Modelling Low Velocity Impact on Structural Composites

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Abstract. Insertion of composite materials into next generation vehicles requires an understanding of their response over the range of relevant loading conditions encountered in the field. This paper focuses on modelling the low velocity, high energy impact on structural composite materials. An experimental procedure, using the four quadrant impact methodology, is presented to characterize composite material response and damage during these events. A model is developed and verified (within 9% for peak force and peak deflection) to predict the composite response to low velocity, high energy events. The model is then exercised to gain a deeper understanding about how mechanical and damage properties influence the structural response of the composite. The model was most sensitive to delamination failure stress, which changed the damage area by a factor of 8 over the range of values examined. Through investigating the effect of boundary conditions, a 67% increase in peak force was found by switching from simply supported to clamped. This work demonstrates a first level analysis and model to predict the composite response to low velocity, high energy loading conditions.

1. Introduction and motivation
A majority of ground vehicles use metal because of its durability, isotropic nature, and ample amounts of data for engineering design [1]. In theory, structural composite materials offer opportunities for improvement over incumbent metal materials [2]. In addition to being lighter weight (i.e., lower density), composites have a large design space which has yet to be fully exploited for vehicle structures [3]. Durability is an issue preventing the widespread use of composite materials in ground vehicle applications [4].

Insertion of composite material into vehicles requires them to be structural and resistant to high impact loads [5]. The response of composite materials to low velocity impacts is an active area of experimentally focused research [6-8]. Modelling the response of composites under the spectrum of loading conditions encountered in the field is necessary for the design of structural composites, but presents a number of challenges [9]. High fidelity composite models also streamline the insertion of new resins into fielded systems as providing model-informed solutions accelerates the design process.

This work focuses on modelling the low velocity, high energy impact on structural composites. An experimental procedure is presented for examining the deformation and damage of thick section composites subjected to low velocity, high energy loading conditions. A finite element based model is developed to accurately predict the composite response during this loading event. The model is verified through comparing the peak deflection, peak load, and damage area with the experimental results. It is then exercised to understand the influence of mechanical properties and damage parameters on
composite performance, giving insight into how changing resin dominated properties would influence trends in panel level response. The model is then used to gain information on how changing boundary conditions would affect the panel response, allowing the exploration of selected boundary conditions without having to create a new experimental setup. The objective of this work is to provide a first level analysis to predict the structural response of and delamination in thick section composites as part of a materials-by-design strategy as summarized in Figure 1.

2. Experimental Methodology

2.1. Impact samples

Composite samples are manufactured for impact testing using an S2-glass fabric infused with a rubber toughened epoxy to a target thickness of 13-mm. A 2-D woven roving fabric of AGY S2-glass fibres [10] with an areal density of 744 g/m2 (24 oz./yd2) was stacked in a quasi-isotropic ([((45/0)5/45]S) lay-up of 22 layers and infused with the rubber toughened, epoxy resin system SC-15 manufactured by Applied Poleramic, Inc. [11]. The infusion was performed using a standard vacuum assisted resin transfer molding (VARTM) procedure with a vacuum pressure of 23-29 mm/Hg and cured in an oven at 60 °C until gelled, then post-cured at 120 °C for at least 4 hours. Four 40.6-cm x 40.6-cm samples were waterjet from a large 89-cm square parent panel to a tolerance of ±0.4-mm. The finished impact samples of S2/SC-15 composites with clamped boundary conditions are listed in Table 1.

Table 1. Thickness, weight, and density of S2/SC-15 impact samples.

| S2/SC-15 | Clamped |
|----------|---------|
| Thickness (cm) | 1.509 ± 0.01 |
| Weight (g) | 4370 ± 50.9 |
| Density (g/cm³) | 1.798 ± 0.012 |
| Areal Density (kg/m²) | 26.6± 0.18 |

2.2. Four Quadrant Impact Methodology

The four quadrant impact (FQI) methodology found in [1, 2, 4, 12] was used since no suitable ASTM standard is available for characterizing the durability of thick-section composite laminates under multiple low velocity impacts (LVI). The FQI methodology calls for four successive impacts into a
single panel as illustrated in Figure 2, allowing for both a quantitative and qualitative assessment of the durability and delamination resistance of the composite laminate [2]. An impact panel was cut to a dimension of 40.6-cm by 40.6-cm to ensure a proper fit into the FQI fixture for multiple LVI characterization. The dimensions of the impact samples and FQI fixture table were constrained by the drop tower configuration (clearance between vertical drop rails) [2]. The FQI fixture table allowed for impact samples to be clamped at a prescribed clamping pressure (distributed among 16 bolts with a pneumatic torque wrench) or accommodated a steel insert that converted the fixture to a simply-supported boundary condition for impact as shown in Figure 3.

A Dynatup 8110 drop-tower equipped with a strain-gage based, 222.4 kN load cell TUP and a 5.0 cm diameter hemispherical impactor is used for each impact. Force-time data during each impact event.

![Figure 2](image_url)

**Figure 2.** Illustration of impact panel face showing top plate picture frame overlay (grayed portion) and specific location for each of the four successive impact events.

![Figure 3](image_url)

**Figure 3.** Section of FQI fixture with installed sample (left) and arrow indicating point of impact. Detailed cross-section (right) of sample being supported by simply-supported insert adapter. To achieve a clamped boundary condition for the sample, simply remove the adapter plate, steel rod supports, and rubber clearance strip and apply a uniform clamping torque to all 16 bolts.
was recorded for a 25 ms duration at a sampling rate of 270 kHz, and post-processed according to guidelines outlined in ASTM D7136 [13]. The mass and height of the impactor used in this investigation are 227.4 kg and 96 cm, respectively, yielding impact energy of approximately 2.14 kJ and an impact velocity of 4.34 m/s. The kinematic impactor displacement is calculated from the force-time trace for each impact by integrating twice over Newton’s kinematic equations. The kinematic displacement is paired with the measured force to yield a force-deflection profile for each impact event with the implied assumption panel displacements are taken to be equivalent to impactor displacements. In the FQI methodology, impacts are performed in one location or “quadrant” at a time to allow for the non-destructive evaluation of the panel in between impact events.

2.3. Impact Damage Evolution
An important aspect of the FQI methodology is the assessment of damage within the panel between each of the successive impact events using a non-destructive method. A custom-built water tank and gantry system was used to capture ultrasonic c-scans of the panels prior to the first impact and after each of the four successive impact events. Using sectioning and microscopy to examine the cross-sectional views at various locations within the damaged panels, it is confirmed that the c-scans were detecting either one of two types of damage: (1) matrix cracking in the yarns under the impact location or (2) delamination between plies away from the impact location. An example of C-scan images showing the cumulative damage after each of the four impacts is shown in Figure 4.

![Figure 4. C-scans of panel damage area for anvil impacts 1-4](image)

3. Numerical model
A finite element model is developed in LS-DYNA to predict the deformation and delamination of the composite during impact. The explicit dynamics solid mechanics model includes the composite panel, supports, top (clamping) plate, and anvils as shown in Figure 5.

![Figure 5. Initial low velocity impact model configuration](image)
3.1. Model setup and boundary conditions
Initially, the composite panel is between the top plate and supports, with a 1-mm gap between each anvil and the composite plate to ensure no fictitious initial penetrations occur. The anvil impact locations are the same as in the experimental setup (although the model uses four anvils, one at each impact location, for simplicity).

The supports have a fixed location boundary condition in all directions. The first anvil has an initial velocity of 4.48 m/s in the vertical direction (z-direction in Figure 5), while the others begin at rest. The remaining anvils are then given a velocity of 4.48 m/s at 0.03 second intervals (the impact and rebound event for each anvil is completed in less than 0.03 seconds). Multiple boundary conditions are explored for the top plate, with its location being fixed in all directions as the baseline case. The friction coefficient between the panel and tooling is set to 0.3.

To represent delamination damage in the panel, individual layers within the composite panel are held together using a surface to surface tiebreak criterion. The baseline failure stress and distance used in this work are 22 MPa and 1.0 mm, respectively. The nodes initially in contact at the interface move together prior to the failure stress being reached, after which the damage is a linear function of the distance between nodes until it reaches the failure distance and full interfacial failure occurs. Contact between the tooling and composite panel is described using the built-in automatic surface to surface contact algorithm in LS-DYNA.

All tooling (top plate, supports, and anvils) is modelled as rigid bodies. The composite panel is described using an orthotropic composite material model. Although there is an option for including composite damage, the failure parameters are selected such that the delamination is the only failure mode. This is done to eliminate the investment required to characterize unnecessary parameters and ensure the model and experimental failure mechanisms align. The composite properties input into the model are given in Table 2.

Table 2. Composite panel properties input into the model (moduli units are GPa) [9, 14]

| E_x  | E_y  | E_z  | ν_yx | ν_zx | ν_xz | G_yx | G_zx | G_xz |
|------|------|------|------|------|------|------|------|------|
| 27.5 | 27.5 | 27.5 | 0.11 | 0.18 | 0.18 | 7.67 | 4.28 | 4.28 |

3.2. Mesh refinement study
A mesh refinement study is performed to ensure numerical results converge as the number of elements increase. The anvil load-displacement curve from the first impact is used as a characteristic output parameter for the model. Figure 6 shows the force-displacement response of the panel under this loading condition for meshes with a variety of refined element sizes (closer to the anvils on the panel), coarse element sizes (further from the anvils), and a number of elements through the panel thickness. The convergence of results shows the solution is mesh independent with at least 114k elements. The 205k element model is selected for this work moving forward because it represents the converged solution but does not add the extra computational time required for meshes with a larger number of elements. For this mesh, the solid elements in the panel near the anvils are 2.00 mm squares (in the xy-plane), the elements in areas with minimal deformation are 6.00 mm squares (in the xy-plane), and all elements are 1.05 mm thick (z-direction). A similar study is performed for the number of tiebreak layers through the thickness of the panel. It is found that increasing the number of layers beyond three does not influence the results; therefore three tiebreak layers will be used for this work.
4. Results

4.1. Model verification
Key outputs from the numerical model include peak anvil-panel contact force, peak deflection of the panel, and the delamination area. The top plate is fixed in the x- and y-directions and a 325 kN force (vertical, z-direction) is applied. Such a high force is required to ensure no movement of the top plate during the impact event. The peak force and displacement output from the model are 151 kN and 30.5 mm, respectively, while the experimental results yield values of 150 kN and 28 mm. To explore damage area predictions, only the first anvil hit is used because subsequent impacts have overlapping damage areas. The model acceptably predicts the delamination between the glass layers in the composite, as depicted in Figure 7, with the model results showing the middle tiebreak layer. This was chosen because the tiebreak layers closer to the panel surface exhibited less delamination than the middle layer and the experimental measurement of delamination is cumulative through the thickness. The shape of the damage area matches well, with the only noticeable differences residing under the top plate. The

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Figure 6. Anvil load-displacement curve for meshes with a range of element sizes

Figure 7. Damage area after the first anvil impact determined (a) experimentally and (b) with the numerical model
4.2. Influence of laminate stiffness

A parametric study was conducted to determine which mechanical properties have the most influence on the model, with results tabulated in Table 3. The fiber direction stiffness did not have a significant influence on the peak force or displacement of the panel because there is minimal fiber extension during the event. Panel in-plane shear stiffness (xy-plane) played an important role in the peak anvil force and displacement. This is because in-plane shear is the primary elastic deformation mechanism of the thin panel. New resin formulations which exhibit stiffer in-plane shear responses would be expected to deflect less during this type of an impact event. The influence of out-of-plane (i.e., interlaminar) shear modulus was not significant for this geometry because the panel was thin enough that the out-of-plane shear deformation was minimal. If the thickness was increased substantially, it is expected that the out-of-plane shear stiffness would become more important. The Poisson ratio had a negligible effect on both force and displacement.

| Table 3. Composite panel properties input into the model (moduli units are GPa) [9, 14] |
|-----------------------------------------------|-----------------------------------------------|
|                  | Peak Displacement |                                    | Peak Force |                                    |
|                  | 50%  | Baseline | 150% | 50%  | Baseline | 150% |
| $E_{1}$, $E_{2}$ | 1.01 | 1.00    | 0.98 | 0.99 | 1.00    | 1.02 |
| $E_{3}$          | 1.01 | 1.00    | 0.99 | 0.99 | 1.00    | 0.99 |
| $G_{12}$         | 1.07 | 1.00    | 0.96 | 0.91 | 1.00    | 1.06 |
| $G_{23}$, $G_{31}$ | 1.02 | 1.00    | 0.99 | 1.01 | 1.00    | 1.01 |

4.3. Sensitivity to delamination parameters

With delamination being the primary damage mechanism, it is important to understand how the tiebreak delamination parameters affect model predictions. The parameters governing the tiebreak are the failure stress and complete failure distance. A fixed location boundary condition was applied to the top plate because it eliminates the additional characterization (i.e., clamp pressure or displacement) required for the clamped boundary condition.

The tiebreak failure stress (delamination stress) had a substantial influence on the damage area, as shown in Figure 8. Increasing the failure stress greatly decreased the delamination area, and doubling the failure stress reduced the damage area to a small area under the anvil. The peak deformation only changed about 8% over the range of failure stresses and the peak force saw a negligible difference. This

![Figure 8](image-url)

**Figure 8.** Damage area predicted for a delamination stress of (a) 58 MPa, (b) 29 MPa, (c) 22 MPa, and (d) 15 MPa
is a critical property to optimize when designing new resin formulations for composite structures expected to experience impact events.

The influence of the complete failure distance is important to understand from a modeling standpoint, but it does not clearly align with a specific measurable mechanical property. The critical distance for complete failure was varied from 0.1 mm to 2.0 mm and had a profound influence on the delamination area, described in Figure 9. A smaller failure distance parameter causes delamination to occur at an accelerated rate because there is a larger stress concentration due to the force being distributed over a smaller area, and which results in faster complete delamination. The peak displacement was sensitive (21% change over the range of distances studied) to the failure distance parameter, but the peak force was not.

4.4. Influence of boundary conditions
The effect of switching between an applied pressure and fixed location boundary condition on the top plate can be examined by comparing Figure 7-b and Figure 8-c. It is noted that the fixed location boundary condition resulted in the panel experiencing less damage because the added constraint from the pressure boundary condition prevents panel deformation.

Removing the top plate creates an even more simplified boundary condition by eliminating contact between the composite panel and top plate from the low velocity impact event. The model was exercised without a top plate and then compared to the model with a perfect clamp boundary condition (includes top plate and the panel sides cannot slide inwards). The model without a top plate experienced much lower peak forces but higher peak deformations, as seen in Figure 10. This is because removing the top
plate constraint allows the panel to bend more, which drives down the peak force by spreading the energy absorption over a longer time.

5. Conclusions
An experimental procedure was presented to characterize the response of structural composite materials under low velocity, high energy loading conditions. A model was developed and verified to be capable of predicting the composite deformation and delamination during these events. The model gave insight into how boundary conditions affect composite response, with a clamped boundary condition resulting in a much higher peak load than the simply supported boundary condition. The model was exercised to understand the influence of mechanical and damage parameters on structural performance. It was found that in-plane shear modulus was the most critical elastic property affecting the composite response. The delamination failure stress had a profound influence on the damage area in low velocity, high energy impact events. The trends observed in this study will be useful for providing model-informed guidance for the development of next generation resins for structural composites.

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