TOWARD THE DEVELOPMENT OF A TEST STANDARD FOR CHARACTERIZING THE ENERGY ABSORPTION OF COMPOSITE MATERIALS: PART II

Paolo Feraboli, Francesca Garattoni, Francesco Deleo
Aeronautics & Astronautics
University of Washington
Box 352400, Seattle, WA, 98195-2400.
E-mail: feraboli@aa.washington.edu

Abstract

One of the key factors preventing the widespread adoption of composites in primary crash structures is the absence of specialized test methods for the characterization of specific energy absorption (SEA). Aside from thin-walled tubular specimens, a limited number of attempts have been made at developing test specimens that are easier to manufacture. The possibility to employ a self-stabilizing corrugated plate specimen has been previously presented. In this study, results from three corrugated plate geometries are compared with those of a flat plate specimen. The latter is tested using ad hoc developed support fixture, which is based on an initial concept proposed by NASA/ Army. Preliminary results show that the flat specimen SEA results do not agree with those of the corrugated ones, thus emphasizing the complex nature of SEA.

Introduction

The four necessary conditions for survival during a vehicle collision are maintaining sufficient occupant space, providing adequate occupant restraint, employing energy-absorbing devices, and allowing for a safe post-crash egress from the craft [1]. Specifically, the energy-absorbing components, primary vehicle structure and secondary systems must all be designed to work together to absorb the vehicle kinetic energy and slow the occupants to rest without injurious loading. Vehicle impact events involve the simultaneous structural response of multiple components, and often the energy-absorbing devices experience combined loading, resulting from axial crushing and bending. However, the complexity of these events is such that often these processes need to be approached individually, and usually the energy-absorbing components are designed to dissipate energy under controlled collapse in simpler loading configurations. In general, while the total energy dissipated during a crash depends on the overall vehicle system deformation, the crash-oriented design of the individual structural subcomponents of simple geometry can provide a great increase in structural crashworthiness and survivability, with an acceptable increase in overall vehicle cost. For this reason, structural elements that provide energy absorption have received special attention in the literature [2-6].

Energy absorbers can be found in the front end of all modern passenger cars, in the form of collapsible tubular rails [4, 5], or in the keel of modern aircraft (figure 1) as collapsible floor supports [6-9]. These elements have been traditionally made of steel or aluminum, which absorb energy through controlled collapse by folding and hinging, involving extensive local plastic deformation. However, the introduction of composites in the primary structure of modern air- and ground- vehicles presents special problems for the designer dealing with occupant safety and crashworthiness. The energy-absorbing behavior of composites is not easily predicted due to the complexity of the failure mechanisms that can occur within the material. Composite structures fail through a combination of fracture mechanisms. These involve a complex series of fiber fracture, matrix cracking, fiber-matrix debonding, and interlaminar damage (delamination) mechanisms. The brittle failure modes of many polymeric composite materials can make the design of energy-absorbing crushable structures difficult. Furthermore, the overall response is highly dependent on a number of parameters, including the geometry of the structure, material system, lay-up, and impact velocity. Thus, extensive substructure testing is usually required within a building block approach to the design of crashworthy structures, in order to verify that a proposed configuration will actually perform as intended.

Figure 1. Composite-intensive energy-absorbing subfloor of commuter aircraft [7]

Recent studies [4, 9] identified the key factors preventing the introduction of composites in primary crash-resistant structures in aircraft and automotive as the absence of:

- available design guidelines,
- accurate and inexpensive simulation tools,
- specialized test methods for the characterization of energy-absorption,
- accessible and adequate composite material property database.

Only a coordinated cross-organizational effort can lead to substantial advances in all these fronts through systematic investigations of current practices and suggested improvements. Such efforts are for example being made the Crashworthiness Working Group of the CMH-17 (Composite Materials Handbook, formerly known as MIL-HDBK-17), which comprises representatives from the aerospace and automotive industry, academia, and government laboratories and operates in parallel with ASTM Committee D-30 on Composite Materials. Similarly, the Energy Management Working Group of the Automotive Composites Consortium (ACC), which comprises members of the three largest US automotive manufacturers and of the Department of Energy, has dedicated over two decades to advancing the understanding and confidence in composite crash structures.

When analyzing the energy absorption behavior of a structure, a few key definitions are required:

- Peak Force, the maximum point on the Force-stroke diagram.
- Average Crush Force, also referred to as Sustained Crush Force, is the displacement-average value of the force history.
- Stroke, also referred to as crush or displacement, is the length of structure/ material being sacrificed during crushing.
- Crush Initiator, or trigger mechanism, a design feature that facilitates the progressive collapse of the structure, thus reducing spikes in the load-stroke diagram. Without a crush initiator, composite structures have a tendency to reach unacceptably high values of peak force, and can fail in an unpredictable and sometimes unstable manner. Triggers can manifest in the form of plug-type insert, chamfer, or embedded ply drop.
- Energy Absorbed (EA). Total area under the Force-Stroke diagram.
- Specific Energy Absorption (SEA). The energy absorbed per unit mass of crushed structure.

The ability of a material to dissipate energy can then be expressed in terms of SEA, which has units of J/g, and indicates a number, which for composites is usually comprised between 15 and 80 J/ g. Setting the mass of structure that undergoes crushing as the product of stroke *l*, cross-sectional area *A*, and density ρ:

$$SEA = \frac{EA}{\rho \cdot A \cdot l} \tag{1}$$

The EA can be calculated as the total area under the force-stroke diagram:

$$EA = \int F \cdot dl \tag{2}$$

where *F* is the instantaneous crush force.

Review of existing work

The vast majority of the work in the area of crashworthiness energy absorption has focused on thin-wall tubular specimens [2-6]. Only a selected number of attempts have been made at developing a coupon-sized test method to determine the SEA of composite materials, and it evolved in two directions. The first approach features simple specimens, such as flat plates with or without built-in crush initiators, and very complex and costly anti-buckling support fixtures. The second approach features self-supporting specimen geometries, which require dedicated molding tool for manufacturing, but don't require the use of specific test fixtures. The Army Research Laboratories (ARL) in conjunction with Virginia Tech performed pioneering work done in the early 1990's at NASA Langley Research Center. The method proposed was considered by several laboratories [10, 11] but was eventually abandoned due to some limitations. Over the years however, the NASA/ ARL coupon idea was further developed, independently and in very different ways, by an engineering services firm based in the UK, Engenuity Ltd, which currently uses it commercially to provide SEA data to several motorsport and automotive companies. Even less effort has been aimed at developing self-supporting specimens, and the German Aerospace Research Center (DLR) is the only one that has developed and currently employs one of semi-circular shape [10]. The following paragraphs will review in detail the advantages and shortcomings of each of the above test methods in order to introduce the proposed test method.

Flat specimens with support fixtures

The ARL group proposed a test method featuring a flat plate rectangular specimen (figure 2 left) and a dedicated test fixture designed to provide buckling stability during crushing [12-14]. Lateral support to the specimen is provided through knife-edges, which fit into a set of four inner vertical posts. Two types of trigger mechanisms, the so-called "steeple" and the "notch" (a staggered, transverse machined profile) were both employed with success. However, the steeple trigger had a tendency to generate a double peak in the initial portion of the load-stroke diagram, possibly due to the formation of a long delamination along the specimen length. The 45-degree chamfered trigger, commonly used in tubular specimens, was not employed because apparently unable to initiate crushing. Limitation of the fixture was that the knife-edge supports promote local tearing of the plate and fronds (figure 2 right). This failure mechanism is responsible for vast amounts of energy absorption, comparable to the amounts dissipated in frond formation, and thus leads to unrealistic SEA values. Although the fixture yielded force-stroke traces that closely resembled those of tubular specimens, the SEA measurements obtained with this method did not compare well with others previously obtained [3] by testing thin-wall tubular specimens of the same material systems and laminate designs. It is likely that the two specimens fail by somewhat different mechanisms. In particular, the off-axis fibers provide hoop constraint to the tubular shape, thus suppressing outward brooming of the longitudinal fibers, and facilitating fiber fragmentation. On the other hand, for flat shapes, no such constraint is available, and it leads to the creation of a strong interlaminar separation front (similar to a traveling wedge test for adhesive joints). It can be summarized that for flat plate specimens, delamination suppression is indeed crucial to maintain high levels of energy absorption, however the material cannot be over-constrained and it has to be left free to follow its natural failure mode.

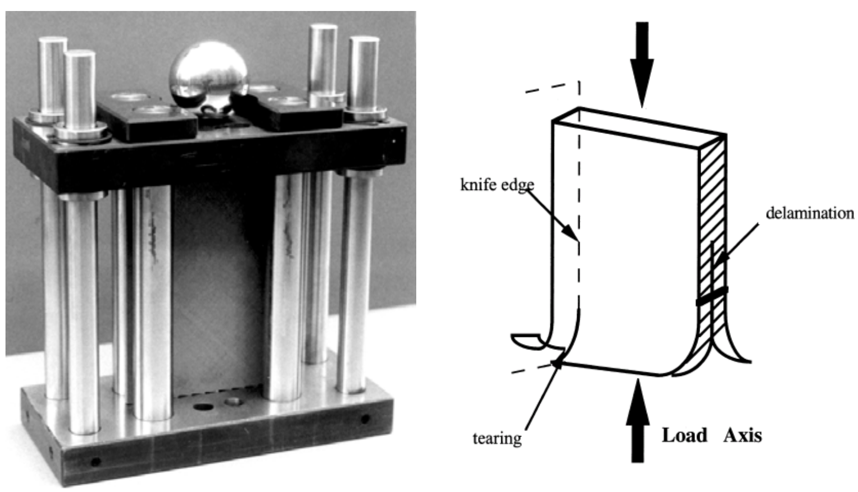


Figure 2. Left) Test fixture and specimen developed by NASA/ ARL [12-14]. Right) Undesirable characteristic of this set-up is the tearing at the supports, which produces unrealistic SEA values [15, 16].

In the effort to understand the validity of the proposed flat plate specimen, Bolukbasi and Laanen [11] conducted a systematic comparison of three structural configurations. Flat plates, angle sections, and C-channels manufactured with identical materials, lay-ups, and crush initiators were crushed under the same quasi-static conditions. Although the number of specimens tested was limited, as the selection of laminate lay-ups, it was confirmed that the flat plates tested with the ARL fixture yielded higher SEA measurements than any of the self-supporting specimens.

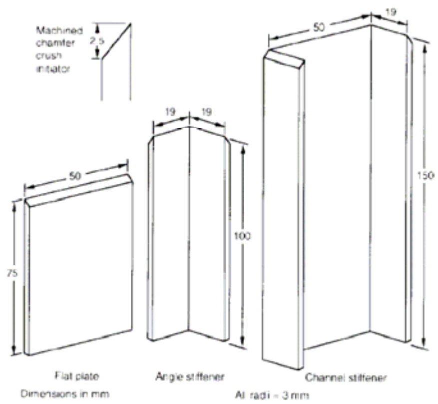


Figure 3. Systematic comparison of specimen geometry on the measured SEA [11].

Table 1. Referring to figure 3, results of the systematic comparison of specimen geometry on the measured SEA in J/g for two stacking sequences [11].

Lay-up	Flat	Angle	C-channel
$[45]_{10}$	89	54	68
$[45_2/0_2/45_2]_s$	96	67	83

Building on the ARL concept, Engenuity [15] developed a rig that provides buckling stability by fully constraining lateral and out-of plane movement of the coupon, while at the same time enables it to deform freely in the proximity of the crush front (Figure 4). The specimen is a flat rectangular plate, and features a trigger with saw-tooth (jagged) edge. Such trigger is planar, as the notched trigger used by ARL, since its profile does not vary through the specimen's thickness, unlike the chamfer and steeple triggers. The fixture features Delrin supports to reduce the friction on the surfaces contacting the specimen, and can accommodate specimens of varying thickness. The greatest difference with respect to the ARL fixture is that the specimen is here allowed to deform freely in proximity of the crush front. This is achieved by leaving an unsupported distance between the specimen supports and the base-plate. This distance, which Engenuity refers to as "spacer height", allows the material to crush in a more natural way. However, the unsupported height affects the degree of delamination suppression that can be guaranteed. This in turn means that material systems with high interlaminar fracture toughness, hence resistance to delamination propagation, can achieve high values of SEA even in presence of large unsupported heights. On the other hand, more brittle systems offer poor crush performance, and fail by delamination propagation on the interlaminar front [15]. To the limit, all materials will absorb large amounts of energy if the spacer height is zero, as in the ARL fixture. This effectively dictates a strong dependence of SEA measurement on unsupported height, and Engenuity varies this spacer height in the range 5 mm - 30 mm for every material characterization operation.

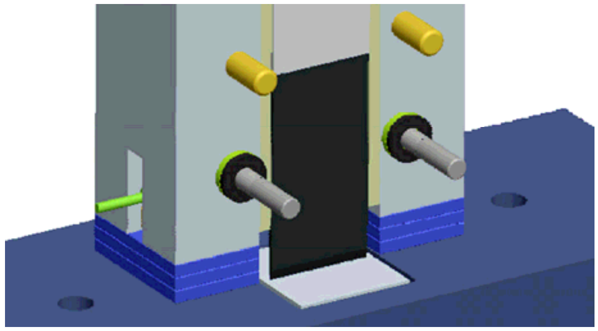


Figure 4. Test fixture and specimen (with relative trigger mechanism) developed by Engenuity.

Contoured self-supporting specimens

In order to compare the SEA of different composite systems and laminate designs, Johnson and Kohlgruber at DLR [10] developed a tube-segment specimen, which is easy to fabricate (does not require an internal mandrel) and gives reproducible crush failures under quasi-static and dynamic axial loads. The end-lips, or flanges, provide additional stability to the semicircular shell, but the specimen is also mounted with adhesive in a contoured aluminum base (Figure 5). A 45-degree chamfer is machined on the other end to initiate crushing. Although it is not clear how the specimen came to be designed to the final proposed geometry, it was shown that the specimen yields desirable and stable crushing force-stroke traces. Current literature is however limited and further work is needed to show how the measured SEA compares with that of other geometries, such as tubular specimens.

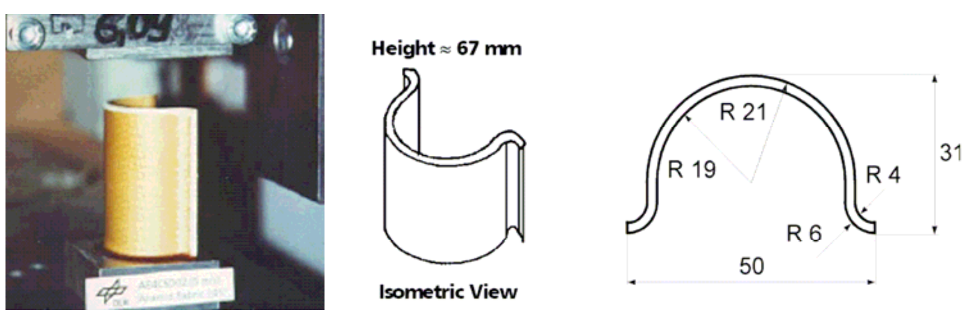


Figure 5. Semi-circular self-stabilizing specimen developed by DLR [10], all dimensions in mm.

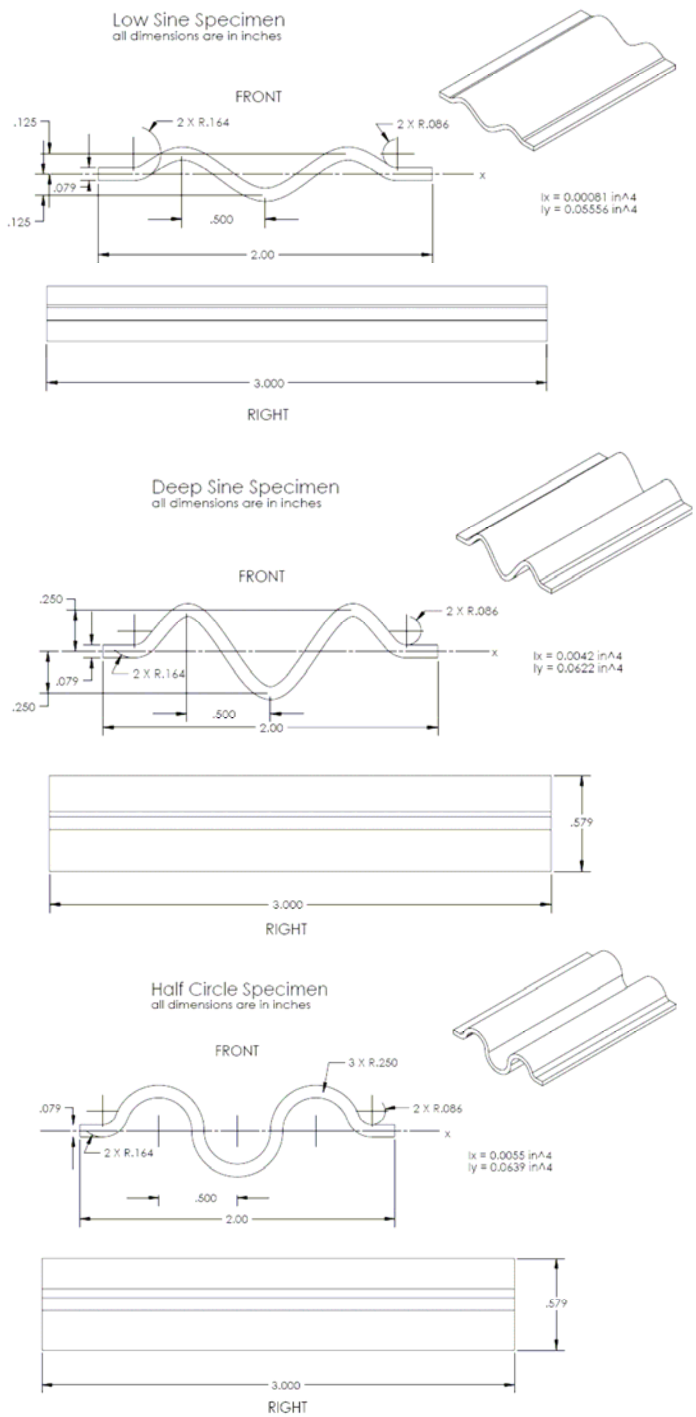
Corrugated Specimens

Reviewing the proposed coupon-level test methodologies [16], the approaches featuring a simple specimen shape and a complex test fixture appear to be characterized by several intrinsic variables that need to be carefully understood (such as unsupported height, degree of constraint, and trigger type). On the other hand, corrugated webs have been used for several energy-absorbing applications in fixed wing, rotorcraft and racecar structures [7, 8, 10] because of their favorable crushing response (Figure 1). In [17] a self-stabilizing specimen having corrugated web geometry was presented. Sensitivity study was performed to investigate the effects of several intrinsic and explicit parameters on the crush characteristics of the specimens. Detailed results of the investigation can be found in [17]. In the present paper, specimens using the same material system, curing cycle, stacking sequence are tested as corrugated webs and as flat plates in a modified NASA/ ARL fixture to compare the failure mechanisms and energy absorption properties.

Three different corrugated shapes are investigated in the attempt to understand how the degree and shape of corrugation affect both stability and crush performance of the section. The specimen denoted “low sine” features a sinusoidal segment, of amplitude 3.2 mm (0.125 in.), repeated three times at alternating sides with respect to the midplane (Figure 6). The specimen denoted as “high sine” features a sinusoidal segment, of amplitude 6.4 mm (0.25 in.), repeated three times at alternating sides with respect to the midplane (Figure 7). The specimen denoted as “semicircle” features a semicircular segment, of radius 6.4 mm (0.25 in.), repeated three times at alternating sides with respect to the midplane (Figure 8). Each repetition of the unit corrugation about the midplane is a half-period. All three segments have end-lips, or straight edges, of material on each side of the corrugation for additional stability. The semicircle specimen is chosen to reproduce results similar to the ones by the DLR [10], although the alternating geometry provides additional stability and removes the need for bonding the specimen to a machined base-plate. The high sine specimen has a nearly identical moment of inertia, and provides insight in the effect of sharper curvature changes on the measured SEA. Lastly, the low sine specimen is supposed to isolate the effect of a lower moment of inertia and more gentle radii on the SEA measurement.

Both corrugated and flat specimens are manufactured with a $[0/90]_{3s}$ lay-up with the same commercial-grade 250F degree cure carbon fiber/ epoxy unidirectional prepreg system. Specimens are manufactured by press-molding through a set of aluminum matching tools (Figure 9). Each coupon (corrugated and flat) is 76.2 mm long (3 in.) and 50.80 mm wide (2 in.) from end-lip to end-lip. Average laminate thickness is 12 plies 0.06 in (1.5 mm). Detailed dimensions are shown in figures 7-9. Corrugated specimens are machined from the molded panel, and are further chamfered with a single-sided 45-degree chamfer (Figure 10) such as the one used in tubular specimens and in the DLR specimen [10]. Flat specimens are machined with a steeple (double 30-degree chamfer) due to the inability to generate stable crushing with a single 45-degree chamfer (mostly attributable to the asymmetric crush initiation)

All tests are conducted at a quasi-static rate of 50 mm/min (2.0 in./ min), which is noticeably below any dynamic effect previously reported for modern systems [5], usually around 1 m/sec (40 in./sec). Specimens are tested in vertical configuration, resting on a polished hardened steel surface (Figure 11). The crushing plate is free to slide along four vertical posts, which use roller bearings for alignment and reduced friction. A selfaligning sphere is used to introduce the load from the test frame onto the crushing plate. For each configuration at least two specimens are tested, which are not sufficient to build a statistical database but can provide insight in the validity of the proposed method.



Figures 6-8. From top to bottom, detailed geometries of low sine (Figure 6), high sine (Figure 7) and semi circle (Figure 8) specimens.

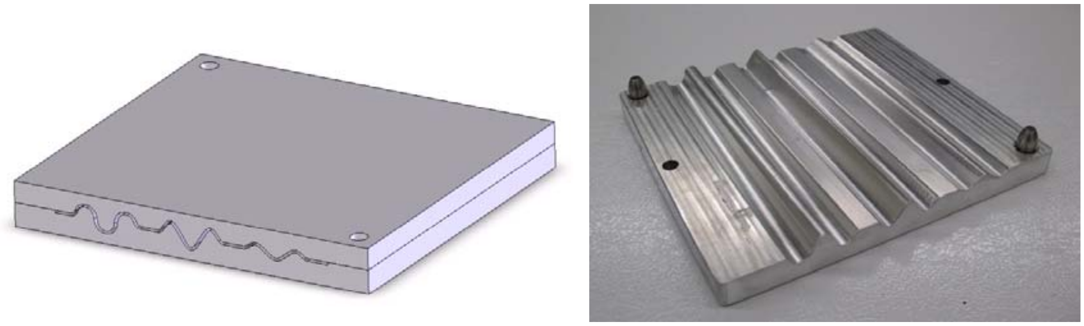


Figure 9. Molding tool.

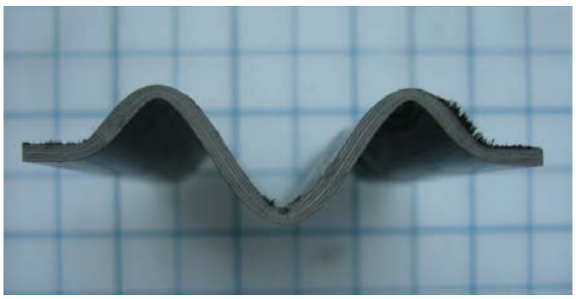


Figure 10. High sine specimen with chamfered end.

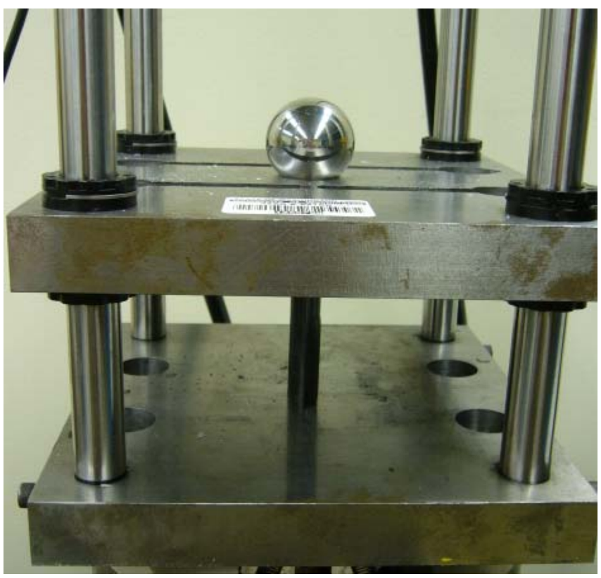


Figure 11. Specimen ready for testing in the test fixture.

All configurations tested achieved stable sustained crushing, with a combination of progressive frond formation and brittle fracturing. In all specimens but the one without the chamfer crushing initiated with load efficiencies near unity, thus suggesting that the simple triggering mechanism is adequate to avoid high spikes in the load trace. Exemplar load-stroke trace of configuration 3 is shown in figure 12, from which the energy absorbed curve can be calculated using (2) and the SEA using (1). The results are normalized to their respective maximum values in order to be plotted in one chart. The EA curve is perfectly linear, and the SEA plot shows also a nearly perfect "elastic-plastic" behavior. A typical crushed specimen is shown in Figure 13, and it exhibits a combination of splaying (or frond formation) and brittle fracturing (transverse shearing). The semi circular specimen exhibited consistently higher SEA that the high-sine specimen, which in turn yielded higher SEA than the low sine specimen (Figure 14).

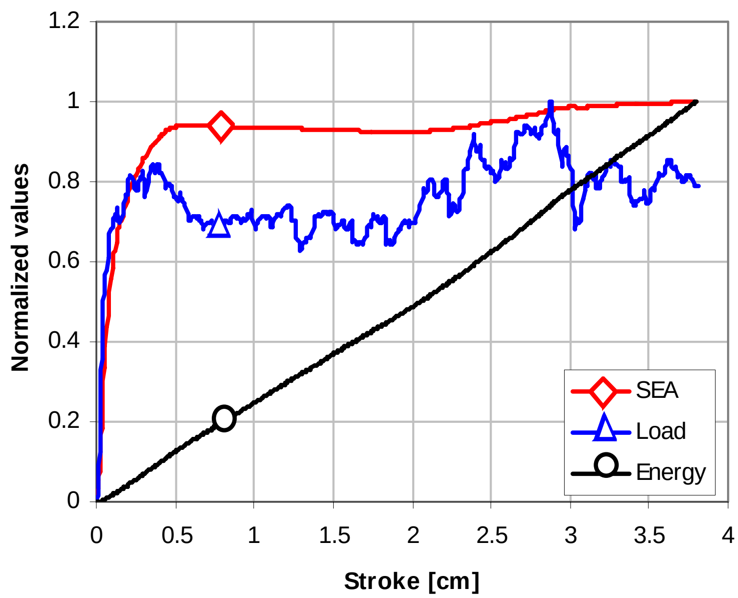


Figure 12. Load, SEA, and EA vs. stroke traces for high-sine corrugated web geometry.

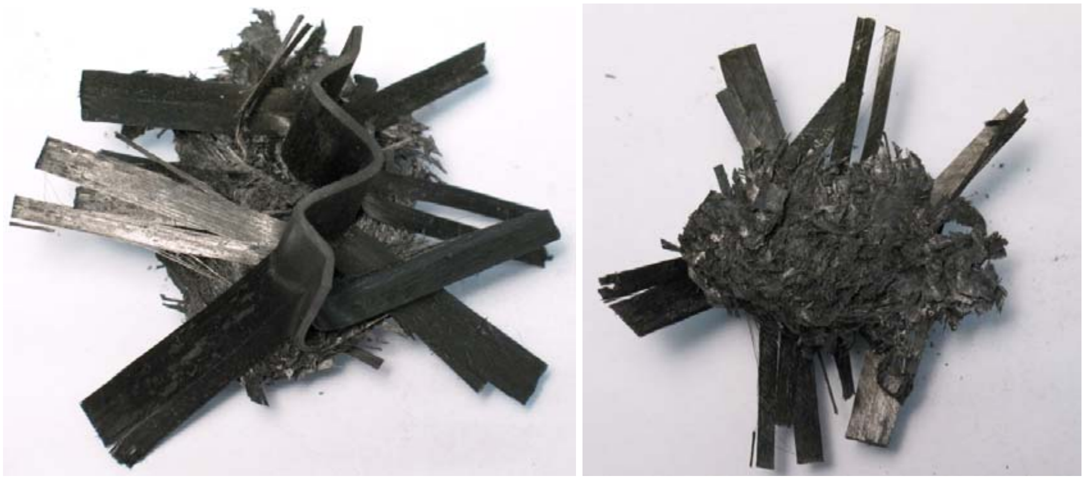


Figure 13. Top and bottom view of high-sine crushed specimen.

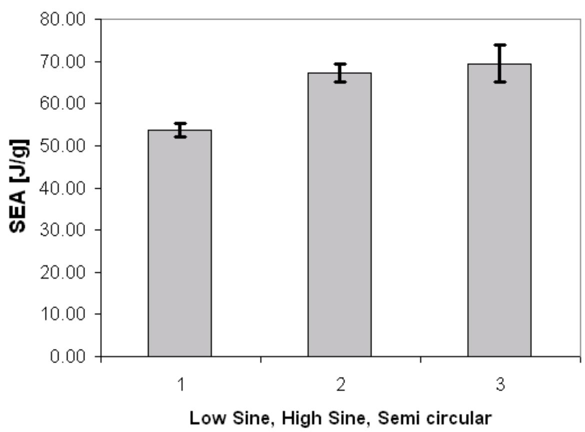


Figure 14. Comparison of corrugation shape on the measured SEA.

Comparison with flat specimens

The NASA/ ARL fixture is modified to accommodate for an unsupported height, which allows the specimen to deform freely in proximity of the crush front (Figure 15). This is achieved by using separate sets of knife-edges that vary in length in order to leave clearance with the base plate. Close-up view from above of the knife edges and the means by which they support the specimen is shown in Figure 16. Unsupported height is varied between 0 and 1 inches, with intermediate values at 0.125, 0.25, 0.5, 0.75 inches. The modified fixture enables the specimen to splay the fronds that are forming in a free fashion, and also prevents accumulation of a thick debris wedge between the knife-edges. On a different note, the fixture is also designed to accommodate specimens of various thicknesses, unlike the original NASA/ ARL fixture.

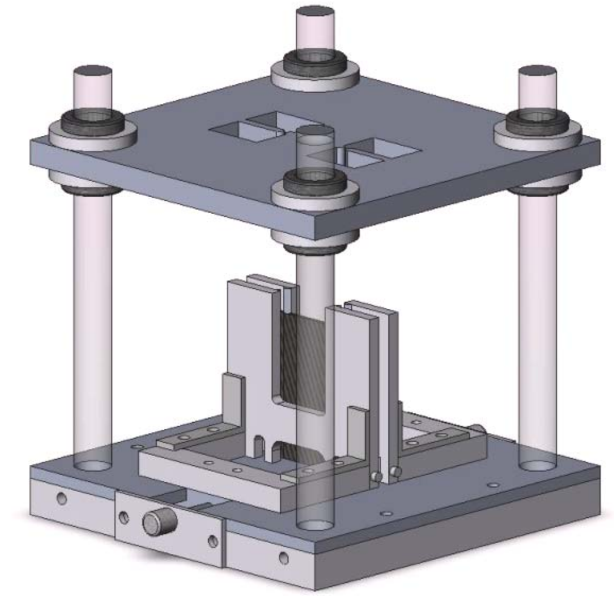


Figure 15. Modified NASA/ ARL fixture for flat specimens

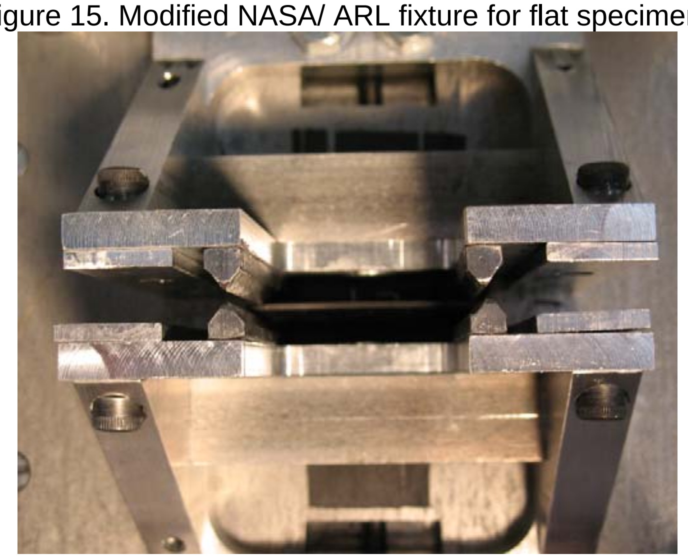


Figure 16. Top view of the knife edges supporting the specimen.

The modified fixture enabled the highlighting of a very interesting phenomenon. For zero value of unsupported height, which means in a situation identical to the original NASA/ ARL fixture, the specimens crush in a stable manner, as shown in Figure 17, which plots the normalized values of load, total energy and SEA against stroke. The SEA curve in particular exhibits a very constant shape, similar to that of the corrugated specimens of figure 12.

However, the same limitation for the 0-inch setup that was mentioned in during the literature review is here repeated. Inspection of the failed specimens reveals that the outermost portions of the laminate (Figure 18), outside the knife-edges, have undergone extensive tearing that may have contributed an unknown amount of energy to the overall measurement.

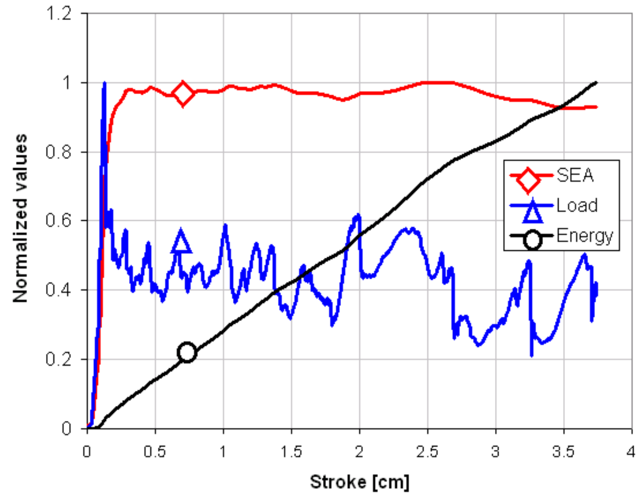


Figure 17. Load, SEA, and EA vs. stroke traces for flat plate geometry at 0 inches of unsupported height (same as original NASA/ ARL fixture).

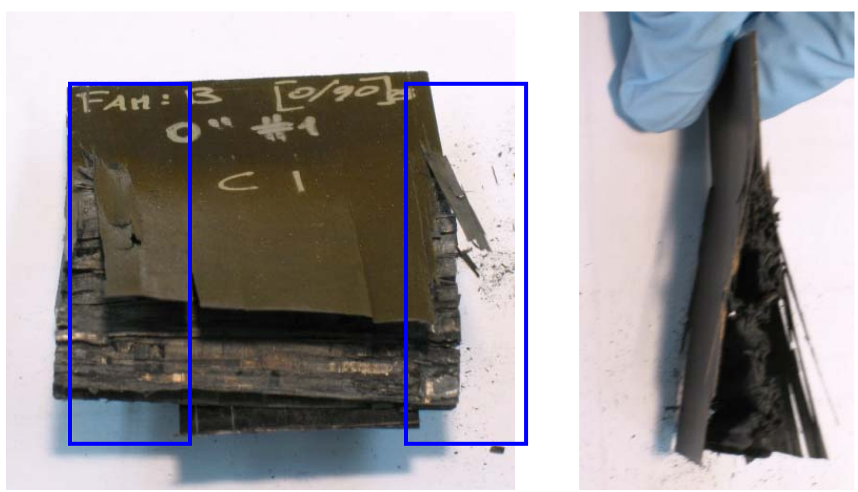


Figure 18. Front and side view of the crushed flat specimen at 0 inches of unsupported height (same as original NASA/ ARL fixture)

Varying the unsupported height to 0.125 inches or above on the other hand, dramatically changes the observed behavior. The fronds that are forming are allowed to deform freely (Figure 19 a, b), while at the same time an evident delamination front is enabled to propagate along the specimen in the proximity of the midplane. This delamination propagates in a fashion similar to a traveling wedge test, until it terminates when the specimen contacts the knife-edges, which act as to suppress the delamination. The freedom of the specimen to fail by frond formation on the other hand prevents it from failing by crushing like the specimen with zero unsupported height. This can be seen in Figure 20, where the specimen exhibits a clean delamination surface. It seems therefore that delamination propagation and crushing are the two competing failure modes, if global buckling is excluded, and they are very sensitive to unsupported height.

The load, energy and SEA curves are plotted against stroke in Figure 21. The EA curve clearly shows that after the initial triggering and formation of the delamination front, which contributes to high amounts of load and energy, its slope dramatically reduces to a nearly horizontal line. The low energy absorption, constant throughout the remaining portion of the test, is due to the propagation of the delamination along the laminate. In parallel, the SEA curve shows a progressive drop in value from the one measured right after triggering, and tends to and tends to an asymptotic value, which is nearly negligible. Unlike the 0-inch support, stable crushing is not achieved, and therefore it is even impossible to determine a true SEA for the plate.

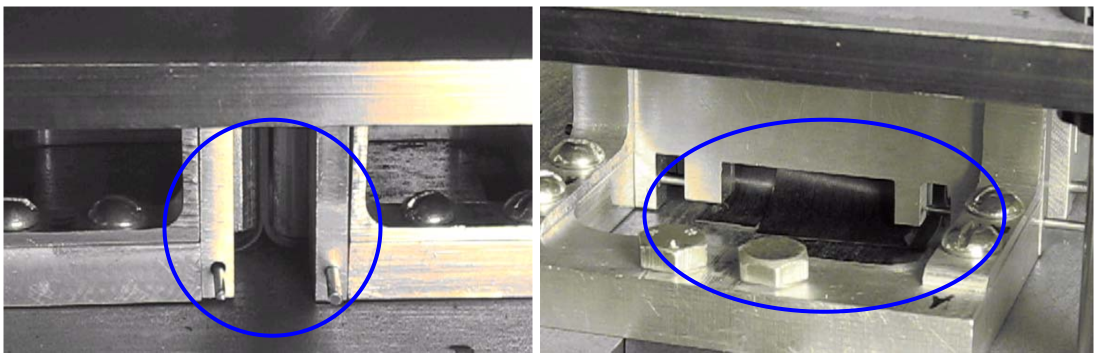


Figure 19 a, b. Flat specimen undergoing splaying in the fixture for unsupported height of 0.125 inches and above.

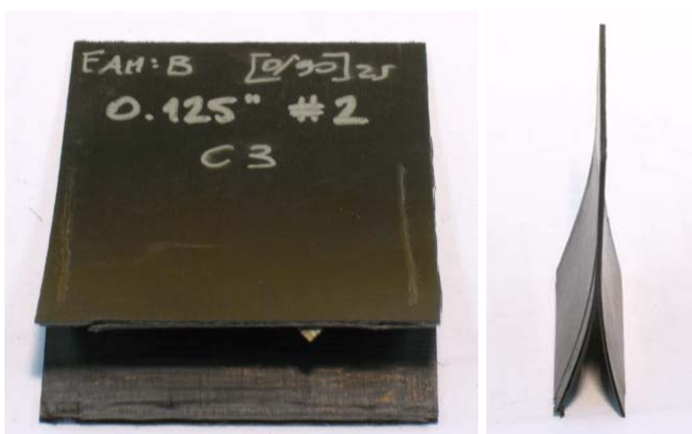


Figure 20. Front and side view of the crushed flat specimen at 0.125 inches of unsupported height or higher.

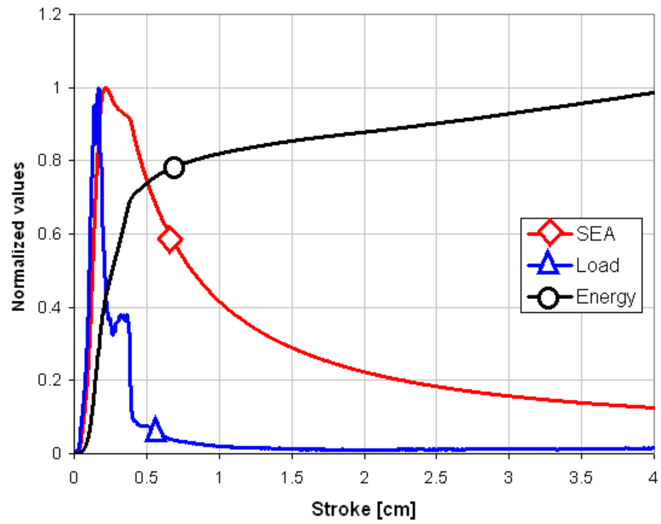


Figure 21. Load, SEA, and EA vs. stroke traces for flat plate geometry at 0.125 inches of unsupported height or higher.

For unsupported heights other than 0 inches, it has not been possible to achieve stable, sustained crushing, which is associated to an average sustained crush force. This in turn makes it impossible to use the definition of SEA itself. Figure 22 shows how the measured value of the SEA varies according to when the test is stopped. The reason is that while the initial portion of the test contributes large amount of energy dissipated (up to 0.5 cm), the remaining portion dissipates a negligible amount. By 1 cm, the SEA has halved, and by 3 cm it is less than a fourth of the initial SEA. Therefore, if the tests are prolonged to stroke values that are progressively larger, the measured SEA will progressively diminish. Therefore it becomes particularly important to refer the value of the stroke where the SEA is calculated, and in order to perform comparisons such value needs to be kept constant. By averaging the values of SEA up to the point where the test is terminated, an average SEA can be calculated, and is shown as constant line in Figure 22. However, such value does not provide a useful or relevant indication of how the material behaves.

Summarizing the SEA values obtained, which are measured for a constant value of approximately 4 cm of the stroke, or about half the specimen length, it is possible to build the curve in Figure 23. The plot shows how the SEA measured from the flat specimens drops drastically for unsupported heights other than 0 inches, and that such value is constant. This in turn seems to suggest that the delamination propagation/ splaying mode remains unchanged between the various spacer heights. Another important observation is that even at 0 inches, the measured SEA falls between 25 and 35 J/g, noticeably less than for the various corrugated specimens of identical lay-up, material system and thickness. The band for corrugated specimens comprises the SEA values for low-sine, high-sine and semicircular shapes, which span the region between 50 and 70 J/g. This in turn suggests that inherently different failure modes occur between the flat and corrugated geometries, and further work is needed to isolate and understand what they are.

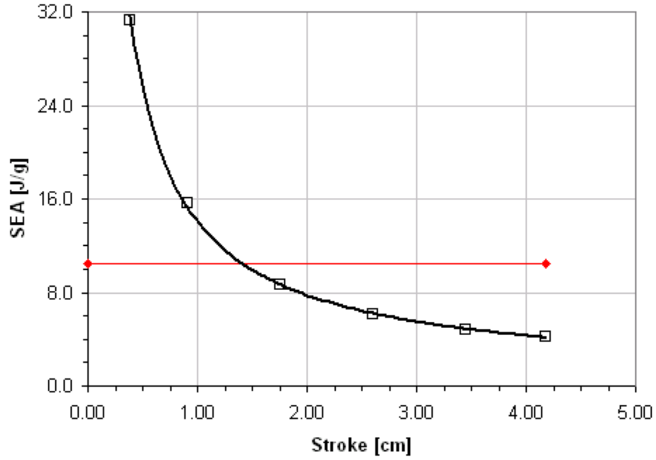


Figure 22. Variation of measured SEA with duration of test (used stroke).

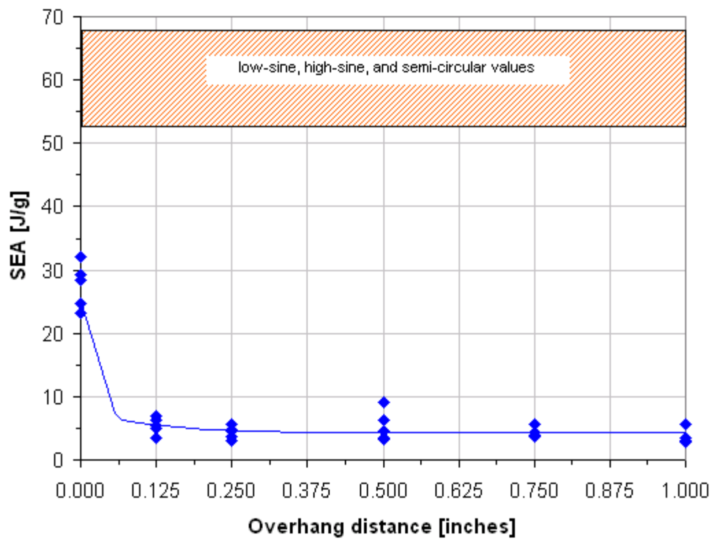


Figure 23. Variation of SEA measured with unsupported height, and comparison with the values from three corrugated shapes.

5. Conclusions

Comparison of the crushing behavior of three different corrugated web specimens and a flat plate specimen was performed. A specialized test fixture was developed to study the ability to measure SEA by means of flat plate specimens, building on a previous fixture proposed by NASA/ Army. The fixture allowed for modifying the degree of constraint of the specimen in proximity of the crush front, and therefore a variable degree of frond formation and splaying. Preliminary results seem to suggest that the self-stabilizing corrugated geometries are able to capture all relevant trends of material, while flat specimens are less likely to give relevant measures of SEA due to the inability to achieve sustained, stable crushing and to recreate the same failure modes as more complex geometries. Further work needs to be performed to fully address experimentally and analytically the differences between the observed failure modes.

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