Abstract

As part of the design for vehicle crashworthiness, energy-absorbing structural elements have been successfully used in every field of transportation, and composites have shown great advantages in energy absorbed per unit mass of material. One of the key factors preventing the widespread adoption of composites in primary crash-resistant structures is the absence of specialized test methods for the characterization of specific energy absorption (SEA). A relatively simple and inexpensive method is required to compare candidate material systems, laminate designs, fiber architectures, processing methods to build an adequate property database. This paper reviews a portion of the existing body of literature concerned with the development of crush test methodologies, and identifies the areas that require the most attention before being considered for adoption as test methods. The recently formed MIL-HDBK-17 Working Group (WG) on Crashworthiness, which comprises representatives from the aerospace and automotive industry, academia, and government laboratories, is presently dedicated to developing suitable test methods. In particular, two test methodologies have been identified as the most mature for development and standardization, one for plate coupons, and the other for tubular specimens. The WG has started to collect and summarize current industry test practices, which are many and not currently agreed upon, and is already working in conjunction with ASTM Committee D-30 on Composite Materials to lay the foundations of tests standards for composite crashworthiness.

Review of test set-ups for plate crush testing

ARL Fixture [1-3].

The first to successfully promote the development of a coupon-level test method with which to characterize the energy absorption of composite plates were the Army Research Laboratories (ARL) at NASA Langley Research Center. The group developed a novel test fixture designed (fig. 1) to accommodate a flat plate specimen, of dimensions 50.8 mm x 76.2 mm, up to 2.3 mm thick, to be used in both a quasi-static (1.3 mm/min) and dynamic (7 m/sec) load frames. They investigated two types of trigger mechanisms, the steeple (a 30-degree chamfer on both sides of the plate), and the “notch” (a staggered, transverse machined profile). The chamfered trigger mechanism
had been previously discarded because of its inability produce the desired initial peak in the load-deflection curve.

An earlier fixture design saw the use of guiding posts in intimate contact with the specimen. However, this feature would lead to accumulation of debris near the crush zone, which would in turn lead to jamming of the specimen and to an undesired increase in measured load. The fixture was redesigned to accommodate a 12.7 mm unsupported area where the debris could move freely, but this led to a change in failure modes from crushing to splitting and delamination, which would yield unrealistic absorbed energy measurements. The fixture was further modified to move the support posts further away from the specimen, thereby preventing any direct contact between them. Lateral support to the specimen was then provided by knife-edges, which fit into keyways located in the posts, which are machined to a specific width to accommodate a designated specimen thickness. Maximum stroke was also increased to 76.2 mm.

Fig. 1. Test fixture and specimen (featuring notch and steeple trigger mechanisms) developed by the ARL.

The steeple trigger has a tendency to generate a double peak in the initial portion of the load-stroke diagram. This behavior appears to be due to the formation of a long delamination along the specimen length, initiated by the creation of a divisive wedge of crushed material at the sharp-tipped end of the plated. Furthermore, the notch trigger appears to generate a sustained crush load a few percent higher than the steeple trigger. The authors suggested a list of changes that should be implemented to improve the current design, including making the knife-supports adjustable in width in order to easily accommodate specimens of varying thickness, using hardened steel posts, which are easily worn and damaged by the high forces exerted by the specimen, and using a better trigger mechanism, such as a J-trigger (such as a molded-in curl at the end of the plate).
The authors also realize that the results obtained with the coupon specimens do not compare directly with the results previously obtained by testing thin-wall tubular specimens of the same material systems and laminate designs. Although the load-stroke traces are similar for flat plates and tubes, it is likely that the two specimens fail by somewhat different mechanisms, due to the self-supporting nature of the tubular specimens. The radius between two adjacent walls in a rectangular tube may in fact provide a stabilizing action which differs substantially from the one provided by the knife-edge supports, which prevent any “outward brooming” of the plies.

The transition to dynamic testing revealed reduced energy absorption for all laminates tested. At dynamic rates it is likely that the failure process is dominated by the steady propagation of delaminations deeply into the laminate, rather than the progressive crushing of fibers. It is then possible that there is a time-dependent competition between the development of mode I delaminations and a localized fiber/resin fragmentation crush front. It is clear that delamination suppression is crucial to maintain high levels of energy absorption. In general, quasi-static tests tend to significantly overestimate energy absorption (fig. 2).

Hogg et al. [4-6] modified the Army fixture to account for variable specimen width and thickness by introducing adjustable knife-edge supports (fig. 3). These are tightened only the minimum necessary to maintain contact with the specimen but minimize friction. The coupon size is 90 mm long and 60, 70, 80, 90 mm wide. Since the width of the edge support is 3 mm on each side, the effective unsupported area for each specimen width investigated is effectively 6 mm less than the nominal. The portion of laminate outside the knife supports can be seen as the lateral overhang of a simply supported plate (fig. 10). The specimen is machined to exhibit a 45-degree steeple trigger, which has shown relatively favorable results in the Army previous work. The specimen is inserted in the fixture resting on the tip, and tested at a quasi-static rate of 20 mm/min.
The load-stroke diagram for the steeple specimen shows a double-stage initial collapse (fig. 4), associated to the crushing of the chamfer and subsequent splitting of the laminate in two fronds. Sometimes the first peak is only barely visible, other times it is clearly defined. The initial peak is followed by a trough, associated with the length of delaminated material, which contributes little load resistance. Eventually the load picks up again, and reaches a region of sustained crushing. It is necessary to employ a crush length larger than the length of this delamination in order to achieve steady state crushing and energy absorption. A short central delamination is associated to small (tight) radii of curvature of the fronds, hence fronds that are widely open apart (fig. 5).

In the region of sustained crushing stress, the fronds tear along the knife-edges, in a fashion similar to the edges of a square tube. It was found that varying the specimen’s aspect ratio, given by the ratio of unsupported width to thickness, changes the measured SEA, namely increasing the width decreases the SEA. This can be explained considering that the knife-edges, while preventing the plate from buckling, also promote local tearing of the laminate (fig. 6). This failure mechanism absorbs a vast amount of energy, comparable to the amount dissipated in friction between the fronds and the base and sides of the jig, thus can lead to unrealistic SEA values.
Fig. 4. Typical load-stroke diagram obtained show double peak and trough before sustained crushing is reached.

Fig. 5. Micrograph picture exhibits splaying of the laminate and major delamination at the midplane.
Fig. 6. Undesirable characteristic of the fixture is the tearing at the supports, which induces unrealistic SEA values.

**Engenuity Fixture [7].**

Based upon the original work done by the ARL at NASA Langley, Engenuity Ltd., an engineering services company based in the UK, developed a fixture for crushing flat coupon specimens (fig. 7). The rig provides buckling stability by fully constraining lateral and out-of-plane movement of the coupon. Friction is reduced by employing Delrin sliders on the sides of the fixture.

The specimen’s dimensions are 80 mm x 40 mm, while the laminate thickness can vary between 1.2 and 10 mm. The specimen’s tip is machined to exhibit a jagged edge, which triggers stable crushing, but it is planar (no chamfer in the transverse direction).

With their specimen and fixture setup, it is possible to reproduce load-stroke curves similar to those of tubular specimens, where a progressive and stable crushing of the laminate about a mean value follows an initial peak (fig. 8).

Their investigation typically covers both quasi-static and dynamic tests (2 m/s), since they have shown that crushing stress and energy absorption exhibit strong strain rate sensitivity (fig. 9). This response is in agreement with previous results on tubular specimens by the ACC [8] as well as other members of the Crashworthiness Working Group. There appears to be a clear threshold between quasi-static and dynamic SEA, occurring between 0.5 and 1 m/s, and is highly material-dependent. The SEA measured at 2 m/s and above oscillates about a mean value, which is 2 to 3 times lower than the SEA value measured in a quasi-static fashion.

According to Engenuity’s experimental data, the specimen/rig configuration greatly influences the force-stroke response, in particular the choice of so-called spacer height. This is defined as the height of the gap between the steel frame and the base plate (fig. 10). Depending on the crushing characteristics of the specimen, whether it occurs by brittle fracture or by frond formation, the relative spacer height has been shown to potentially affect the measurement of sustained crush stress (here defined as the load per unit of cross-sectional area of the specimen). For materials that fail in a brittle fashion and with small debris, spacer height bears no influence on the measured crushing stress. However, in case of a material that tends to form large fronds and
debris, an insufficient spacer height can lead to unrealistic measurements of crushing stress and energy absorption. However, the spacer height can be varied in the range 5 mm to 30 mm, and beyond a certain height, the average crush stress reaches an asymptotic value, which is independent from the fixture setup. It is therefore necessary to perform a thorough calibration for every material system and lay-up to be characterized in order to determine the correct spacer height.

![Test fixture and specimen](image)

Fig. 7. Test fixture and specimen (with relative trigger mechanism) developed by Engenuity.

![Load-stroke curves](image)

Fig. 8. Typical load-stroke curves for materials with good and poor SEA characteristics.
Automotive Composites Consortium and Department of Energy [9-15].

The Department of Energy (DOE) and the Automotive Composite Consortium (ACC) have dedicated a lot of effort to developing a test fixture and specimen (fig. 13 and 14) with which to characterize the energy absorption properties of different composite material systems. In particular their goal was to reproduce and isolate the spaying failure mode typical of composite thin-wall tubes, associated with the formation of fronds during crushing (fig. 15). In particular the fiber forms covered in their investigation comprised a chopped compression molding system, a continuous cross-ply laminate, a triaxial braid, and a continuous strand mat.

The specimen consists in a laminate of length 178 mm, and thickness comprised between 1.6-4.7 mm, and flat tip (no built-in trigger). Crush is initiated by means of a contoured (curved) contact profile. The fixture features an observable crush zone, a 51 mm effective stroke, frictionless roller for contact constraint, interchangeable contact profile, and roller supports to prevent buckling. However, in specimens exhibiting lower elastic properties, a metal push plate is used to reduce the unsupported length of the
specimen and prevent global buckling. The specimen is clamped in the top plate by grip inserts. Tests are conducted at quasi-static rates between 5 and 51 mm/min.

A sensitivity study explores two contact radii (6.3 and 12.7 mm), three degrees of constraint (none, loose, and tight), and three specimen widths (12.7, 25.4, and 50.8 mm). The contact profile acts as an outside collapse trigger, similar to the plug-type initiator used by the ACC [8].

Stable crushing occurs in a repeatable fashion under tight or at least loose constraint, but the unsupported (no constraint) condition doesn’t yield reasonable results (fig. 13). It is also found that an increase in profile radius causes a decrease in measured SEA, likely due to the more flexural rather than axial compression deformation experienced by the specimen tip (fig. 14). As for specimen width, it appears that the larger specimen yields higher SEA values, likely due to the amount of intact fibers enclosed in the larger area (fig. 15). For the continuous strand mat specimens the load increases up to fracture, at which point it would drop to zero, and the sequence repeats at regular intervals. This phenomenon is particularly evident in no or loose constraint conditions, and is somewhat alleviated in the tight constraint condition. For materials exhibiting such low elastic properties it is not possible to reach a stable, sustained crushing load, indicating a limitation on the usability of the material for energy-absorbing applications, but also a lower limit in the range of materials that can be successfully characterized.

Results from previous ACC/DOE work have shown a great dependence of SEA on the strain rate, being at least 10-30% higher at quasi-static loading rates. They suggest that a detailed understanding of the rate dependency of damage mechanisms, hence energy absorption characteristics, needs to be gained.

![Fig. 11. Test specimen used by the DOE.](image-url)
Fig. 12. Three different views of the test fixture developed by the DOE.
Fig. 13. Influence of degree of buckling constraint on load-stroke traces, and explanation of the three constraints investigated.

Fig. 14. Influence of profile (external plug-type trigger) on load-stroke diagram.
Considerations on the four set-ups

Each of the four testing methodologies is characterized by a different specimen as well as fixture designs, which are summarized in tables I-III. A comparison of the various traits will be given in this paragraph, and some observations will be derived that will help in the development of future test methodologies.

Some advantages and problem areas have been identified for each of the specimens tested. With regards to trigger mechanisms, it appears that the 45-degree chamfer did not yield the same satisfactory results as in the case of tubular specimens. However, this finding first observed by the Army was not subsequently substantiated by other research. The steeple, notch, and saw-tooth (jagged) triggers all exhibit similar responses, but the advantage of the last two is that they prevent the origination of the large, initial delamination that splits the laminate into two fronds, hence induces the double spike in the load-stroke trace. The DOE specimen, instead of using a molded-in J trigger as suggested by the Army employs a flat specimen with a J base plate, which has the same effect of inducing splaying of the frond.

Table I. Specimen dimensions:

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
<th>Length/Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARL</td>
<td>76, 152</td>
<td>51, 102</td>
<td>2.0, 4.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Engenuity</td>
<td>80</td>
<td>40</td>
<td>1.2-10.0</td>
<td>2</td>
</tr>
<tr>
<td>London</td>
<td>90</td>
<td>60, 70, 80, 90</td>
<td>n/a</td>
<td>1.5-1.0</td>
</tr>
<tr>
<td>DOE</td>
<td>177.8</td>
<td>12.7, 25.4, 50.8</td>
<td>1.6-4.7</td>
<td>14-3.5</td>
</tr>
</tbody>
</table>

Table II. Specimen set-up:

<table>
<thead>
<tr>
<th>ID</th>
<th>Trigger</th>
<th>Base</th>
<th>Bottom support</th>
<th>Lateral support</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARL</td>
<td>Steeple, Notch, (45° chamfer)</td>
<td>Flat</td>
<td>Resting</td>
<td>Knife (whole length)</td>
</tr>
<tr>
<td>Engenuity</td>
<td>Saw-tooth</td>
<td>Flat</td>
<td>Resting</td>
<td>Widths and sides/ free</td>
</tr>
<tr>
<td>London</td>
<td>Steeple</td>
<td>Flat</td>
<td>Resting</td>
<td>Knife (whole length)</td>
</tr>
<tr>
<td>DOE</td>
<td>Flat</td>
<td>Curved</td>
<td>Hanging</td>
<td>Rollers widths/ free</td>
</tr>
</tbody>
</table>
The knife-edge supports used by the Army and the London fixture have the merit of promoting a failure mode that is representative of true crushing of the material. The DOE and Engenuity fixtures on the other hand leave maximum freedom to the specimen in proximity of the damage formation zone, and future tests should aim at maximizing the degree of freedom of the specimen in the vicinity of the tip. The location and shape of the supports needs to be changed for the Army and London specimens to allow frond formation and curling at the tip. As originally observed by the Army, it is necessary to decouple specimen support from loading support, and an improved design of the London fixture could be derived using a separate set of guiding frames for the moving crosshead. The Engenuity fixture, which decouples the support and the load introduction structures, also allows for free crushing to occur at the tip, but has the disadvantage that it requires extensive calibration to determine a suitable spacer height for each material system.

As for the general appearance of the load-stroke diagrams, the Army fixture has the advantage that it yields plots that most closely resemble those typical of tubular specimens. The fixture by Engenuity Ltd. Is somewhat similar but has the tendency to exhibit too many serrated oscillations. The fixture by the University of London shows an undesirable trough due to the initial splaying, and then tends to require a large stroke before attaining a mean crushing force. The DOE specimen appears to be very sensitive to the shape and degree of end constraint, which can lead to plots of difficult interpretation. It appears that for the large radius and for no or loose supports the specimen tends to exhibit the formation of a trough similar to the ones given by the steeple triggers. However, if an adequate degree of support is obtained, and a relatively tight radius is achieved, the specimen has the potential to yield interesting and relevant force-stroke curves.

The support provided by the DOE specimen, although inefficient for very low modulus materials, is in general the most suitable for accurate SEA measure, as the rollers provide the minimum amount of friction compared to the knife-edge supports or to the fully supported specimen used by Engenuity.

With regards to specimen size, it appears that the most significant factor is the slenderness ratio of the plate. The DOE and the University of London report contrasting results with respect to specimen width, the former observing an increase in SEA, the latter a decrease. It is likely that in the London fixture the amount of energy absorbed in tearing at the support, which is independent for the unsupported width, has a decreasing influence on the overall energy absorbed. In general, although it is suggested to maintain a minimum length to width ratio of 1.5, it is necessary to better understand the size effects reported by the DOE.

Lastly, it is necessary to characterize and understand the dynamic threshold effect (preliminary identified in the range of 0.5-1 m/s), and to verify that dynamic SEA values
can be reduced by at least a factor of two compared to quasi-static results. In that case it would be necessary to perform future tests under dynamic conditions, at a velocity set safely above the individuated threshold. As an alternative two test methodologies could be specified, one at quasi-static and one at the dynamic rate.

Conclusions

The development of a simple and inexpensive test method by which to characterize the Specific Energy Absorption of composite material systems and laminate designs is required. Thee test methodologies were found in the literature, and they all derive from the common Army fixture developed in the early 1990’s. Sensitivity studies were done more or less systematically to identify the dependence of the test specimen and fixture on intrinsic and extrinsic variables. Most often a stable, sustained, splaying failure of the specimen was obtained, which resembled the crushing behavior of tubular specimens, which has received more attention over the years. Some trends were observed, but there is the need for further investigating some of the behaviors observed before attempting to develop a unified test method. Furthermore, this type of test method is likely to remain forever highly dependent on the fixture/ specimen combination due to the complexity of the failure modes that occur both in the proximity and away from the crush front. Hence this kind of test method, just like the one for tubular specimens, will always yield a measure of a structural property, not of a material property.

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References


Biographical Notes

Paolo Feraboli joined the Department of Aeronautics and Astronautics of the University of Washington in the summer of 2005, as Assistant Professor in Aircraft Structures and Materials. He was previously Visiting Researcher at NASA Langley Research Center in the Mechanics and Durability Branch. Paolo earned his Ph.D. from the University of California at Santa Barbara, and holds degrees in Mechanical Engineering from the University of Bologna, Italy. His major areas of interests are composite structures design for damage resistance and tolerance, and experimental material characterization. He is chairman of the MIL-HDBK-17 Working Group on Crashworthiness, which is promoting in conjunction with the ASTM D30 Committee the development of the first test standard for composite energy absorption. Prior to moving to the U.S., Paolo worked for Automobili Lamborghini S.p.A. in Sant’Agata Bolognese where he contributed to the development of composite structural components for the Murciélago lineup.