2008

Test Methods for Composites Crashworthiness: A Review

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Abstract

Crashworthiness is a material's ability to absorb energy during a vehicle crash. Modern automobiles, aircraft, rail vehicles, and marine vessels incorporate crashworthy structures. The use of composite materials, with their high specific strength and stiffness, can result in efficient and safe vehicles. Mechanical testing is essential for obtaining a deeper understanding of the crashworthiness capabilities of composite materials. This review highlights the many aspects involved in crashworthiness testing of composites, including a brief overview of the field of crashworthiness, general crushing behavior, typical testing methodologies, and the effect of the loading rate and friction on test results.

Introduction

Mechanical testing is an essential part of the study of composites crashworthiness. It has historically been, and remains, the primary means by which the crashworthiness behavior of composites is determined. Testing is foundational to building empirical relationships and computational models for use in the design of crashworthy composite structures. The following review highlights the many aspects involved in crashworthiness testing of composites. Topics discussed include a brief overview of the field of crashworthiness, general crushing behavior, typical testing methodologies, and the effect of the loading rate and friction on test results.

Crashworthiness and Vehicle Safety

Crashworthiness is a material's ability to provide high levels of specific energy absorption and sustained crushing over a long displacement during a vehicle crash, while retaining some post-crushing integrity[1]. The crashworthy structure's role is to provide a sound "living space" around the vehicle's occupants, and to absorb enough energy to reduce the perceived forces to within the occupants' tolerance[2]. Rather than failing catastrophically, it is preferable to design a vehicle to collapse in a controlled manner, which ensures safe dissipation of kinetic energy and minimizes serious injuries[3]. Structures designed for controlled collapse can be lighter and more material efficient than the often heavier structures designed for catastrophic failure[4]. Thus a crashworthy structure for any type of vehicle can provide a safer environment for occupants, and potentially reduce material cost and fuel consumption, and increase the vehicle's range and payload.

Crashworthy structures are prevalent in all types of vehicles, including automobiles, aircraft, rail vehicles, and marine vessels. Current legislation for automobiles places limits on the allowable impact forces experienced by the occupants to prevent permanent brain damage and other serious injuries[5]. Safety is paramount for Formula One race cars, which also benefit tremendously from their incorporated crashworthy structures[6]. Likewise, the structures of fixed and rotary winged aircraft must be able to absorb much of their kinetic energy upon impact[7]. Rail vehicles possess enormous amounts of kinetic energy that can, if not adequately managed, result in occupant injuries or fatalities, and heavy property damage during a crash[8]. Crashworthiness is also imperative for marine vessels, where collisions with other vessels, floating objects, off-shore platforms, or grounding can result in occupant injuries or fatalities, loss of cargo, or environmental damage due to leakage of hazardous substances[9,10].

Although metals have been used extensively, the high specific strength and stiffness of composites make them excellent alternatives for crashworthy structures[11]. Energy absorbed in the crushing of metals comes primarily through plastic deformation after yield[12]. For composites, however, energy is absorbed through a combination of crack growth, fiber-matrix debonding, fiber pull-out, microfragmentation, brittle fracture of the fibers and matrix, friction, as well as plastic yield[1,12-15]. High energy absorption per unit mass is possible if the proper failure mechanisms are

initiated and maintained during the crash event[16]. The particular failure mode, owing to the non-homogeneity and anisotropy that are characteristic of composites, depends on a complex interaction between many variables, which include the fiber volume fraction, fiber orientations, laminate stacking sequence, specimen thickness, the behavior of the fiber-matrix interface, the properties of the constituent materials, the geometry of the specimen, crush initiating device, the crushing surface's roughness, temperature, and load application rate[13,17,18].

Crashworthiness Crush Testing

Much has been learned about the crashworthiness of composites through experimental research. The particular test fixtures, specimen geometries, and materials tested vary widely, but the basic test procedures are generally common.

Crashworthiness test specimens are made of materials and geometries that are representative of their design application, and usually include crush initiating triggers. The triggers promote progressive crushing and preempt catastrophic failure by providing a zone of stress concentration which initiates crushing, and away from which the crush propagates[19]. Triggers may be features machined or formed into the specimen, or may be external devices that force specific specimen deformation and failure.

Behavior of the Crush Test Specimen

Crushing initiates with a well-defined crush zone, at which point the maximum, or peak, compressive load is achieved. Thereafter, progressive crushing proceeds through the specimen at a constant average load, which may be less than or equal to the peak load[12]. This behavior is evidenced by the force and displacement data, which may be plotted (see Figure 1), and reduced to quantities relevant to the particular study. The drop from the peak to the average crushing load is strongly dependent on the trigger geometry, and can potentially be reduced to zero[13].

Czaplicki et al.[19] described the fundamental sequence of the crushing process. First, the crush load must be supported by one of a number of structural elements in the specimen. When this element fails, another element must take over in order to prevent catastrophic, non-energy absorbing collapse. Thus, the serrated region of the load-displacement curve is evidence of the passing of the primary load support from one structural element to another. According to Hull[13], the initial slope of a single serration represents an essentially elastic material response and depends on the stiffness of the specimen, the crush zone, the test fixture, and the test machine. As the test proceeds, the stress in the crush zone becomes sufficiently high to initiate further crushing. Crushing stops when the load becomes less than is required to propagate cracking in

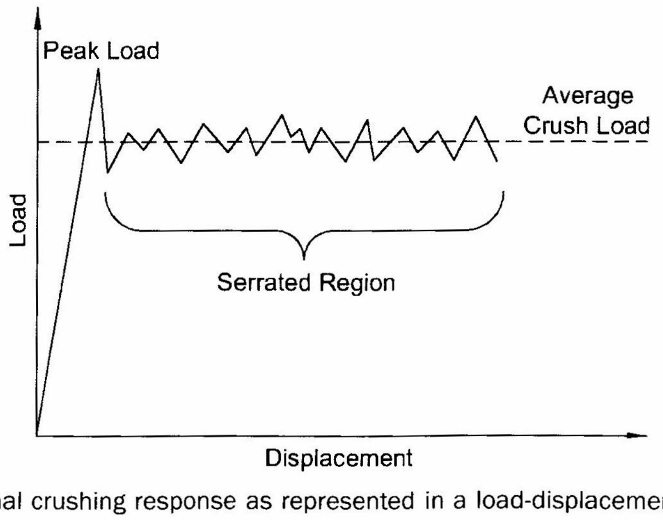

Figure 1. Notional crushing response as represented in a load-displacement plot for a typical crashworthiness crush test.

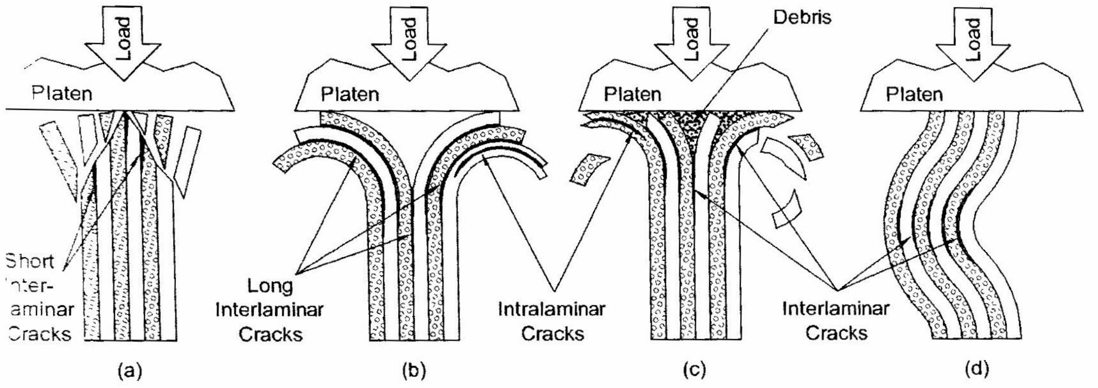

Figure 2. Crush failure modes as defined by Farley and Jones[14]: (a) transverse shearing, (b) lamina bending, (c) brittle fracture, (d) local buckling.

the crush zone. This sequence is repeated continuously for the duration of the test. Thus, the serrated region exists because the stress required to initiate crack growth is higher than that needed to propagate it. Lavoie and Kellas[11] observed that a sharply serrated curve indicates many fracture events during crushing, whereas a smoother curve is characteristic of failure dominated by delamination.

Observed Crushing Failure Modes

Farley and Jones[14] categorized crushing behavior into three basic crushing modes: lamina bending, transverse shearing, and local buckling. During crushing, small cracks develop and grow, the length of which determines the specific crushing mode or modes. Interlaminar cracks occur at the interface between adjacent laminae, intralaminar cracks grow within the individual lamina, and longitudinal cracks form transversely through one or more laminae and grow along the specimen's length.

For the transverse shearing crushing mode, illustrated in Figure 2a, short interlaminar and longitudinal cracks develop that result in the formation of partial lamina bundles, which are groupings of fibers and matrix, of single or multiple laminae. These lamina bundles act as columns, which support the increasing crush load until the cracks grow large enough to cause fracture, whereupon a wedge-shaped cross section is produced. The principle energy absorption mechanism is the fracturing of the lamina bundles[14].

Lamina bending, shown in Figure 2b, involves the formation of long interlaminar, intralaminar, and parallel-to-fiber cracks, which form lamina bundles that partially separate from the specimen. Though the lamina bundles bend excessively, they do not fracture. Energy is absorbed through crack growth and friction between the damaged specimen and the test machine platen, and between adjacent lamina bundles[14].

Both lamina bending and transverse shear failure modes involve crack growth that causes the resulting lamina bundles to eventually fail. Crack growth in the matrix is a function of the material's mechanical properties, especially toughness. Cracks in the matrix have been observed to grow by the fracture mechanics classifications of mode I, opening, and mode II, shearing. In the case of tubular specimens, hoop fibers can heavily influence the mode I crack growth behavior and consequently the resulting failure mode. Many composites exhibit a combination of lamina bending and transverse shear, and are thus said to fail by brittle fracture[14] (see Figure 2c).

Figure 2d shows the local buckling failure mode, which occurs through localized plastic deformation of the reinforcing fibers or the matrix material, or both. In addition, fiber splitting may occur and local delamination may take place between laminae. Generally, a locally buckled specimen remains intact and therefore maintains some level of beneficial post-crush integrity[14].

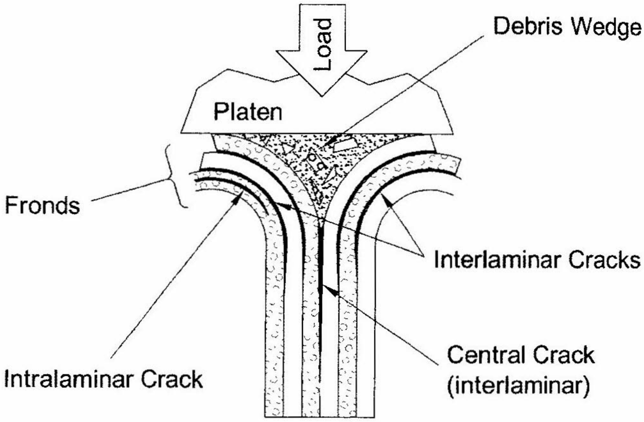

Figure 3. Splaying crushing mode as defined by Hull[13].

Through his examination of crushed composite specimens, Hull[13] observed three fundamental failure phenomena: Euler buckling, progressive folding (shell buckling), and brittle fracture. From these phenomena, Hull described two resulting general failure modes: splaying and fragmentation.

Splaying is characterized by deep interlaminar and intralaminar cracks. In addition, fronds often form, which are long, continuous, petal-like strips of damaged composite. Fragments from the crushed region form a debris wedge, which forces the laminae to split, bend, and delaminate. In addition, a long, central, interlaminar crack is opened in the specimen (see Figure 3). Energy is absorbed through crack growth, bending of the laminae, and friction[3]. Frictional forces in the crush zone occur between the debris wedge and the fronds, between adjacent laminae in the fronds as they bend through different radii of curvature, and by the splayed fronds sliding across the platen. In addition, compressive forces are present in the crush zone, and occur at the test machine platen on both the fronds and the debris wedge[13].

Similar to Farley's[14] description of the transverse shearing failure mode (Figure 2a), the fragmentation mode, as classified by Hull[13], involves the growth of short interlaminar and longitudinal cracks that ultimately result in matrix and fiber fracture. Because the fragmentation mode results in the fracture of reinforcing fibers, it is generally expected to absorb more energy than the splaying mode. Carruthers et al.[3] report that fragmentation is characteristic of composites with high interlaminar and intralaminar shear strengths.

Hull[13] observed that crushing is actually a combination of both splaying and fragmentation, and concluded that the dominant mode will be determined by the prevailing failure phenomenon. He also observed that tube specimens with a large proportion of hoop fibers tend to fail by fragmentation, whereas those with a large proportion of axial fibers tend to fail by splaying. This may be attributed to the hoop constraints imposed by the circumferentially oriented fibers, which resist the opening of the central interlaminar crack and the subsequent splaying of the fronds.

Important Quantities for Crashworthiness

As Carruthers et al.[3] discussed in their crashworthiness review, the load and displacement data may be used to calculate important quantities that emphasize the particular crashworthiness characteristics of interest. These include specific energy absorption, specific sustained crushing stress, energy dissipation density, and the energy absorbed per unit length.

Specific energy absorption (SEA) is the energy absorbed per unit mass of crushed material, and can be written as:

$$\mathrm{SEA} = \frac{E}{\rho A \delta} = \frac{\int_0^{\delta} F d\delta}{\rho A \delta} \qquad [1]$$

The total energy absorbed, E, is obtained by integrating the load, F, over the total crushed displacement, δ. The mass is the product of the composite's density, ρ, the specimen's cross sectional area, A, and δ. This analysis can be simplified by using the average crushing load, $\overline{F}$, multiplied by δ to approximate E. Dividing $\overline{F}$ by A results in the average crushing stress, $\overline{\sigma}$, and original equation is now approximated as the specific sustained crushing stress (SSCS).

$$SSCS = \frac{\overline{F}}{\rho A}\frac{\delta}{\delta} = \frac{\overline{\sigma}}{\rho} \qquad [2]$$

SEA and SSCS are commonly used for comparing the energy absorption capabilities of different materials or structures in which weight is an important consideration[3]. Hull[13] advocated SSCS as the most useful and distinctive parameter for relating the performance of different material systems and geometries.

The other crashworthiness quantities are less commonly used, but still relevant for certain applications. The energy dissipation density is defined as the energy absorbed per unit volume. This quantity may apply when the space available for the structure or the crush zone is restricted, or when mechanisms other than deformation contribute significantly to the specimen's energy absorbing capability. Energy absorbed per unit length is valuable for structures restricted to a well defined crush zone[3].

Test Machines for Crush Testing

An assortment of test machines and equipment exist that are suitable for crashworthiness testing. Tests can be conducted over a range of loading rates that vary from quasi-static to dynamic. Quasi-static load rates are typically on the order of millimeters per minute, whereas dynamic rates can be as high as many meters per second.

For quasi-static load rates, tests are usually performed on standard electromechanical or servo hydraulic testing machines. After the specimen is mounted onto the loading platens or into a test fixture, it is crushed through a prescribed displacement. The applied loads are usually measured using a load cell, and displacements may be measured via crosshead motion. Strain gages and shadow Moré have been used to detect out-of-plane displacements of specimens or critical regions of a test fixture[20].

Dynamic tests are typically performed with drop towers or impact sleds. A drop tower consists of a mass that is fixed to an impacter, which is raised to a desired height above the specimen. The weighted impacter is released to fall and crush the specimen. Alternatively, the specimen may be mounted to an impact sled, which is driven into a fixed object at a predetermined impact velocity. For both towers and sleds, impact loads are obtained indirectly using accelerometers. The accelerometer data, combined with the time history of the test event, are used to calculate the displacement of the crush zone. Zhou et al.[1] employed optical sensors to measure the impact velocity, and reactive force transducers in the test fixture's base to measure the impact load on the specimen. Addition information regarding detailed aspects of dynamic testing, along with criteria for evaluating the quality of the test results is provided by Johnson and Browne[21].

The Test Machine for Automotive Crashworthiness, or TMAC, was designed and built by MTS Systems Corporation at the request of the Automotive Composites Consortium and the National Transportation Research Center at Oak Ridge National Laboratory. The TMAC was built specifically for crashworthiness studies, and is uniquely capable of conducting controlled progressive crush testing at constant velocities up to 8 m/s[15].

Crush Test Load Rates and Strain Rates

The effect of load and strain rates on the energy absorbing behavior of composites is a current research topic being explored by several laboratories[3,13,15,22-26]. Attempts to generalize the effect of load and strain rates on a specimen's behavior have been difficult and inconclusive because the results seem to apply only to specific specimens and tests[3]. Brimhall[15] concluded that the

variation in energy absorbing behavior at different load rates was due largely to the change in the frictional behavior at quasi-static versus dynamic load rates. Through an experiment that minimized friction, he concluded that the specific energy absorption was virtually the same at both quasi-static and dynamic load rates. However, Jacob et al.[22] states that the load-displacement curve, initial peak load, magnitude of the energy absorbed, and the time required to absorb this energy are all functions of the crushing speed. Hull[13] observed that some fiber arrangements are affected by load rate and have an associated change in crush mode. Jacob et al.[24] reported that the strain rate can affect the matrix behavior and the failure modes, and concluded that beyond a certain threshold velocity, the composite material's energy absorption capacity suddenly drops.

According to Jacob et al.[4], the energy absorbing mechanisms vary with load rate. The important factors for energy absorption at high load rates were found to include the magnitude of the energy dissipated in delamination (interlaminar crack growth), debonding, and fiber pull-out. For low load rates, the important factors were the strain energy absorption of the fibers and the geometric configuration.

Farley and Jones[14] suggested that if the mechanical properties that control the failure mechanisms are influenced by the strain rate, then the crushing speed is likely to affect the energy absorption behavior of the specimen. For example, the matrix stiffness and failure strain may be functions of the strain rate, so it is expected that the energy absorbed through crack growth during transverse shearing or lamina bending failures will be a functions of the crushing speed. Conversely, only transverse shearing is exhibited in brittle fiber reinforcements whose mechanical properties are generally insensitive to strain rate. Thus the fracturing of the lamina bundles is generally not a function of crushing speed. However, the coefficient of friction can be a function of speed and therefore its contribution to the energy absorption during the lamina bending failure mode is expected to depend on the crushing speed.

The Effect of Friction in Crashworthiness Testing

Friction has been found to have a major effect on crashworthiness test results, and has been shown to be responsible for more than 50% of the total energy absorbed during crushing[3,12]. Friction is associated with the penetrating debris wedge in the crush zone, the sliding of the fronds or lamina bundles across the test machine platen, and the sliding of adjacent laminae as they pass through their deflection arc[12]. Fairfull and Hull[12] studied the effect of friction on the energy absorbing behavior using tubes of circular cross section. They confirmed that less friction between the specimen and the crushing platen resulted in less energy absorption. However, even when minimized, friction was still determined to account for more than half of the overall energy absorption.

For conical shells, the debris wedge moves across the platen as crushing progresses because of the cone's increasing dimensions. Fairfull and Hull[12] concluded that cones tend to have higher energy absorption capacity than circular tubes, which is the likely result of the increased friction associated with the outwardly moving debris wedge. They also suggested that the serrations in the load-displacement curve may be due to the slip-stick nature of the friction in the crush zone. Hull[13] concluded that friction between the specimen and the test machine platen has a large effect on the crush zone morphology because it contributes to the forces acting on the splaying fronds. In addition, the frictional resistance to the penetration of the annular debris wedge in circular tubes of a variety of material systems was found to be a significant contributor to the overall energy absorption[12]. Fairfull and Hull[12] noted that brittle materials with high interlaminar friction tend to fracture in discrete fragments, whereas flexible materials with low friction tend to delaminate and produce continuous fronds. Additionally, in order to completely characterize the results of a particular test, they recommended that the specific energy absorption data note the surface conditions of the crushing platen.

Brimhall[15] suspected friction's major influence on the energy absorption as well, and conducted experiments to determine its effect on tubes of square cross section. He also hypothesized that friction is the primary reason behind the difference in behavior at various load rates. This asser-

tion is consistent with Hull's[13] observations of friction, but Hull attributed the energy absorption's dependence on load rate to the great amounts of heat developed by friction in the active crush zone.

Crashworthiness of Material Systems

The energy absorbing capability of a composite material depends in part on the mechanical properties of the constituent materials. The fiber and matrix material may be chosen from innumerable possibilities based on the expected performance of the resulting composite.

Fibers are available as unidirectional sheets or tapes, woven mats, continuous strand mats, random chopped mats, or in tows for winding. Common fiber types include carbon, glass, and aramid, which may be used singly or in combination to form hybrid systems. Carbon and glass fibers usually fail by brittle fracture, whereas aramid fibers, because of their relatively high toughness, tend to fail in a ductile manner. Aramid's ductile behavior results in failure dominated by folding and buckling, which provides post-crush structural integrity[4].

The properties of the matrix materials have been observed to greatly affect the energy absorption capacity of the composite. Common matrix materials include both thermoplastic and thermosetting polymers such as epoxy, vinylester, polyurethane, phenolic, polyester, and polyetheretherketone (PEEK). In general, thermoplastics exhibit greater fracture toughness than thermosetting polymers. PEEK possesses a notably high fracture toughness, which is on the order of 10 times greater than epoxy, and, as a result, has been shown to greatly increase the energy absorbing performance during crushing[20].

Hull[13], Lavoie and Kellas[11], and Jacob et al.[4,25] have performed extensive studies comparing the energy absorption obtained from composites with different constituent materials. Many useful conclusions have been formulated regarding the effects of the constituent materials' mechanical properties, the fiber volume fractions, and fiber lengths (for short fiber reinforcements). Additionally, the effect of fiber orientations and lamina stacking sequences on the energy absorption in composite laminates has received attention[3].

Sandwich composites consist of two thin composite facesheets separated by and bonded to a lightweight core material. The facesheets are composed of fiber and matrix combinations as previously discussed, while the core may be, for example, structural foam, balsa wood, or a honeycomb material.

Crashworthiness Test Specimen Geometries

A myriad of test specimen geometries have been used for crashworthiness studies. Many of the geometries emulate the structure for which research is being conducted, whereas others are employed for the general study of the effect of one or more variables on energy absorption. Specimen dimensions vary widely depending on the application, test equipment capacity, and the particular test being performed. For the specimen height dimension, Johnson and Browne[21] recommended it be sufficient to fully establish the crush mode as it would occur in the intended application and to absorb all of the desired input energy.

Many crashworthiness specimens have self-supporting, structure-like geometries, such as circular, square, or sine wave (corrugated) cross sections. If the dimensions are chosen judiciously, self-supporting specimens do not require external supports to prevent global buckling and catastrophic failure. Flat specimens, on the other hand, are not self-supporting and require specialized fixtures to achieve stable crushing behavior. However, flat specimens are advantageous for their simple geometry and ease of manufacturing.

One of the most common specimen geometries is the circular cross section tube as shown in Figure 4a. Hull[13] made extensive use of circular tubes for observing the failure modes and mechanisms of crushing. Fairfull and Hull[12] used circular tubes to study frictional effects during crushing. In a separate test, they were able to determine the coefficients of friction by rotating the ends of the circular specimens against platens of various surface textures.

Square (see Figure 4b) and rectangular cross section tubes are also frequently used as they

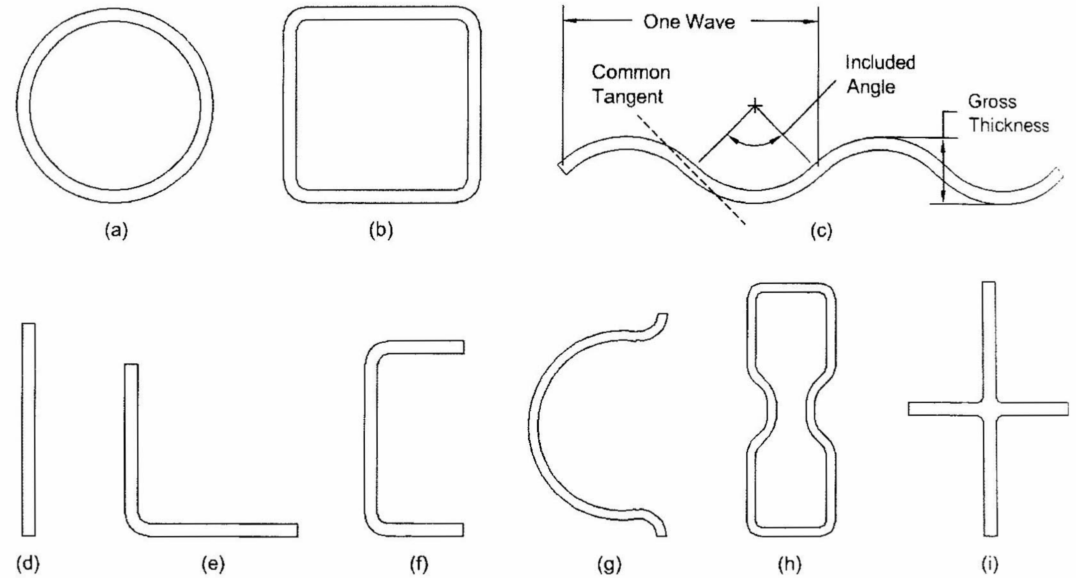

Figure 4. A sampling of test specimen cross sections: (a) circular, (b) square, (c) sine wave web. (d) flat, (e) angle, (f) channel, (g) DLR segment, (h) hour glass, (i) X-column.

represent common structural shapes, especially in automotive frames. Brimhall[15] used square tubes to quantify the contribution of friction to the total absorbed energy. Thornton[27] and Czaplicki et al.[19] used square (and circular) tubes as a platform for comparing the effect of crush initiating triggers on energy absorption.

Caruthers et al.[3] reported that square and rectangular tubes are less energy absorbent than circular tubes due to the stress concentrations of the corners. Jacob et al.[4] ranked common cross sections in order of increasing energy absorption capability: rectangular, square, and circular tubes, respectively. Hull[13] noted from his experiments that square and rectangular tubes did not generate the conventional crush zone morphology in their flat-walled sections, which tended to fail by buckling. He concluded, therefore, that square and rectangular tubes were less energy absorbent and structurally weaker cross sections when compared to circular ones.

The sine wave web specimen's cross section is a sinusoid-like shape, composed of tangentially joined circular arcs (Figure 4c). The geometric variables involved in the sine wave web include the specimen width (total number of waves), gross thickness, specimen width-to-gross thickness ratio, and the included angle[28]. According to Zhou et al.[1], the sine wave web specimen more closely represents actual structural elements than circular tubes, and could be used directly in airframe structures as part of built-up assemblies. Feraboli and Garattoni[29] used corrugated specimens, or variations of the sine wave web, in their effort toward developing a standardized crush test method. In addition to the tangentially joined circular arcs of the sine wave web, they used sinusoidal curves with two different amplitudes, which were designated as high and low. Feraboli and Garattoni concluded that the corrugated sine wave geometry was self stabilizing and was able to capture the relevant behavior of the composite material during crushing.

Flat specimens (Figure 4d) are advantageous because they are simple to fabricate and cost effective. Lavoie et al.[20,30,31] advocated the use of flat coupon specimens as a cost and time efficient means of evaluating different material systems, lamina stacking sequences, crush initiating triggers, and scaling effects. They also viewed flat coupon specimens as an important alternative to full- and sub-scale structural testing. Bolukbasi and Laananen[7] were able to predict the energy absorption capability of composite angle and channel cross sections (Figure 4e, f) to within 3% using data from flat coupon specimens. Jacob et al.[5,22,25] employed flat coupon specimens to eval-

uate the relative energy absorption capacity of several composite material systems. Mamalis et al.[..]. Jacob et al.[5,32], and Brimhall[15] used flat coupon specimens to correlate their energy absorbing behavior to that of square tubes by isolating the fiber and matrix damage and frond formation that occur during crushing of the tubes. Despite their simplicity and usefulness, however, Lavoie et al.[20] caution that flat coupon specimen tests are not a general substitute for higher fidelity structural testing. Furthermore, they require a supporting fixture for stability, which, as Fleming and Nicot[33] point out, can greatly influence the flat coupon's crushing response.

Johnson[26] reported on the development of the segment specimen at the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The DLR segment specimen is composed of a semi-circular cross section that terminates on each end with a flange (see Figure 4g), and is bonded to an aluminum support plate. Like the flat coupon specimen, the purpose of the segment specimen is to permit quick assessment of a material's energy absorption behavior by being easy and inexpensive to fabricate. However, unlike the flat coupon specimen, the segment specimen is self-supporting and does not require a special test fixture to prevent global buckling. DLR used their segment specimen to compare the SEA of selected material systems under both quasi-static and dynamic load rates.

There are several other interesting specimen configurations as well. Johnson et al.[34] and Mamalis et al.[35] studied the energy absorbing behavior of hourglass cross sections (Figure 4h) intended to be used in automobile frames. Fleming and Nicot[33] developed an X-column specimen as shown in Figure 4i. This specimen was intended to provide a simple geometry for validating finite element models that would offer some of the simplicity of the flat specimen while at the same time being self supporting. However, the X-column appeared to be particularly sensitive to trigger and laminate lay-up configurations, which made its stability unreliable and its failure modes difficult to predict. Conical shells of circular and square cross section are yet other geometries employed in crashworthiness studies[35]. For example, Bisagni et al.[6] investigated the behavior of circular conical tubes for use as side impact energy absorbers in Formula One race cars. It is interesting to note that cones do not require added crush initiating triggers because stable crushing automatically begins at the cone's narrower end[3].

Crush Initiating Triggers

A crush initiating trigger is an important feature in a crashworthiness test. Without a trigger, specimens are likely to fail by global buckling or catastrophic brittle fracture[13]. These types of failure are undesirable for structures required to absorb large amounts of energy in a controlled manner. A trigger is a geometric feature located on one end of the specimen, which acts to produce a localized failure at a load less than that required to initiate catastrophic collapse, and to establish and propagate stable, controlled crushing[27,28]. With a properly designed trigger, the specimen experiences progressive, stable crushing that advances down its length[13]. The size and geometry of trigger has been observed to influence the energy absorption[19,27,28].

Perhaps because of its simplicity, the bevel trigger is most frequently used, followed by, among others, the steeple and notch triggers. As shown in Figure 5a, a bevel trigger is a width-wise chamfer machined across one end of the specimen. The steeple trigger (Figure 5b) is essentially two back-to-back bevels whose common apex is at the center of the specimen's thickness. The saw-tooth-like notch trigger of Figure 5c and the tulip trigger of Figure 5d have apices oriented transversely across the specimen's thickness.

In an isotropic material, according to Thornton[27], cracks tend to propagate in a plane parallel to the trigger's apex. The anisotropy of a composite laminate, however, generally causes cracks to preferentially grow through the matrix in an interlaminar manner rather than fracturing the fibers. Thus, Thornton hypothesized that a trigger with an apex normal to the plane of interlaminar cracks would be advantageous for maximizing energy absorption. He therefore conducted crushing experiments to compare the performance of the bevel trigger with that of the tulip which, respectively, have apices parallel and normal to the interlaminar crack planes. The tulip trigger nucleated a larger numbers of cracks than the bevel trigger, and required higher crushing loads

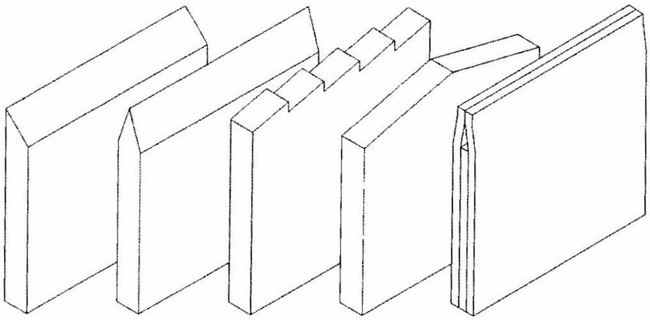

Figure 5. A sampling of configurations for crush initiating triggers: (a) bevel, (b) steeple, (c) notch, (d) tulip, (e) ply drop off.

to propagate the interlaminar cracks. Thornton observed that the average crush load for the tulip trigger was more stable and notably higher than that of the bevel. He concluded that the tulip trigger is a good choice for structurally weak cross sections, such as the rectangle or square, because it effectively raises the average crush stress to values typical of stronger sections. Additionally, Thornton observed that the tulip trigger required greater displacement prior to reaching the peak load, which effectively "softened" the initial impact. In application, this means less shock would be induced in the supporting structure of the energy absorbing device. Building upon Thornton's work, Czaplicki et al.[19] found that at quasi-static load rates, the tulip trigger produced shorter interlaminar cracks and a higher density of fracture lines than the bevel trigger. This resulted in a greater amount of fracture and ultimately more energy absorption. In addition, the tulip trigger produced a less pronounced peak load and a higher, steadier average crush load. Conversely, the bevel trigger caused longer interlaminar cracks, more delamination, a lower density of fracture lines, and therefore less energy absorbed.

Lavoie et al.[11,20,30,31] made use of the steeple and notch triggers for evaluating their test fixture and studying specimen scale effects during crushing. When compared to the notch trigger, they observed that the steeple produced lower crush loads during the early stages of crushing, but only marginally lower loads overall at quasi-static load rates. They also found that the steeple trigger produced a dominant central interlaminar crack, whereas the notch trigger resulted in multiple smaller cracks that required more energy to propagate. For an epoxy matrix, Lavoie et al. observed 20% lower energy absorption for the steeple trigger than for the notch. With a PEEK matrix, however, the energy absorption for the two triggers was approximately the same, owing to PEEK's relatively high fracture toughness. Thus, Lavoie et al. concluded that the matrix material may minimize the effect of the trigger geometry on energy absorption.

Bolukbasi and Laananen[7] made exclusive use of the bevel trigger in their crushing experiments of flat coupon, angle, and channel specimens. Fairfull and Hull[12] also used the bevel trigger for their evaluation of frictional effects during crushing. For crushing corrugated and sine wave web specimens, Feraboli and Garattoni[29] used the bevel trigger, Zhou et al.[1] used the notch trigger, while Hanagud et al.[28] used both the bevel and notch triggers. In addition, Hanagud et al. used a ply drop off trigger, which is built into the specimen during fabrication rather than machined (see Figure 5e). As the specimen is assembled, the mid laminae are cut shorter than the outer laminae, and the trigger is formed by bringing the longer outer laminae together to create a steeple-like geometry. Thuis and Metz[36] also experimented with built-in triggers similar to the ply drop off, where the inner laminae were cut to different lengths in various combinations. While Thuis and Metz had relative success using these built-in triggers in circular tube specimens, Hanagud et al.[28] ultimately abandoned the ply drop off trigger for sine wave web specimens due to its difficult fabrication process and its low performance compared to other triggers.

The plug trigger is an external device over which a tubular specimen is crushed, and is used to obtain a particular crush zone behavior. As the specimen is crushed, the tube wall is forced through a specific deformation path imposed by the plug (see Figure 6). Kindervater[2] utilized cone shaped plug triggers for some of his experiments with tubes. One noteworthy variation of the standard plug trigger was Brimhall's[15] attempt to isolate the energy associated with the corner tearing that often occurs during the crushing of square tubes. For this experiment, he used a long, tapered plug trigger, which, upon specimen loading, acted to split the corners of the tube without inducing frond formation and the associated matrix and fiber damage.

Crush triggering in the testing of flat coupon specimens by Jacob et al.[4,5,22-25,32], Brimhall[15], Mamalis et al.[17], and Starbuck et al.[37] was provided by the test fixture. Their fixtures function much like a plug trigger by forcing the flat specimen to deform along a specific path, which creates locally high stresses and initiates crushing.

Fixtures used for Crashworthiness Testing

Self supporting specimens, as previously discussed, generally do not require external support beyond what is required to uniformly load the specimen ends during testing. However, the simplicity and potential cost savings of testing non-self-supporting flat coupon specimens has promoted the development of specialized test fixtures that allow crushing of the specimen to occur while preventing global buckling and catastrophic failure.

Kindervater[2] conducted tests with flat coupon specimens using an end-loaded coupon compression fixture as shown in Figure 7. The specimen was clamped inside the fixture and the load was applied through the upper anvil. The fixture was used for both quasi-static and dynamic loadings, which were measured via a built-in piezoelectric load-cell.

Lavoie et al.[11,30,31] developed a test fixture for use with flat coupon specimens, and employed it to evaluate different material systems, optimum laminate lay-ups, various triggers, and specimen scaling effects. DLR employed this fixture design to test flat specimens[26], and Bolukbasi and Laananen[7] used it to compare the behavior of flat coupons with that of composite angles and channels. Feraboli and Garattoni[29] also used this fixture design to crush self supporting corrugated specimens, but did so without the knife edges or support rods. The fixture, as shown in

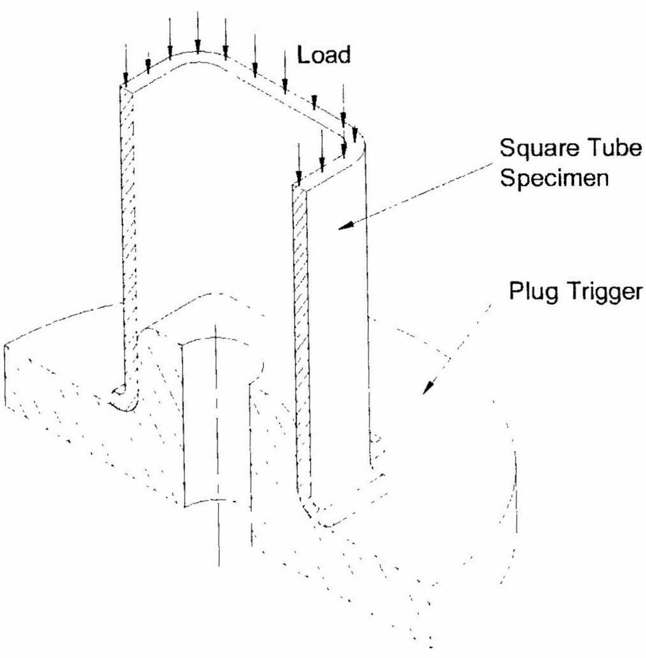

Figure 6. Section view of a square tube specimen being crushed over a standard plug trigger.

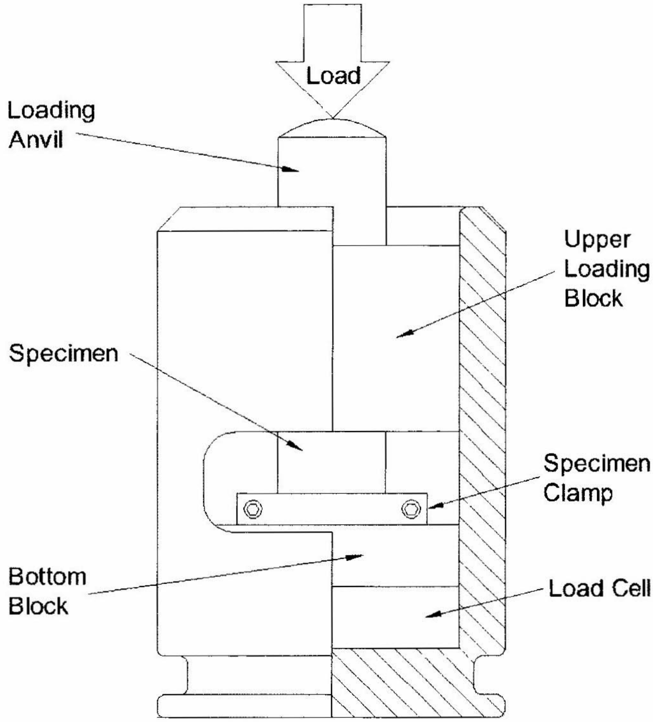

Figure 7. Representation of the end-loaded coupon compression fixture used by Kindervater[2].

Figure 8, consists of a horizontal sliding plate guided by four rods and bushings. The specimen is independently braced against global buckling by four support rods with inlaid knife edges. As it is shown in the figure, the fixture is configured for the smaller of two possible specimen sizes. The larger specimen is loaded in the fixture perpendicularly to the smaller specimen, and the smaller support rods are replaced by the larger rods shown as dashed lines. For both specimen sizes, load is applied at the center of the sliding plate quasi-statically through a seated steel ball, and dynamically through a load-distributing cylinder. Crushing is initiated at the bottom of the specimen, which is forced to tear around the knife edges of the specimen supports. Figure 9 shows a representation of a crushed specimen where such tearing around the supports has occurred.

Cauchi Savona and Hogg[18] extensively modified Lavoie's fixture design to include moveable knife edges to accommodate various plate widths and thicknesses, and a loading block through which force is applied to the specimen (see Figure 10). The knife edges are set to lightly contact the specimen so it is supported against buckling. When the load is applied at the top of the specimen, crushing initiates at the bottom, and tearing around the knife edges occurs.

Dubey and Vizzini[16] also developed a fixture to test flat coupon specimens. As shown in Figure 11, the fixture consists of four guide rods that simultaneously support the specimen against global buckling, and guide the moving block through which the quasi-static load is applied. Early test results were skewed by excessive friction and binding that occurred as the specimen was forced to tear around the guide rods. To alleviate this problem, the specimen was scored to various depths where it contacted the rods, which allowed it to tear easier and without binding. The authors noted that this fixture may be configured for crushing at angles of incidence to simulate off axis loading of specimens.

As discussed, a common characteristic of the three previously described test fixtures (Figures 8, 10, and 11) is their specimen supports cause the specimen to tear during crushing (see again Figure 9), and debris may become trapped in the fixture and hinder the crushing process. This may lead to inconsistent results when comparing the energy absorption of different material systems. As a consequence of the tearing, being tensile in nature, fibers with higher tensile strengths will absorb more energy than those with lower strengths, which may produce data that do not ac-

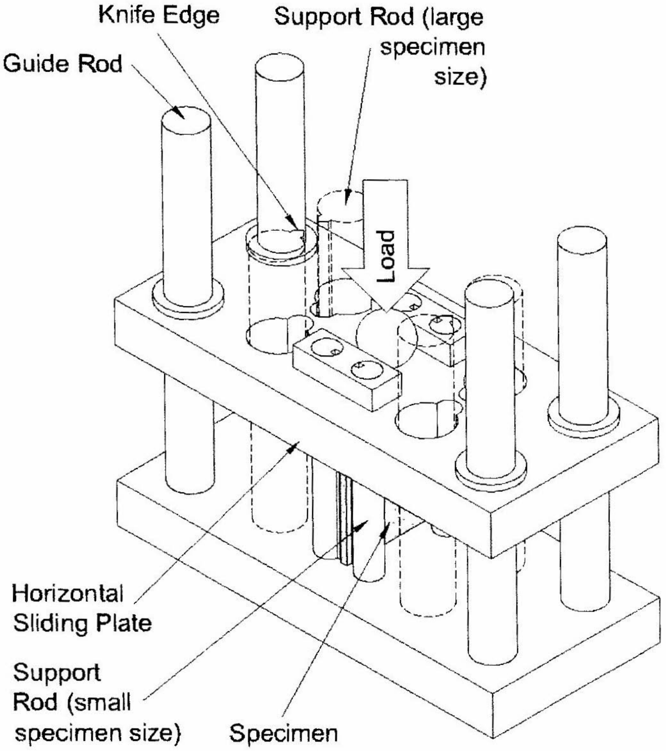

Figure 8. Representation of the crush test fixture use by Lavoie et al.[11,20,30,31] for flat coupon specimens shown configured for quasi-static loading of the smaller specimen size.

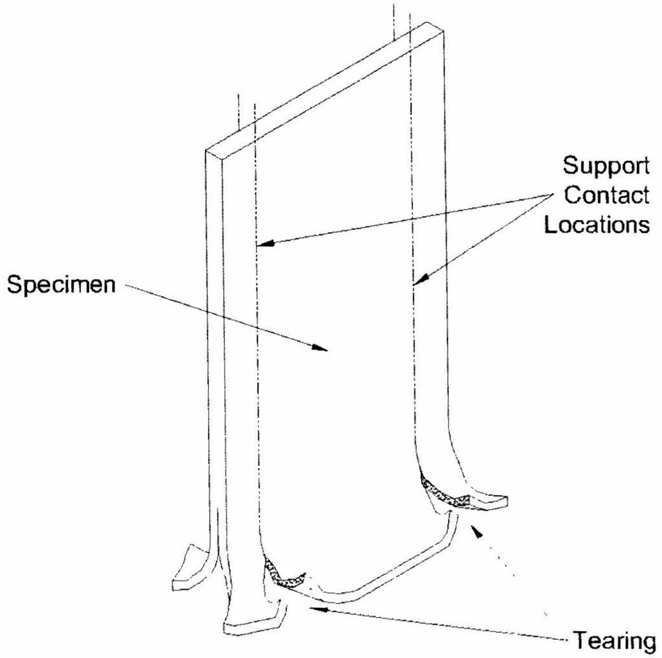

Figure 9. Crushing and tearing of a flat coupon specimen. Phantom lines represent the locations where the support rods contact the specimen and tearing occurs during crushing.

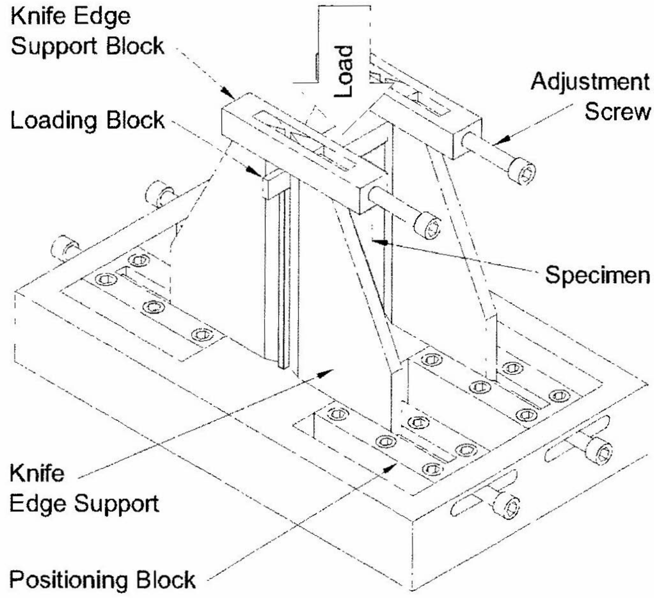

Figure 10. Representation of the crush test fixture use by Cauchi Savona and Hogg[18] for flat coupon specimens.

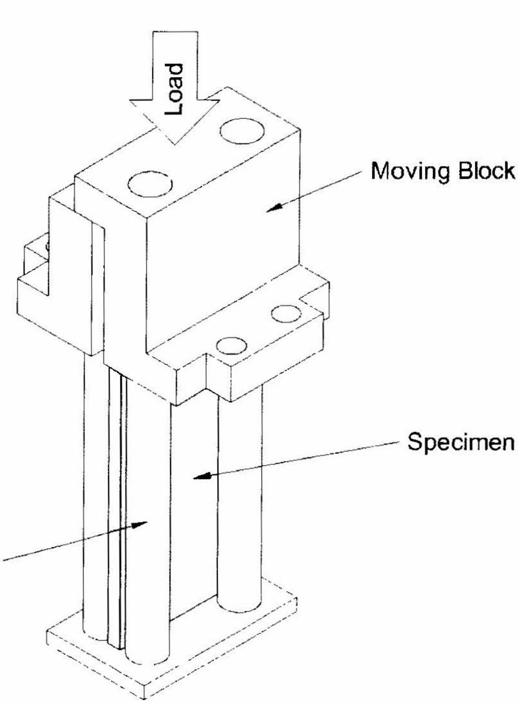

Figure 11. Representation of the crush test fixture used by Dubey and Vizzini[16] for flat coupon specimens.

curately represent the crushing behavior of the application. The trapped debris may also lead to increased friction and binding, further skewing the test result. Johnson[26] reported that the tests conducted by DLR using the fixture design of Lavoie et al. were troubled by trapped debris and friction. In addition, the full length supports do not allow unmitigated interlaminar crack growth in the specimen. This constraint may act to reduce delamination and hinder the opening and growth of cracks, which would result in higher energy absorption than for a specimen allowed to crush unconstrained. In an effort to overcome these data altering effects, a number of fixtures have been designed that attempt to alleviate the tearing and the artificial crack growth constraint.

Engenuity Limited, a commercial engineering firm operating in the United Kingdom, has developed a test fixture to crush flat coupon specimens without specimen tearing (see Figure 12). The specimen is housed in the fixture between friction reducing Delrin® sliders, and secured by the cover plate and access door. During the test, the specimen is loaded through the loading slide, supported against buckling by the surrounding housing, and crushed against the spacer block below. In the region of the crush zone, however, the specimen is unsupported over a gap height, which can be adjusted with drop-in spacer blocks of various thicknesses. The gap provides a passage for the crushed fronds and debris to escape without tearing or interfering with the test in progress. The main body of the fixture can be tilted back via the hinge in the fixed base, which allows for convenient changing of the specimen and adjustment of the spacer blocks[38].

Engenuity has performed both quasi-static and dynamic tests with their fixture using a standard electromechanical test machine. For dynamic tests, the data over the initial portion of the displacement is disregarded as the machine ramps up to the desire speed[38].

Another test fixture for crushing flat coupon specimens was developed at the University of Washington. This fixture features knife edges and out-of-plane support plates to prevent buckling (see Figure 13). In addition, like the Engenuity test fixture, it has an unsupported gap that precludes tearing of the specimen and allows it to splay with less imposed constraint. To date, the reported use of the University of Washington fixture has been to compare different material systems, assorted trigger geometries, and the effect of varying the gap height on SEA under quasi-static load rates[39].

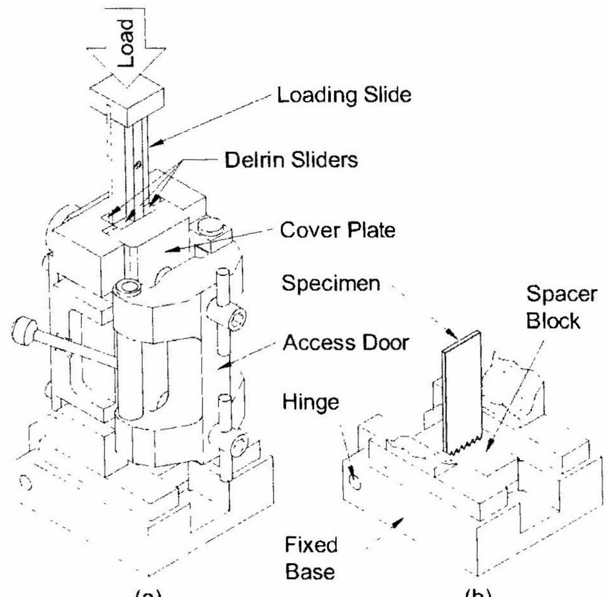

Figure 12. (a) Representation of the test fixture developed by Engenuity Limited[38] for crushing flat coupon specimens. (b) Cut away view revealing the specimen and the spacer block, which adjusts the unsupported gap height.

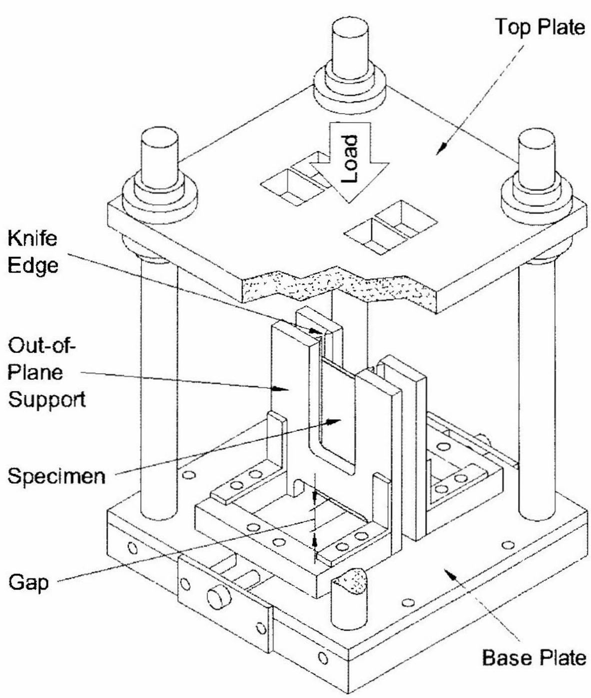

Figure 13. Representation of the test fixture developed at the University of Washington for crushing flat coupon specimens[39].

Takashima et al.[40] also designed and implemented a test fixture for crushing flat coupon composite specimens without inducing tearing. The specimen rests on the under-support plate, is supported against buckling by the out-of-plane displacement-constraint plates, and is crushed against the loading plate through which the load is applied (see Figure 14). As with the previous two fixtures, this fixture features an unsupported gap that allows the specimen to fail unimpeded by the out-of-plane supports. To minimize friction, a silicone grease lubricant was applied to all of the areas of contact between the specimen and the fixture. During testing, the gap height was constant, but could be adjusted between tests via the joints. Takashima et al. employed this test fixture to study the effects of the gap height and specimen width and thickness on the energy absorbing behavior of unidirectional flat coupon specimens at quasi-static load rates.

A number of other test fixtures have been developed for crushing flat coupon specimens, but as a means of isolating a specific failure behavior or energy absorbing mode. Jacob et al.[5,32] developed a test fixture for correlating flat specimen behavior with that of square tubes. The fixture was developed for both quasi-static and dynamic load rates and may also be used to screen materials and study the relative effects of some of the variables influencing energy absorption. As shown in Figure 15, this test fixture includes an interchangeable contact profile block, a specimen contact constraint, roller ways, and adjustable load cell brackets. The specimen is supported against buckling by the roller ways as it is forced downward through the contact profile and the adjustable constraint. The constraint has three positions: tight, loose, and no constraint. Despite the fixture's anti-buckling supports, the authors found that the specimens still buckled above the roller ways for the tight constraint condition. Therefore a metal plate was bonded onto the upper end of the specimen, which eliminated further buckling.

Mamalis et al.[17] created the "curling test" and fixture, shown in Figure 16, for evaluating the influence of basic material and geometric parameters related to crashworthiness. During a test, the flat coupon specimen is pushed through the fixture, where it is forced to deform and crush along a specific path. This test method simulates the deformation and crushing mechanisms acting on the fronds of tubes that fail by lamina bending or splaying.

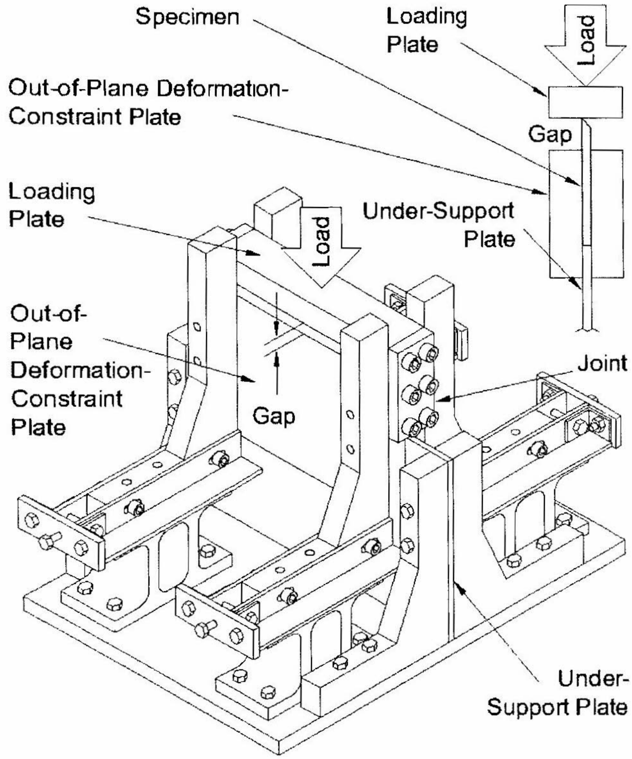

Figure 14. Representation of the test fixture developed at Nihon University for crushing flat coupon specimens[40]. The inset diagram reveals the specimen and the manner in which it is supported and loaded.

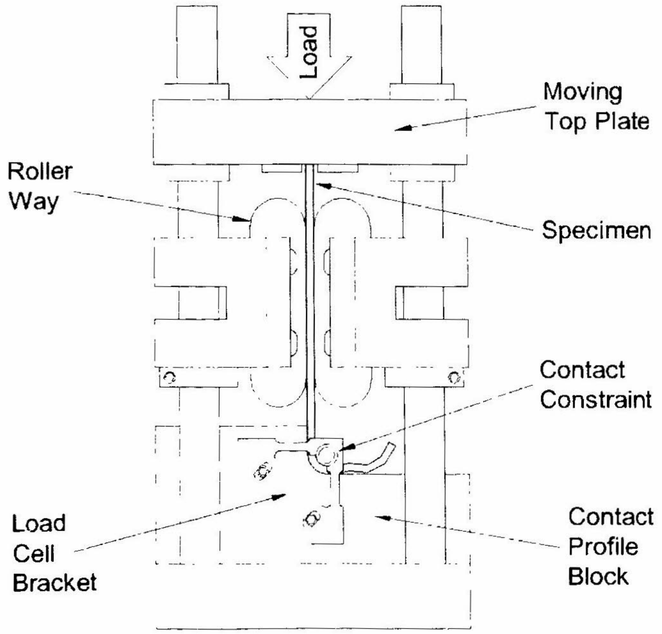

Figure 15. Representation of the crush test fixture used by Jacob et al.[5,22,25,32] for flat coupon specimens.

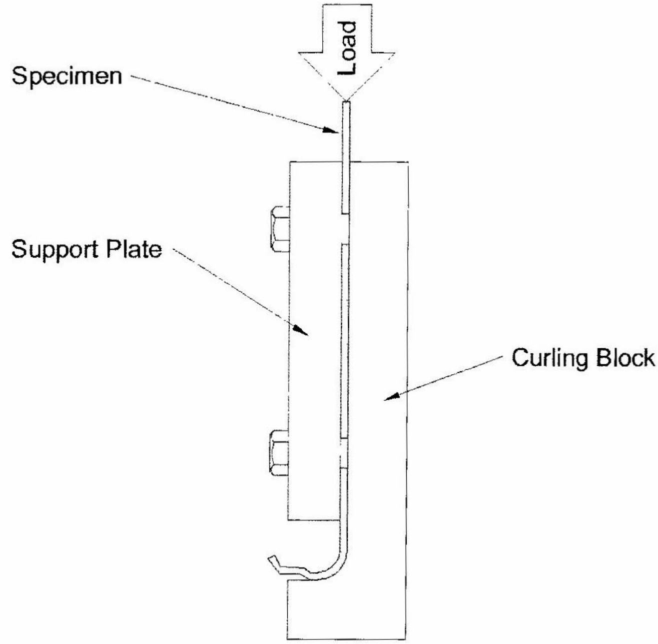

Figure 16. Representation of the curling test fixture use by Mamalis et al.[17] for crushing flat coupon specimens.

As part of his effort to isolate the various energy absorbing modes during crushing of square tubes, Brimhall[15] developed a test fixture for an experiment referred to as the "strip test." Its purpose was to use flat specimens, the strips, to quantify the contribution of friction to the energy absorbed during crushing of the tubes over a plug trigger. The strip test fixture, schematically shown in Figure 17, consists of rollers which minimize sliding friction and support the flat specimen against global buckling. The largest roller can be locked in order to simulate the friction from a plug trigger for comparison with data from actual tube tests. Brimhall's fixture can be used at quasi-static and dynamic load rates.

Although sandwich composites are used commonly in the transportation industry, only limited research has focused on developing and evaluating test methods for establishing their crashworthiness capabilities. Mamalis et al.[41] investigated the failure modes and crushing characteristics of foam core sandwich composites under progressive crushing. Load was applied directly to the specimen ends without the use of a test fixture or lateral supports. Though the majority of the tested sandwich specimens failed by global buckling, those specimens that experienced progressive crushing resulted in high energy absorption. Researchers at the University of Utah[42-46] have investigated test methodologies for crush testing sandwich composites for automotive applications. These investigations have focused on specimens consisting of two thin carbon fiber-reinforced facesheets and balsa wood or polyurethane foam cores. The test methodology developed for drop tower crush testing of sandwich composites was patterned after that used for quasi-static crush testing of sandwich composites at the University of Utah[42,43] and specified in ASTM C 36447. As shown in Figure 18, the flat sandwich specimen is placed into the stationary bottom fixture half and held in position by the clamps. The top fixture half is attached to the crosshead and dropped onto the specimen. The angled supports of the top fixture serve to maintain the specimen's alignment in the fixture, and can act as an optional crush triggering device. Stapleton and Adams[45,46] used the University of Utah sandwich composite crush test fixture to study how the facesheet and core materials, geometries, and fixture-based crush trigger devices influenced the energy absorption of composite sandwich specimens.

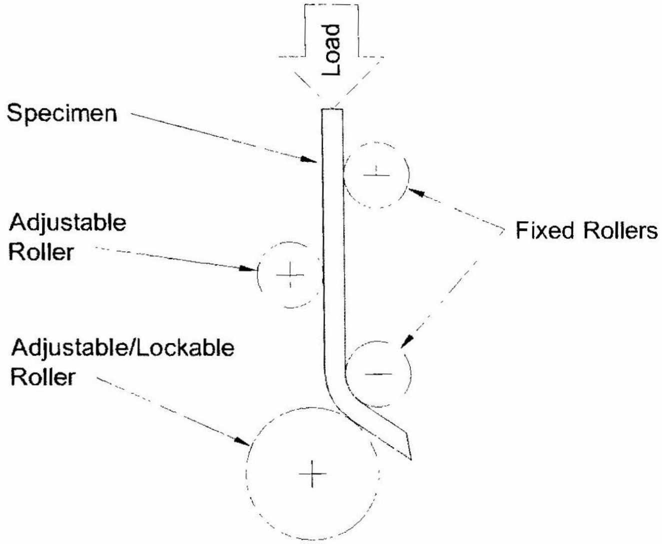

Figure 17. Representation of Brimhall's[15] strip test fixture for crushing flat coupon specimens and observe the energy absorbed by friction.

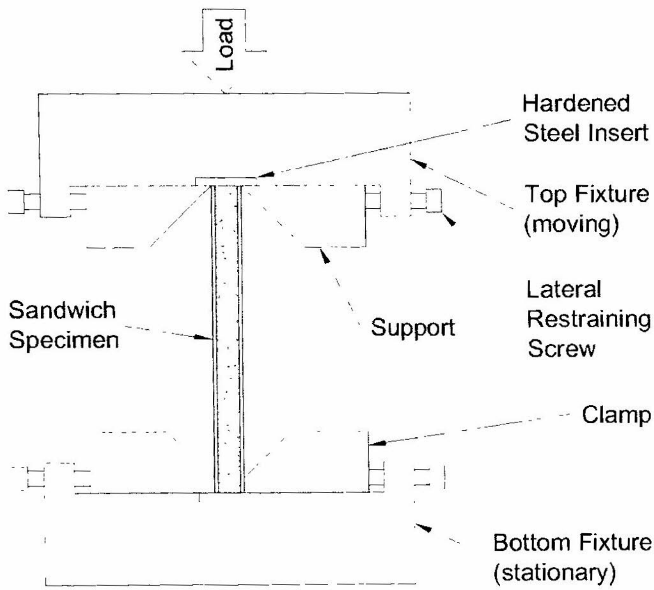

Figure 18. Schematic of the University of Utah sandwich composite specimen crush test fixture[42-46].

Summary

Knowledge of the crashworthiness capabilities of composites is essential to the design of safe and efficient vehicles. Much of this knowledge to date has been gained through experimentation performed with a variety of test machines, specimens, and fixtures.

The complex process of energy absorption of composite materials is affected by numerous variables such as the failure mode, friction, the strain or load rate, material system, specimen geometry, crush initiating trigger, and the possible use of a test fixture. The basic failure modes include transverse shearing, lamina bending, brittle fracture, local buckling, fragmentation, or splaying. Many material systems consisting of various combinations of fiber types and matrix

materials are available, and yield a wide range of energy absorption behavior. The specimens geometry is selected to represent the design application or to allow the observation of specific energy absorbing variables during testing. There are many crush initiating trigger configurations including the bevel, steeple, notch, tulip, and ply drop off, which act to induce stable, progressive crushing. Unlike flat coupon specimens, self supporting specimens, such as tubes and sine wave webs, do not require a test fixture to prevent global buckling during testing. However, the simple shape and easy fabrication of the flat coupon specimen often balance the additional requirement of a test fixture.

The persistent demand for safer and more efficient vehicles continues to advance the state-of-the-art in the crashworthiness of composite materials. Researchers must continue to improve and expand current experimental methods in order to gain further understanding of the crushing process, obtain higher fidelity crush data, and to verify and validate computational models.

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