PREDICTING THE IMPACT PERFORMANCE OF LOW-COST 3D WOVEN COMPOSITE COMPONENTS

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Abstract

Understanding the failure response of composite components during dynamic events is key to capturing the structural response of an assembly. This is of particular significance for the automotive industry in modeling vehicle crashworthiness and occupant protection systems. Towards this goal, a 3D woven composite has been evaluated for use in structural automotive applications. 3D woven preforms were manufactured from Mitsubishi TRH50 12K, a low-cost carbon fiber, and then injected with Huntsman LY3585 automotive epoxy. A large number of coupon-level experiments were performed on both flat and curved samples to characterize material performance. Material response under various conditions including multiple thicknesses, loading directions, velocities, and coupon geometries was evaluated and data collected was used to calibrate the Abaqus Ply Fabric material model for use in Abaqus/Explicit finite element analyses.

In addition to evaluating coupons and calibrating the material model, tapered tube components were manufactured by 3D weaving tapered tubular preforms with the same material system that was used in panels. Preforms were then injected using a mandrel to create a component with a closed cross-section. These 3D woven composite tubes were used to validate the calibrated material model by subjecting the structures to bending tests at quasi-static, medium, and high-rate loading conditions. Four-point and three-point (spherical impactor) load heads were used to elicit multiple failure modes. Post-processing and analysis of collected tube impact and bending data illustrates the ability for the selected material model to capture many of the load-displacement trends and failure modes during quasi-static and dynamic events. This work demonstrates that a material model designed for use with composites made from 2D reinforcement is applicable to 3D woven composites for automotive applications under given conditions.

1. Introduction

3D woven composites have a large design space where the degree and arrangement of fiber interlocking can be tailored to a specific application. Aerospace structures have adopted 3D woven composite technology in a variety of applications with a focus on parts where damage resistance and damage tolerance are design critical. Most notably, 3D woven composites are a key technology advancement used in fan blade and containment cases in the CFM International LEAP engine found in Boeing 737MAX and Airbus A320neo aircraft, contributing to a savings of over 225 kg per engine [1]. As a result of uniquely designed 3D interlocking topologies, discrete lamina do not exist in the same form as seen in traditional 2D laminated composites. This interlocking tends to limit crack propagation and result in a more progressive failure, which has been studied recently for ballistic impact [2].

An understanding of the crashworthiness performance of a material is required to design structures for occupant safety systems in the automotive industry. Predictive material models are needed to do this effectively. Building upon the use of 3D woven composites in aerospace applications with demanding damage tolerance requirements, similar 3D woven composites have been found to exhibit superior energy absorption characteristics in crushing [3]. A low-cost material system was selected to evaluate both the applicability and predictability of 3D woven composite performance in crashworthiness applications. 3D composite crush behavior was investigated experimentally and structural crush performance was predicted using the CZone crush model [4]. A crush model alone, however, is not sufficient for structural performance prediction. In addition to investigating the crush performance, this paper presents an overview of the experimentation and validation of a macroscale damage model to help predict structural damage under various loading rates.

2. Approach

A component designed for structural crashworthiness applications must be supported by predictive material models that capture both the crush response and structural performance with progressive damage. The CZone crush model is used to predict the performance of 2D composites in crush. Inputs for this model include an experimental investigation of the crush response in various loading configurations and at multiple dynamic rates. Results from these crush tests are presented in this paper. Application and validation of the CZone material model will be presented in a subsequent paper.

A macroscale progressive damage model is needed in the event that in-plane composite damage is coupled with crush. The objective of experimentation was to collect and understand composite performance characteristics that are necessary inputs for macroscale damage modeling using the ABQ_PLY_FABRIC material model for Abaqus Explicit [5]. ABQ_PLY_FABRIC is a VUMAT user subroutine based on a continuum damage model developed by Johnson & Simon [6] that has been used for modeling conventional 2D woven fabrics. This paper examines the applicability of this model to 3D woven composites. A variety of material properties are required to populate this damage model. Conventional tensile, compressive and shear mechanical properties were tested and recorded. A cyclic shear test, in which a test coupon was loaded and unloaded to increasing strains, was used to capture the degradation of shear stiffness with increasing damage. In addition, a modified Charpy test, adapted for composites, was used for capturing the energy release rate parameters of the material. To validate the macroscale damage model, a sub-component was tested in bending. All experiments were conducted by Engenuity, Ltd. and experimental results were used directly as material model inputs. All simulation results presented in this paper were conducted prior to experimental validation testing.

2.1. Materials and Fabrication

Composites evaluated and summarized in this paper were manufactured using low-cost automotive-grade carbon fiber and epoxy resin. Composite design, weaving, and manufacturing was completed by Albany Engineered Composites (AEC). Mitsubishi TRH50 12k untwisted fiber was woven on a 3D Jacquard loom using a layer to layer topology (unique description of fiber interlocking). Architectures with nominal molded part thicknesses of 2.55 mm and 4.59 mm were instanced from the same topology. These thicknesses correspond to preforms with five and nine warp layers, respectively, with both having a nominal fiber volume fraction of 58%. Preforms were woven to achieve a design warp content of 60%, with the remaining 40% in the weft direction.

Preforms were molded using a resin transfer molding process with Huntsman Araldite® 3585 epoxy resin and Aradur® 22962 cycloaliphatic polyamine hardener. Prior to injection, Würtz PAT657/HC internal mold release (IMR) was mixed with the resin to both aid in de-mold and also to maintain a material system representative of high-rate manufacturing. Parts were cured for 15 minutes at 120°C, followed by a free-standing 2 hour post-cure at 150°C.

In addition to flat panels, a tapered tube with a closed rectangular cross-section was selected to represent a generic structural sub-component. Figure 1 shows a diagram of the tapered tube geometry with nominal dimensions. The tube was manufactured using an RTM process and reinforced by a 3D woven preform manufactured on a captured shuttle loom. The 3D woven reinforcement in this part is unique in that there is continuous fiber around the circumference as well as in the axial direction. This is achieved without darting of the preform, resulting in high-quality seamless reinforcement with a constant fiber volume fraction and thickness of 2.55 mm along its length.

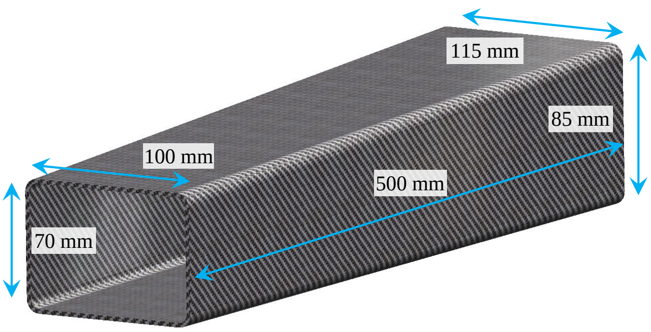

Figure 1. Sub-component tapered tube geometric representation with nominal dimensions

2.2. Crashworthiness Characterization

A method for modeling crush is required to assess energy absorption characteristics for crashworthiness applications. CZone is a numerical approach to modeling composite behavior in crushing by treating the mean crush stress as an effective material property [4]. Various inputs are required for this model and some of these tests are described here to effectively capture the crush response. The approach used to collect this data will be presented here. Validation of this approach will be presented in another publication.

Test coupons from both composite thicknesses were evaluated in crush at multiple rates under various loading configurations. Engenuity has found that the response of composites in crushing has geometric dependence. For example, a material that is constrained from out-of-plane motion during crush (corners of a structure) tends to have a different mean crush stress than in an unconstrained region. The two boundary conditions used during crush tests are referred to as ‘suppressed’ and ‘free’. A suppressed condition is created by means of controlling out-of-plane deflection at the crush front. It is worth noting that ‘suppressed’ in this case refers to the suppression of delamination, which is directly applicable to composites with two-dimensional fiber reinforcement. Due to the lack of discrete lamina, a fundamental characteristic of three-dimensional woven reinforcement, delamination in the traditional sense of the word is not applicable. Therefore, simply the word ‘suppressed’ will be used herein.

Coupons were evaluated at low, medium, and high crush rates, corresponding to approximately 0.5 m/s, 3.5 m/s, and 6.0 m/s, respectively. Both thin and thick composites were evaluated in both suppressed and free crush conditions at each of these rates.

Each coupon was machined with an initiator prior to crush testing. The purpose of the initiator is to locally increase compressive stresses to the point of beginning a crushing failure mode. Previous work has evaluated crushing performance using a single-chamfered initiator for 3D woven composites [3]. A crenulated initiator was proposed for this work by Engenuity, so a comparison study was carried out to confirm the minimal effect seen between double-chamfered and crenulated initiators. Comparison coupons were tested in quasi-static crush at 100 mm/minute. The mean crush stresses for both thicknesses and initiators were measured between 15 mm into crushing and ending 65 mm. Details are found in the results section 3.1.1 in Table 1. A comparison between crush initiators is seen in Figure 2.

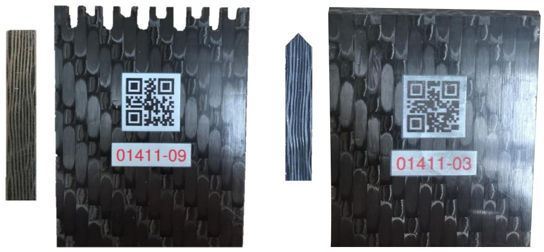

Figure 2. Crenulated crush initiator (left) vs. double chamfered initiator (right)

2.3. Damage Modeling

2.3.1. Material Characterization

Composites were evaluated in tensile, compressive, and shear loading at quasi-static rates. Tensile and compressive experiments were conducted in both warp (0°) and weft (90°) directions. In-plane shear was also evaluated in a notched coupon test configuration. Modulus and strengths for both thicknesses of 3D composite under tensile and compressive loading are summarized in Table 2.

2.3.2. Sub-Component Response

Composite tubes were evaluated in four-point and three-point bending configurations, illustrated in Figure 3. Supports were 368 mm apart, each with a 12.5 mm radius. The height of the supports was offset by 12.2 mm to ensure the tube top surface was horizontal, allowing for load transfer perpendicular to the tube surface. 127 x 50 x 5 mm steel plates were attached to the base of the tubes to avoid stress concentrations and prevent damage at the supports. Twin bars (span 130 mm, radius 22.5 mm) were used for the four-point bend configuration tests. The twin bar load head setup was not free to rotate during tests. A spherical impactor with radius 50 mm was used for the three-point bend tests.

Both three- and four-point bend tests were conducted at three different rates. Quasi-static tests were conducted in a 250 kN servo hydraulic machine at a prescribed displacement rate of 10 mm/minute.

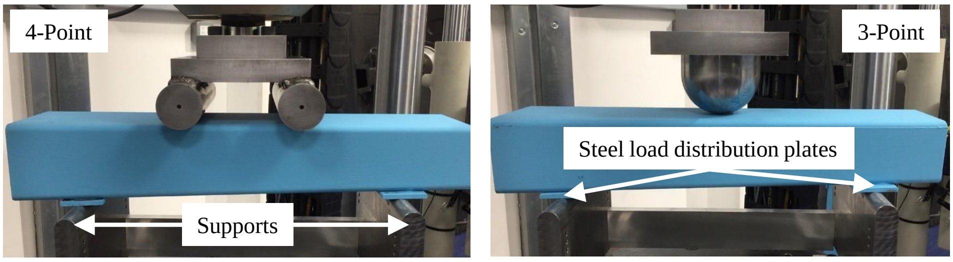

Figure 3. Tapered tube experimental setup for 4-point (left) and spherical 3-point (right)

Dynamic tests were conducted in a drop tower. Impact velocity was 4 m/s for the medium dynamic rate tests, and 7 m/s for the high rate dynamic tests. The impactor mass was 51.6 kg for the four-point bend configuration and 51.3 kg for the three-point bend configuration.

2.3.3. Macroscale Simulation

The tapered tube was modeled as a five ply 2D laminate with S4R shell elements. A 20% reduction in stiffness properties was applied to a 10mm horizontal band halfway up the vertical faces, to simulate the region in which the shuttle weaving process requires a shuttle reversal. The steel plates were given elastic properties, while the impactors and supports were modeled as rigid bodies. General contact was applied to the model. The bending simulations for all six test setups were predictive and submitted prior to testing.

3. Results and Analysis

3.1. Crashworthiness Performance

Figure 4 shows mean crush stress values with error bars representing one standard deviation. Low, medium, and high rate coupons were tested in a specialized drop tower. The trend is clear for the free crush configuration that the measured mean crush stress decreases when compared with quasi-static crush results and also with increasing crush rate. With the exception of the low crush rate, suppressed crush testing also supports this trend, which highlights the importance of collecting crush data at various rates. Standard deviations were small for both thin and thick 3D woven composite configurations, suggesting a high level of confidence that these materials will exhibit repeatable and predictable behavior in a structure.

3.1.1. Crush Initiator

A comparison study was done to determine the effect of crenulated vs. chamfered crush initiators for all crush testing. Mean crush stresses were found to be similar for both crenulated and chamfered initiators, confirming the choice of crenulation for subsequent crush evaluation. Results are reported in Table 1.

3.1.2. Crush Compression Ratio

The crush compression ratio (CCR) of a material is defined as $\sigma_{compression}/\sigma_{crush}$. Composites with a high CCR are desirable for design of structures with stress concentrations and off-axis loading conditions. If the CCR for a composite is small (mean crush stress of the material is similar to the compressive strength), structures designed with that material may suffer from compressive failure in areas away from the crush front, resulting in sub-optimal energy absorption and structural performance.

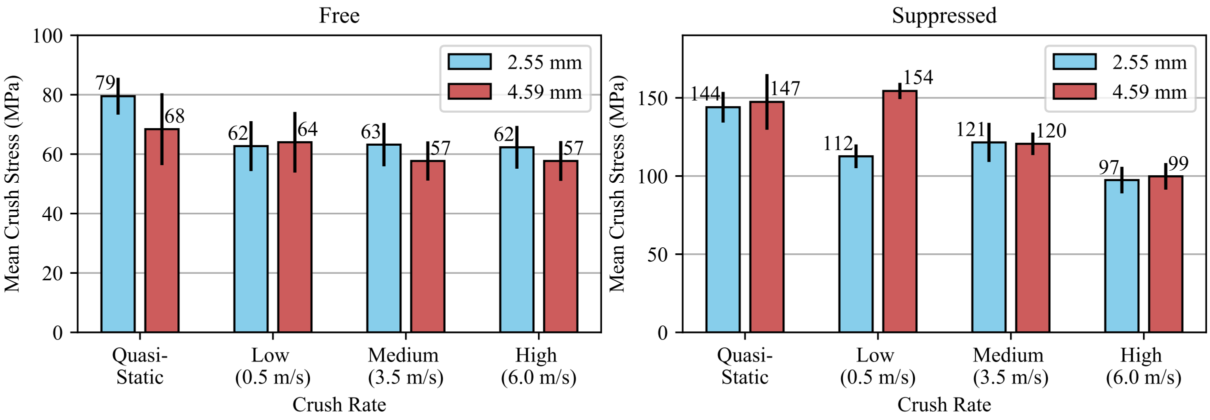

Figure 4. Free and suppressed mean crush stress for both 2.55 mm and 4.59 mm composite thicknesses at quasi-static, low, medium, and high rates.

Table 1. Mean crush stress comparison for both crush initiators and composite thicknesses under quasi-static loading

Experimental Data	2.55mm thick		4.59mm thick	
	Crenulated	Chamfered	Crenulated	Chamfered
Mean Crush Stress (MPa)	81.7	85.3	85.3	81.8
Standard Deviation (MPa)	5.3	15.1	9.8	8.9
Coefficient of Variation (%)	6.5	17.7	11.5	10.9

The crush compression ratios for both thicknesses of evaluated 3D woven composite under both free and suppressed crush loading conditions are shown in Figure 5. The trend between the two thicknesses is the same; higher suppressed mean crush stress results in a lower CCR. The thicker composite was found to have a higher CCR in both free and suppressed cases due to both having a higher compressive strength and slightly lower mean crush stress.

3.2. Structural Performance

Quasi-static tensile and compressive stiffness and strength in both 0° and 90° directions are required for macroscale damage model inputs. Experimental results used as inputs for the simulation are listed in Table 2.

Table 2. Tensile and compressive performance

Experimental Data	2.55mm		4.59mm	
	0°	90°	0°	90°
Tensile Modulus (GPa) (COV%)	81.5 (4.5%)	47.0 (6.1%)	82.4 (5.5%)	55.6 (5.4%))
Tensile Strength (MPa) (COV%)	920 (3.4%)	455 (8.3%)	961 (2.3%)	602 (2.3%)
Compressive Modulus (GPa) (COV%)	77.0 (15.9%)	43.0 (18.5%)	77.2 (2.1%)	52.9 (12.1%)
Compressive Strength (MPa) (COV%)	525 (9.2%)	311 (6.2%)	634 (2.6%)	445 (8.8%)

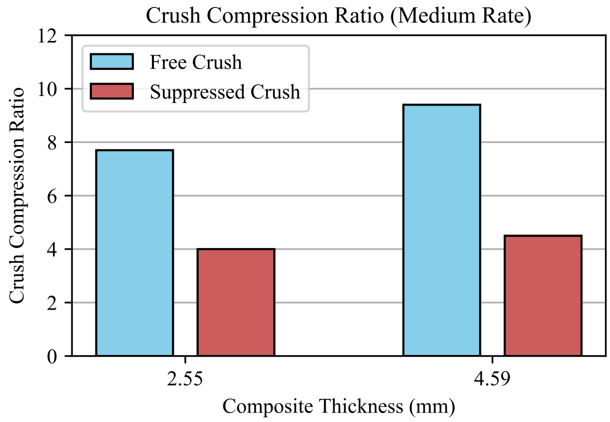

Figure 5. Crush compression ratio for 0° free and suppressed boundary conditions at the medium test rate

3.2.1. Simulation Results

The four-point bend simulations predicted the load vs. displacement response (Figure 6) of the 3D woven composite material at the evaluated rates reasonably well. Good correlation between simulation and experimental results for quasi-static, medium, and high-rate loading is observed.

The four-point bending high dynamic rate simulations predicted initial localised damage under the rollers, followed by crack propagation down the vertical faces of the tubes, shown in Figure 7. The tests showed excellent correlation with the prediction: failure modes were matched and peak loads correlated to within 5%. The initial experimental stiffness was captured in each analysis configuration.

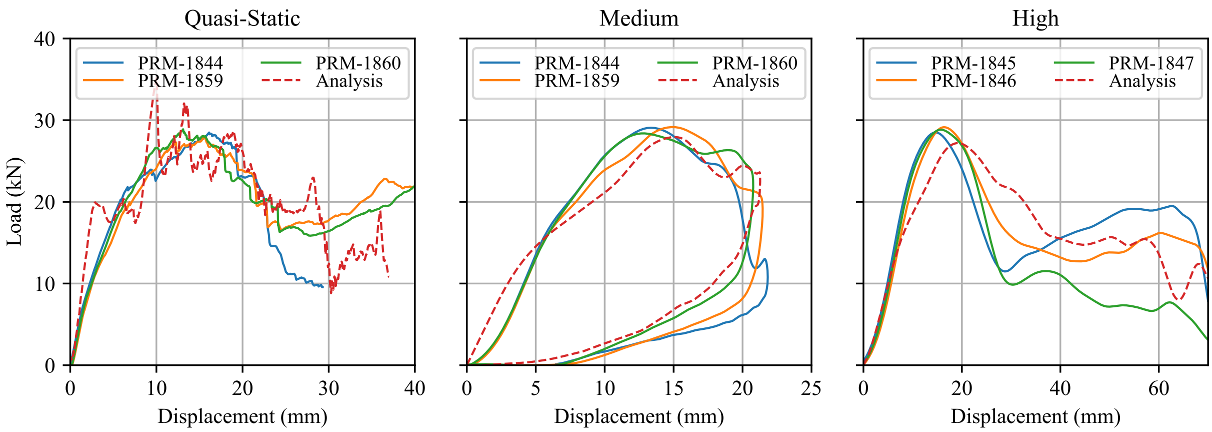

Figure 6. Load vs. crosshead displacement curves show simulation results (dashed red line) on top of three repeat experimental tubes for four-point bending tests. Quasi-static (left), medium-rate (center) and high-rate (right) comparisons are shown.

The four-point bend medium dynamic rate simulation predicted that the energy of the falling mass would not be enough to significantly damage the tube. This occurred in all three test repeats. Correlation of peak displacement was accurate: the analysis predicted the maximum intrusion level would be 21.3 mm and the mean test level was 21.4 mm. The simulation prediction was within 5% of the experimentally observed mean peak load.

The four-point bend quasi-static rate simulation predicted failure through localised deformation and top

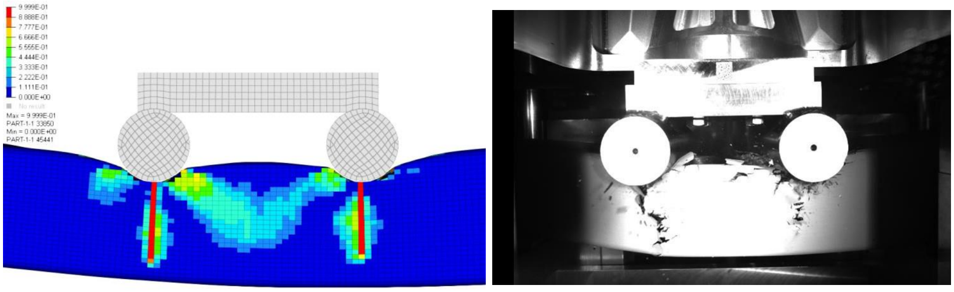

Figure 7. Simulation results show a solution dependent variable representing damage (left) and a photo showing the corresponding experiment that exhibits the same failure mode (right).

face cracking. This again correlated well with the failure modes seen in the tests. The overall shape of the load vs. displacement prediction was in line with the experimental results, although the load increased in a more progressive manner in the latter.

The three-point bend predictions were not as closely matched with experiments as the 4-point bend predictions. The tubes tended to fail at a higher strength in the tests than was predicted during simulation. However, the localised failure mode under the impactor was captured by the analyses. Sensitivity studies found the three-point bend predictions to be particularly sensitive to the energy release rate values that were measured in the modified Charpy test. Alternatives to Charpy testing are being investigated to more accurately measure the fracture energy release rate of this material.

Failure mechanisms in the two test configurations are largely different; four-point bend tests initially load the tube side walls in in-plane tension, compression, and shear - experimental values which were captured in the experimental test plan. The spherical impactor used in three-point bending initially loads the structure primarily in bending, resulting in similar initial stiffnesses between predictions and experimental results. The simulation predicted through-thickness failure of the top face, followed by through-thickness damage and penetration of the top face of the composite tube earlier than was experienced experimentally. Characterization of the energy release for through-thickness damage via an alternative approach is expected to improve the correlations for three-point bending tests.

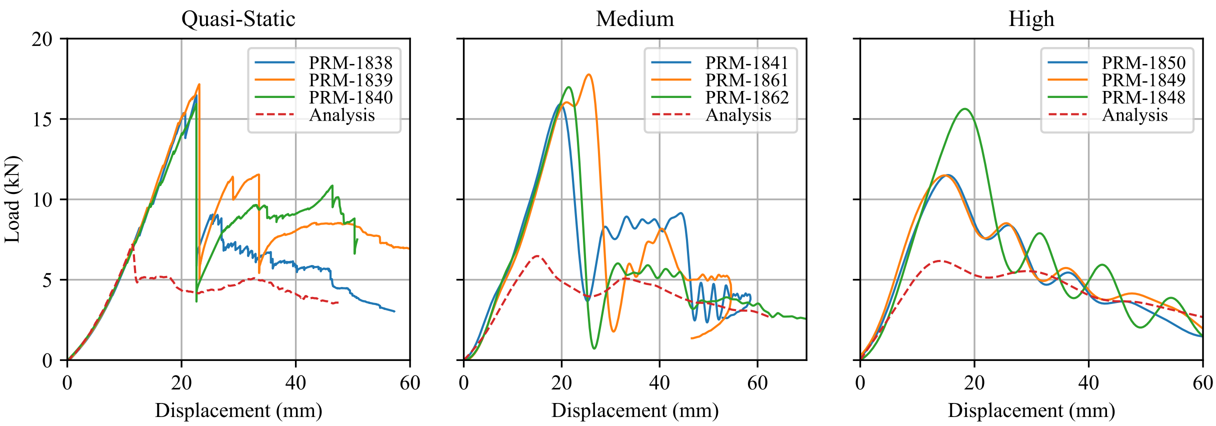

Figure 8. Load vs. crosshead displacement curves show simulation results (dashed red line) on top of three repeat experimental tubes for three-point bending tests. Quasi-static (left), medium-rate (center) and high-rate (right) comparisons are shown.

4. Conclusions

Mechanical testing of a 3D woven composite material system was performed. Experiments were conducted at multiple loading rates, material orientations, and composite thicknesses. In addition to evaluating material crush performance, tensile, compressive, and shear response were also investigated. Crush coupons were crushed with both free and suppressed boundary conditions at rates up to 6.0 m/s. Crush data was collected to prove the validity and stability of the material during crush events, which a structural composite part may be exposed to. A user subroutine for Abaqus/Explicit was applied to this composite using the collected in-plane experimental data for calibration. Validation tests were performed on sub-component structures under multiple load rates and boundary conditions, which resulted in the following conclusions:

1. ABQ_PLY_FABRIC was calibrated for this 3D woven composite using experimental coupon test results. It was then applied to the validation bending setup in a purely predictive manner where predicted responses were generated prior to validation testing.

2. The experimental load-displacement response for tubes in both four-point and three-point load cases showed consistency between repeat samples for all load rates. Additionally, predicted failure modes using the damage model were seen in each corresponding validation condition. Four-point bend load-displacement responses were captured well at all test rates with the damage model.

3. Energy release rate in through-thickness loading conditions and failure is an important parameter for capturing through-thickness penetrating damage.

4. 3D woven composites have a favorable crush compression ratio, indicating their applicability to component applications. In addition to a stable crush response, coefficients of variation on crush tests were small, indicating a repeatable crush response.

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