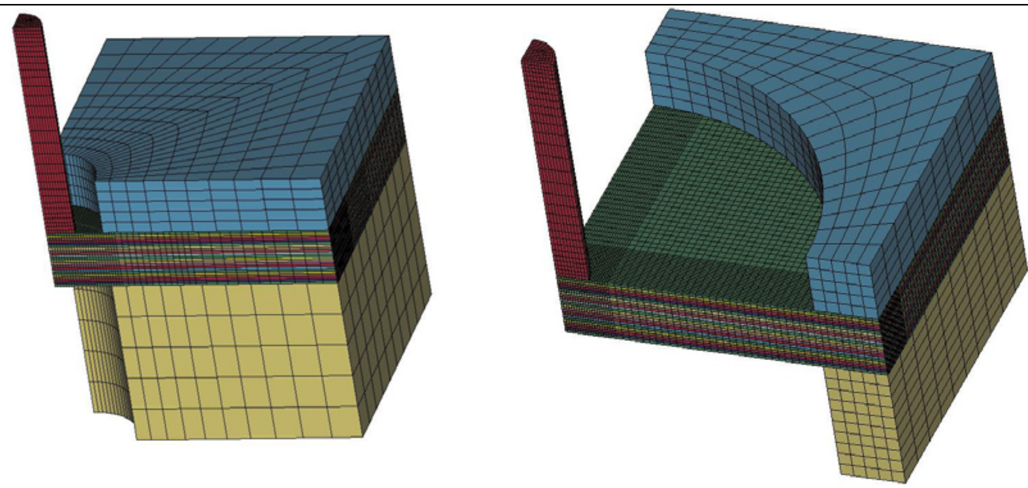


Figure 3. Comparison of contact force-displacement curves.

they can be used for low- and high-velocity impact simulations with the proper incorporation of high strain rate effects.

7. Results and Discussions

The test circular plates (22 layers of woven glass/SC-15 epoxy) are simulated using solid elements (single-point integration) in LS-DYNA. The blunt steel punch (12.7 diameter and 50.8 mm long) is modeled as elastic material, whereas the solid supports at the top and bottom with circular cutouts are modeled using rigid elements. The plates are modeled with 22 layers of elements in the thickness direction and a fine mesh around the punch. Simple contact has been defined between the upper (lower) supports and the plate. Eroding single surface contact has been defined between the steel punch and the composite plate. Figure 4 shows the meshed models for plates with 25.4- and 100-mm-diameter support span using quarter-plane symmetry.



(a) 25.4-mm Support Span

(b) 100-mm Support Span

Figure 4. Quarter-plate model for 25.4- and 100-mm span punch shear tests.

For modeling the plate delamination using TIE-BREAK interface, physical interfaces were defined at every two layers through the thickness. Thus, there are 10 interfaces for probable delamination. For modeling using MAT 162, the interface element layers are defined by providing different orientation angles at specified interface layers (interface locations are kept the same for models with and without TIE-BREAK interface). The material properties used in this simulation are presented in table 1. Boundary conditions are defined with simple contact between the upper and lower supports to the plate with ends unrestrained.

Figures 4a and 4b show the comparisons of contact force-displacement curves for the 25.4- and 100-mm support span plates. The simulation has been carried out with MAT 162 and MAT 162 with TIE-BREAK. The overall response is captured reasonably well, but certain regions show some different behaviors between models and experiment. Oscillations in the simulated results are mainly due to erosion of failed elements.

From the experimental results for the 25.4-mm span plate, delamination initiated with a 1.27-mm displacement of the punch. Penetration of the punch was initiated between displacements of 1.27–3.39 mm. As shown in figure 4a, the simulation at this region does not capture the experimental measurement in the case of MAT 162, which arises from the initial contact instability. A sudden drop occurred once the delamination initiated. A similar phenomenon is also observed in the simulation of a 100-mm span plate as well, and is shown in figure 4b. However, improved results can be achieved for both cases as shown in figure 4 by using the

TIE-BREAK interface for delamination, which can be attributed to the presence of physical delamination planes. It is believed that the delamination computation alone in MAT 162 is not enough to capture the physical phenomenon that occurs during delamination; thus, the use of TIE-BREAK interfaces may be useful in ballistic modeling. However, the minimum number of TIE-BREAK planes is yet to be determined.

A displacement of up to 5.17 mm in the 25.4-mm span plate and a displacement up to 8.89 mm in the 100-mm span plate correspond to their ultimate load capacities, where the fiber fails due to high local transverse shear around the periphery of the punch; after that, the fibers fail due to the tensile stress developed due to bending and stretching. The simulation shows fiber failure mainly due to punch shear, but also due to the initiation of tensile failure at the bottom of the plate. Beyond these two conditions, extensive fiber tensile failure is observed along with the shear failure, followed by plug forming and pushing out. The simulated post-failure using both MAT 162 and MAT 162 with the TIE-BREAK interface agree well with the experimental results for both plates.

8. Conclusions

Experimental tests were conducted on plain weave S-2 Glass/SC15 epoxy composite thick-section laminates under quasi-static punch shear loading. Experimental observations and results were reported and compared with the simulations using LS-DYNA, with MAT 162 as a material model. The TIE-BREAK interface option for modeling delamination was also examined. Reasonable agreement between experimental and simulated results were obtained.

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