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Test Methodologies for Determining Energy Absorbing Mechanisms of Automotive Composite Material Systems

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ABSTRACT

To identify and quantify the energy absorbing mechanisms in automotive composite material systems, test methodologies were developed for conducting progressive crush tests on composite specimens that have simplified test geometries. The test method development focused on isolating the damage modes associated with the frond formation that occurs in dynamic testing of composite tubes. A new test fixture was designed to progressively crush composite plate specimens under quasi-static test conditions. Preliminary results are presented under a sufficient set of test conditions to validate the operation of the test fixture. The experimental data, in conjunction with test observations, will be used in future work to identify the characteristic damage and failure modes, and determine the specific energy absorption capability of candidate automotive composite material systems.

INTRODUCTION

In passenger vehicles the ability to absorb impact energy and be survivable for the occupant is called the “crash worthiness” of the structure. This absorption of energy is through controlled failure mechanisms and modes that enable the maintenance of a gradual decay in the load profile. The crashworthiness of a material is expressed in terms of its specific energy absorption E_S (SEA) which is characteristic to that particular material. It is defined as the energy absorbed per unit mass of material. Mathematically $E_S = \sigma / \rho$, where ρ is the density of the material and σ is the mean crush stress.

In the crashworthiness of automotive structures, the primary issues to the automotive industry are the overall economy and the weight of the material. To reduce the weight and improve the fuel economy, polymer composite materials have replaced more and more metal parts in vehicles. The tailorability of composites, in addition to their attributes of high strength-to-weight and stiffness-to-weight ratios, corrosion resistance and fatigue resistance, makes them very attractive for designing crashworthy structures. The challenge is determining what specific design features are needed in the geometry and selecting materials that will enable greater safety while simultaneously decreasing the bulk and weight, without negatively affecting the overall economics of fabrication and production.

In comparison to metals, most composites are generally characterized by a brittle rather than ductile response to the applied loads, especially in compression. The major difference, however, is that metal structures collapse under crush or impact by buckling and/or folding in accordion type fashion involving extensive plastic deformation, whereas composites fail through a sequence of fracture mechanisms. The actual mechanisms, e.g., fiber fracture, matrix crazing and cracking, fiber-matrix debonding, delamination, and inter-ply separation, and sequence of damage are highly dependent on lamina orientation, crush speed, triggers and geometry of the structure.

Much of the experimental work to study the effects of fiber type, matrix type, fiber architecture and specimen geometry on the energy absorption of composite materials has been carried out on axisymmetric tubes (1-22). Tube structures are relatively easy to fabricate and close to the geometry of the actual crashworthy structures. These tubes were designed to absorb impact energy in a controlled manner by providing a trigger to initiate progressive crushing. A trigger is a stress concentrator that causes failure to initiate at a specific location within a structure and propagate through the body in a controlled predictable manner. The most widely used method of triggering is chamfering one end of the tube. The brittle fiber reinforced composite tubes crushed in the fragmentation and splaying modes while progressive folding was exhibited by ductile fiber reinforced composite tubes.

Both material and structural damage processes need to be well understood to accurately model and design crashworthy automotive composite structures. In the progressive crushing of composite tubes there are many different failure mechanisms that contribute to the overall energy absorption of the structure. To isolate the damage mechanisms and quantify the energy absorption contributed by the splaying mode, composite plate specimens were tested using a unique test fixture. Practical considerations related to the cost of production of the test specimens were of paramount importance in developing the test methodology. Composite plate specimens are very cheap to fabricate and it has been observed that plate specimens progressively crush in modes very similar to the damage modes that occur during progressive crushing of composite tubes.

TEST FIXTURE DESIGN

A new test fixture design was developed for determining the deformation behavior and damage mechanisms that occur during progressive crushing of composite materials. The fixture was designed to isolate the damage modes associated with the frond formation (splaying mode) in composite tubes by testing plate geometries. The fixture can be used in conventional screw-driven or hydraulically actuated load frames and is intended for quasi-static loading but may be adaptable to conducting dynamic tests with minor modifications. The design of the test fixture can accommodate different plate widths (up to 50 mm), plate thicknesses (nominally 3 mm ± 1.5 mm), contact profile shapes, and contact profile constraints.

The design is a modified version of an existing test fixture used for crush testing of composite plates (23). Features incorporated into the design include an observable crush zone, long crush length, interchangable contact profile, frictionless roller for contact constraint, and out-of-plane roller supports to prevent buckling. A schematic of the test fixture is shown in Figure 1 and photos are shown in Figures 2-3. The primary components of the fixture are:

1. Top plate
2. Base plate
3. Profile block
4. Roller plate
5. Grip plate and insert
6. Linear shaft and bearing
7. Load cell
8. Roller way

The composite plate specimen is clamped in the top plate by the grip inserts. The specimen is then loaded in compression and crushed through the contact profile as defined by the profile block via the top plate that is connected to the load train using a shaft coupler. The top plate is displaced downward, relative to the base plate and profile block. Alignment is maintained by using four linear shafts and linear bearings. Attached to the roller plates that are positioned on the linear shafts by shaft collars are the roller ways. The roller ways are used to reduce the unsupported length of the specimen thereby preventing the specimen from buckling. The brackets on each side of the profile plate were designed to serve two functions. The first function is to provide a method of constraining the specimen to deform along the path of the contact profile. This is accomplished by using oil-impregnated bronze sleeve bearings in each bracket and installing a precision ground shaft that acts as a roller. The second function is a development effort to measure the vertical and horizontal reaction forces experienced by the specimen during the deformation process. The severity of the contact profile constraint is determined by the position of the load cell brackets and is adjustable using slotted positioning holes. Slotted holes are used throughout the test fixture design to accommodate different plate thicknesses and maintain alignment with the centerline of the load train.

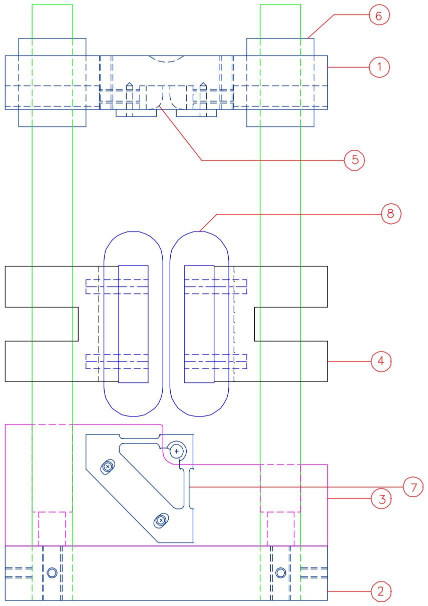

Figure 1. Schematic of test fixture design.

EXPERIMENTAL RESULTS

The fixture was designed to study what effects the plate width, plate thickness, load rate, profile constraint and profile shape had on the energy absorbing characteristics of composite plates. Furthermore, the objective of the profile constraint was to determine if different damage mechanisms could be activated depending on the position of the roller.

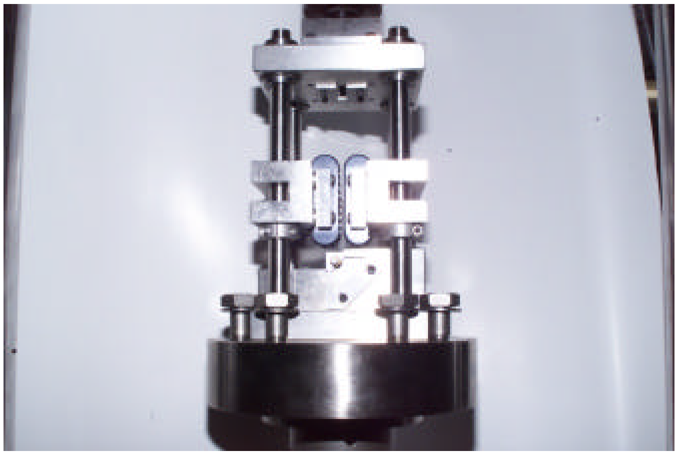

Figure 2. Test fixture assembly.

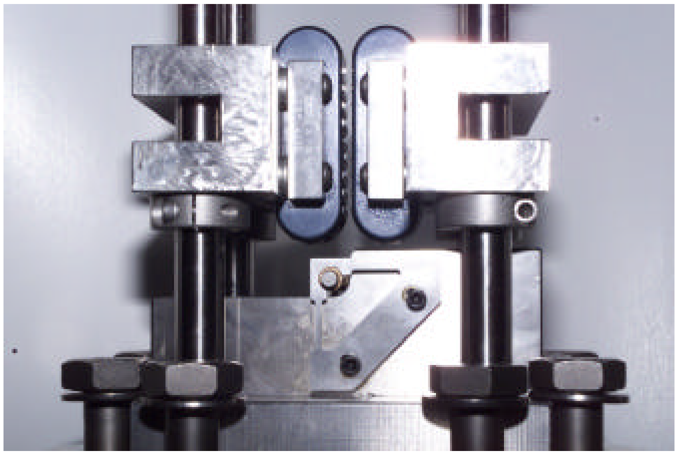

Figure 3. Roller ways and contact profile constraint.

To validate the fixture operation a series of experiments were conducted on candidate automotive composite material systems. The specimens had a nominal length of 178 mm and a width of 50 mm, and a 45°-chamfer was used as the crush initiator. A loading rate of 5.0 mm/min and a profile radius equal to 6.4 mm was used throughout all the testing. The load-deflection response was recorded using a computerized data acquisition system. An idealized load-deflection response for progressive crushing is illustrated in Figure 4. The area under this curve is the total energy absorption and the initial peak load and sustained crush load are identified.

The material systems that were tested included a graphite/epoxy cross-ply laminate, a graphite/epoxy braided material, and a glass-reinforced continuous strand mat (CSM). The cross-ply laminate was fabricated using the hand lay-up process and Akzo Fortafil prepreg #602. There were two plates fabricated, designated as #CP1 and #CP2, where the #CP2 plate was not adequately consolidated because of losing vacuum pressure partially through the cure cycle. The graphite/epoxy braided specimens were fabricated using Akzo #556 carbon fiber with Ashland Hetron 922 epoxy vinyl ester. The lay-up was a triaxial braid with 0/+30/-30 fiber orientations and the panel designation was #10-13. The CSM specimens were machined from plates that were fabricated using glass-fiber reinforcement in a Baydur polyurethane resin.

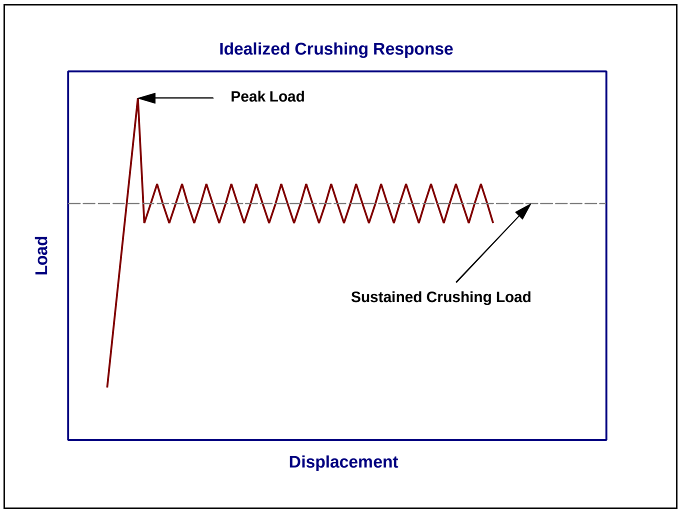

Figure 4. Idealized load-deflection response.

LOAD-DEFLECTION RESPONSE

The experimental data from the measured load-deflection responses are summarized in Tables 1-4 in terms of the initial peak load, sustained crush load, and specific energy absorption (SEA). Representative responses are plotted in Figures 5-8. In Table 1, the data for CP1-6 corresponds to an erroneous test condition where the tight roller constraint was not uniform across the width of the specimen.

Table 1. Akzo Prepreg #602 Cross Ply Panel #CP1.

Constraint	*Specimen*	*Initial Peak Load (N)*	*Sustained Crush Load (N)*	*SEA (J/g)*
None	CP1-4	5489	5280	11.1
	CP1-5	7562	4372	13.8
Loose	CP1-1	4532	3581	19.9
	CP1-2	4617	4194	21.2
	CP1-3	3807	3505	13.6
Tight	CP1-6	4421	5039	25.5
	CP1-7	4092	1103	5.2

General observations from the test results are the following. For the #CP1 cross-ply panels the no constraint condition resulted in the highest initial peak load and the highest sustained crush load relative to the other constraint conditions. For panel #CP2 the constraint condition had a minimal effect on the initial peak load but the SEA was significantly higher for the tight constraint condition. When the constraint condition corresponded to the no and loose conditions, the poorly consolidated panel (#CP2) had significantly lower SEA's compared to #CP1. The results for the braided material show a lower initial peak load but a higher sustained crush load and a higher SEA when the loose condition was used compared to no constraint. The CSM material had the highest initial peak load of all the material systems that were tested.

Table 2. Akzo Prepreg #602 Cross Ply Panel #CP2.

Constraint	*Specimen*	*Initial Peak Load (N)*	*Sustained Crush Load (N)*	*SEA (J/g)*
None	CP2-1	5962	3971	7.9
	CP2-2	4310	3259	7.1
Loose	CP2-3	4595	2176	6.3
	CP2-4	4437	1463	6.9
Tight	CP2-5	4670	4619	20.1
	CP2-6	4583	3020	15.1

Table 3. Baydur Glass Fiber CSM.

Constraint	*Specimen*	*Initial Peak Load (N)*	*Sustained Crush Load (N)*	*SEA (J/g)*
None	CSM-1	7478	4829	10.8
	CSM-3	8157.8	4444	9.7
	CSM-6	8334.2	4561	10.1

Table 4. Akzo 556 Tri-axial $0^{o}/\pm 30^{o}$ Braid Panel #10-13.

Constraint	*Specimen*	*Initial Peak Load (N)*	*Sustained Crush Load (N)*	*SEA (J/g)*
None	0-7	4233	1917	7.4
	0-8	3674	1001	6.9
Loose	0-6	3490	2417	14.2
	0-9	3366	2934	20.2

OBSERVATIONS

The predominant damage mechanism for the cross-ply plate was delamination. The no constraint condition resulted in larger delamination growths, larger number of delaminations, and greater permanent deformations. Compared to panel #CP1, the lower SEA in panel #CP2 can be attributed to the weaker interfacial bond strength, resulting from the poor consolidation, requiring less energy to delaminate. The plateau in the load-deflection responses (see Figure 5) corresponded to complete delamination between all the layers. For the braided material, the active damage mechanisms were localized crushing, fiber fracture on the tensile side of the specimen, and fiber buckling of the off-axis tows on the compressive side of the specimen. The fiber buckling was more extensive when the no constraint condition was used, whereas the fiber fracture was more predominant in the tight constraint tests. From Figure 7, the loose constraint condition produced a nearly ideal response for progressive crushing. In the CSM specimens, finite length fractures across the entire width were observed. The load would monotonically increase until fracture occurred and then the load would drop to almost zero (see Figure 8). Approximately the same magnitude of load was measured at each of the fracture points and the fracture lengths were approximately the same.

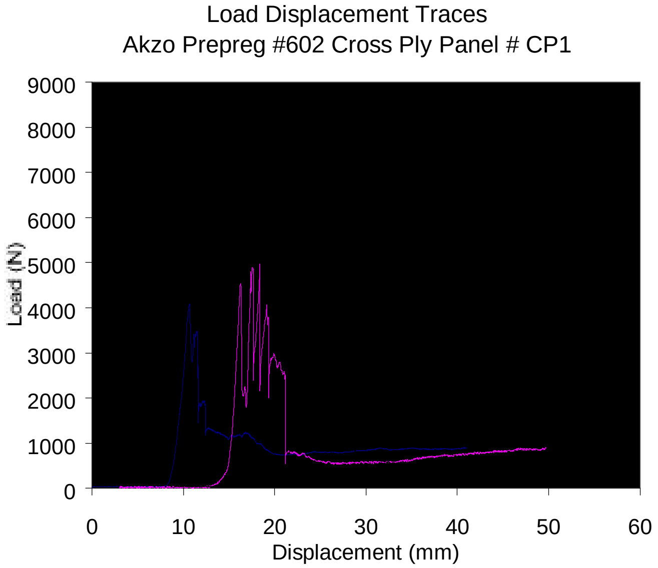

Figure 5. Load-displacement traces for #CP1.

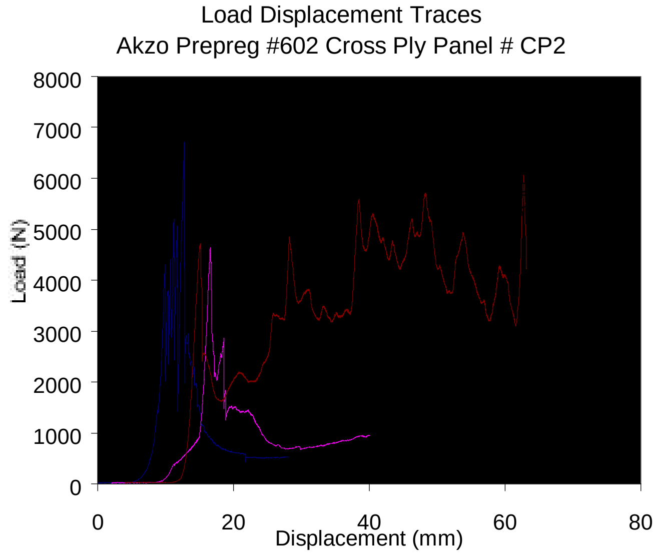

Figure 6. Load-displacement traces for #CP2.

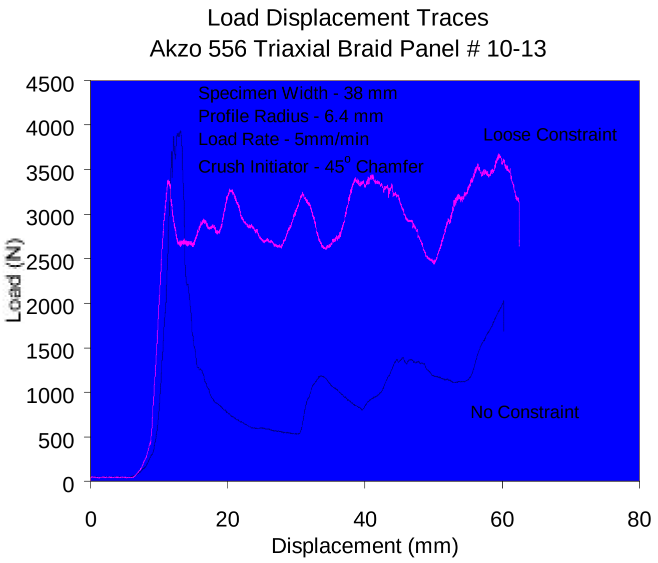

Figure 7. Load-displacement traces for #10-13.

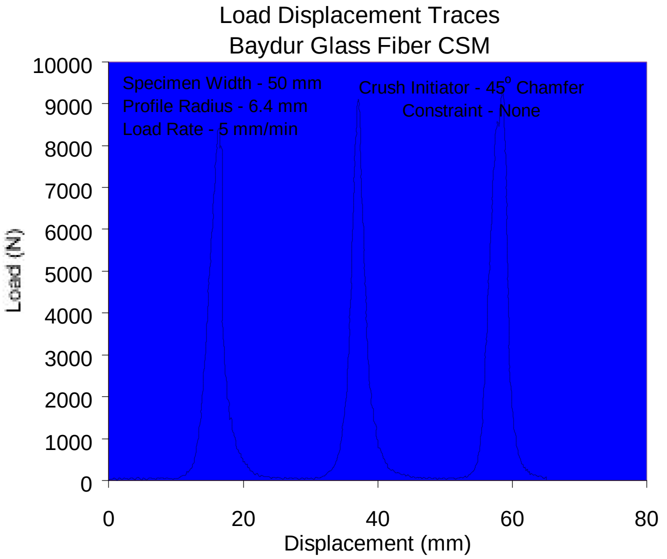

Figure 8. Load-displacement trace for CSM.

The initial tests conducted on the CSM material resulted in the specimens buckling between the top plate and the roller ways. The roller ways were successful in preventing out-of-plane buckling in the carbon fiber specimens. The low buckling strength of the CSM material resulted in having to use a metal push plate to reduce the unsupported specimen length. The metal plate was 50 mm in length and was bonded to the end of the CSM specimen using 5-minute epoxy. This specimen configuration was only successful when the roller was positioned in the no constraint condition. When a loose constraint condition was attempted the initial peak load increased and the CSM specimens buckled. Future work on this material system will require a longer metal push plate.

CONCLUSION

A unique test fixture was developed for determining the energy absorbing mechanisms in automotive composite material systems. The objective of the test method was to quantify the energy absorption and identify the failure mechanisms associated with the observed frond formation in progressive crush testing of composite tubes. This was accomplished by testing composite plates under progressive crush loading conditions. The activation of different damage mechanisms was demonstrated by a series of validation tests on representative composite material systems. A profile constraint was incorporated in the test fixture design for the purpose of activating the different damage mechanisms. Modifications to the basic specimen geometry are required when testing material systems that have a low axial stiffness to prevent a global buckling failure mode.

Future testing will be conducted to quantify the effects of specimen width, profile radius, profile constraint and loading rate on the specific energy absorption and failure modes. The experimental data in conjunction with the test observations can be used to develop analytical models for predicting the crashworthiness of automotive composite structures.

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