Energy Absorption in Polymer Composite Materials for Automotive Crashworthiness

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ABSTRACT

The energy absorption capability of a composite material is critical to developing improved human safety in an automotive crash. Energy absorption is dependent on many parameters like fiber type, matrix type, fiber architecture, specimen geometry, processing conditions, fiber volume fraction, and testing speed. Changes in these parameters can cause subsequent changes in the specific energy absorption of composite materials up to a factor of 2. **This paper is a detailed review of the energy absorption characteristics in polymer composite materials. An attempt is made to draw together and categorize the work done in the field of composites energy absorption that has been published in the literature in order to better understand the effect of a particular parameter on the energy absorption capability of composite materials. A description of the various test methodologies and crushing modes in composite tubes is also presented. Finally, this paper raises certain design issues by examining the work rate decay necessary to keep the deceleration below 20g during an impact crash.**

KEY WORDS: Crashworthiness, Energy Absorption, Composite Materials, Crushing.

INTRODUCTION

In passenger vehicles the ability to absorb impact energy and be survivable for the occupant is called the “crashworthiness” of the structure. There is an important difference between crashworthiness and penetration resistance. Crashworthiness is concerned with the absorption of energy through controlled failure mechanisms and modes that enable the maintenance of a gradual decay in the load profile during absorption. However penetration resistance is associated with the total absorption without allowing projectile or fragment penetration.

Current legislation for automobiles requires that vehicles be designed such that, in the event of an impact at speeds up to 15.5 m/sec (35 mph) with a solid, immovable object, the occupants of the passenger compartment should not experience a resulting force that produces a net deceleration greater than 20g. US helicopter requirements of safely surviving a descent, under no power; at 15 m/sec is another example of crashworthiness legislation. Crashworthy structures should be designed to absorb impact energy in a controlled manner, thereby bringing the passenger compartment to rest without the occupant being subjected to high decelerations, which can cause serious internal injury, particularly brain damage.

Vehicle size and mass provide a certain degree of protection but can have negative inertial effects. Driven by the need to overcome these negative effects of both size and mass coupled with mandates for increased fuel efficiency, an attempt is being made to use composites in the development of energy dissipating devices. The ability to tailor composites, in addition to their attributes of high stiffness-to-weight and strength-to-weight ratios, fatigue resistance and corrosion resistance, makes them very attractive in crashworthiness. The challenge is the use of specific features of geometry and materials in enabling greater safety while simultaneously decreasing the weight, without negatively affecting the overall economics of fabrication and production.

To reduce the overall weight and improve the fuel economy of vehicles, more and more metal parts are being replaced by polymer composite materials. Contrary to metals, especially in compression, most composites are generally characterized by a brittle rather than ductile response to load. While metal structures collapse under crush or impact by buckling and/or folding in accordion (concertina) type fashion involving extensive plastic deformation, composites fail through a sequence of fracture mechanisms involving fiber fracture, matrix crazing and cracking, fiber-matrix de-bonding, de-lamination and inter-ply separation. The actual mechanisms and sequence of damage are highly dependent on the geometry of the structure, lamina orientation, type of trigger and crush speed, all of which can be suitably designed to develop high energy absorbing mechanisms.

The crashworthiness of a material is expressed in terms of its specific energy absorption, E_S, and interlaminar fracture toughness, G_{IC}, which are characteristic to that particular material. Specific energy absorption is defined as the energy absorbed per unit mass of material. Mathematically $E_S=\sigma / \rho$, where ρ is the density of the composite material and σ is the mean crush stress. Interlaminar fracture toughness is defined as the measure of the damage tolerance of a material containing initial flaws or cracks. Mathematically $G_{IC} = \pi K_{IC}^2/E$, Where E is the Young's modulus and K_{IC} is the fracture toughness parameter. To get a proper command over the parameters and terms used in this paper please refer to Table 1 on page 52.

MATERIAL PERFORMANCE REQUIREMENTS

Consider a midsize car of mass 1000 kg (2200 lbs) traveling at a velocity of 15.5 m/sec (35 mph). The kinetic energy of the car is equal to $0.5\ m\ v^2 = 0.5*1000*(15.5)^2 = 120125$ J, where m is the mass of the car = 1000 kg (2200 lbs) and v is the velocity with which it is traveling = 15.5 m/sec (35 mph). In the event of an impact, crashworthy materials would have work done on them to absorb this kinetic energy over a time frame that ensures the deceleration of the car to be less than 20g [1], above which the passengers will experience irreversible brain damage because of the relative movements of various parts of the brain within the skull cavity. Therefore 120 kJ of work needs to be done on the crashworthy material. One can calculate the minimum safe time frame over which this work needs to be done to ensure the safety of the passengers using the basic equation of motion

$$v = u - at \tag{1}$$

where v is the final velocity of the car which is equal to zero since the car comes to rest, u is the initial impact speed and a is the maximum allowable deceleration which is equal to 20g. This minimum time was calculated to be equal to 0.079 seconds. Therefore the maximum allowable rate of work decay that will ensure the safety of the passengers is equal to 120125 / 0.079 = 1521 kJ/sec. So while testing materials in the lab to determine the magnitude of energy absorbed by a specimen, it is also equally important to determine the rate of this energy absorption. No discussion of energy absorption rates was found in the literature on crashworthiness. The load increases very rapidly in the initial stages of the load displacement curve for materials undergoing crushing to some maximum value after which stable crushing takes place. Now it is in this initial stage of the crash that the work decay rate might exceed the safe allowable limits. So though these materials may record very high-energy absorption values they might still not ensure the much needed passenger safety. It will be in the interest of improved safety to usefully couple these materials with other materials which when crushed have a lower initial peak load but not necessarily a high-energy absorption capability. This will smear the initial peak load response of the coupled material over a wider range which in the process lowers the net initial peak load to a value that is well within the maximum allowable rate of work decay. The specific energy absorption of unidirectional axial carbon/PEEK composites is recorded to be 180 kJ/kg. Therefore to absorb 120 kJ of kinetic energy one will only need 120125 / 180000 = 0.66 kg (1.45 lbs) of the carbon/PEEK composite located in specific places in the car. This clearly leads to an important practical conclusion that only a reasonable amount of composite is required to meet the necessary impact performance standard. Please see Figure 1 on page 67 which shows the amount of different crashworthy material that will be required in the event of a crash to ensure a safe rate of work decay in a car of mass 1000 kg (2200 lbs) traveling at a particular velocity.

TEST METHODOLOGIES

Crush tests can be carried out in two conditions namely quasi-static and impact conditions.

Quasi-static Testing

In quasi-static testing, the test specimen is crushed at a constant speed. Quasi-static tests may not be a true simulation of the actual crash condition because in an actual crash condition, the structure is subjected to a decrease in crushing speed, from an initial impact speed, finally to rest. Many materials used in designing crashworthy structures are rate sensitive. That means their energy absorption capability is dependent on the speeds at which they are crushed. So the determination of materials as good energy absorbers after quasi-statically testing them does not ensure their satisfactory performance as crashworthy structures in the event of an actual crash.

The following are some advantages of quasi-static testing.

1. Quasi-static tests are simple and easy to control.

2. Impact tests require very expensive equipment to follow the crushing process because the whole crushing takes place in a split second. Hence quasi-static tests are used to study the failure mechanisms in composites, by selection of appropriate crush speeds.

The following is a major disadvantage of quasi-static testing.

- Quasi-static tests may not be a true simulation of the actual crash conditions since certain materials are strain rate sensitive.

Impact Testing

The crushing speed decreases from the initial impact speed to rest as the specimen absorbs the energy.

The following is a major advantage of impact testing

- It is a true simulation of the crash condition since it takes into account the stress rate sensitivity of materials.

The following is a major disadvantage of impact testing.

- In impact testing, the crushing process takes place in a fraction of a second. Therefore it is difficult to study the crushing unless provided with expensive equipment like a high-speed camera.

CRUSHING MODES AND MECHANISMS

Catastrophic Failure Modes

Catastrophic failure modes are not of interest to the design of crashworthy structures. It occurs

- When unstable intralaminar or interlaminar crack growth occurs.
- In long thin walled tubes because of column instability.

- In tubes composed of brittle fiber reinforcement, when the lamina bundles do not bend or fracture due to interlaminar cracks being less than a ply thickness.

The following are the disadvantages of catastrophic failure in the design of crashworthy structures.

1. Catastrophic failure is characterized by a sudden increase in load to a peak value followed by a low post failure load. As a result of this the actual magnitude of energy absorbed is much less and the peak load is too high to prevent injury to the passengers.
2. Structures designed to react to loads produced by catastrophically failing energy absorbers are heavier than structures designed to react to loads produced by progressively failing energy absorbers.

Progressive Failure Modes

Progressive failure can be achieved by providing a trigger at one end of the tube. A trigger is a stress concentrator that causes failure to initiate at a specific location within the structure. From there on, the failure, in a controlled predictable manner, progresses through the body at the loading speed. A trigger reduces the initial load peak that accompanies failure initiation followed by stable collapse. The most widely used method of triggering is to chamfer one end of the tube. A number of other trigger geometries such as bevels, grooves and holes that have been investigated in laboratory specimens are not as easy to use in vehicle structures.

The following are the advantages of progressive failure in the design of crashworthy structures.

1. The energy absorbed in progressive crushing is larger than the energy absorbed in catastrophic failure.
2. A structure designed to react to loads produced by progressively failing energy absorbers are lighter than structures designed to react to loads produced by catastrophically failing energy absorbers.

Characteristic Types of Progressive Crushing Modes [2]

1. Transverse Shearing or Fragmentation Mode

- The fragmentation mode is characterized by a wedge-shaped laminate cross section with one or multiple short interlaminar and longitudinal cracks that form partial lamina bundles. Please see Figure 2 on page 68.
- Brittle fiber reinforcement tubes exhibit this crushing mode.
- The main energy absorption mechanisms is fracturing of lamina bundles
- When fragmentation occurs, the length of the longitudinal and interlaminar cracks are less than that of the lamina.
- Mechanisms like interlaminar crack growth and fracturing of lamina bundles control the crushing process for fragmentation.

2. Lamina Bending or Splaying Mode [3]

- Very long interlaminar, intralaminar, and parallel to fiber cracks characterizes the splaying mode. The lamina bundles do not fracture. Please see Figure 3 on page 69.
- Brittle fiber reinforcement tubes exhibit this crushing mode.

- The main energy absorbing mechanism is matrix crack growth. Two secondary energy absorption mechanisms related to friction occur in tubes that exhibit splaying mode.
- Mechanisms like interlaminar; intralaminar and parallel to fiber crack growth control the crushing process for splaying.

3. Brittle Fracturing

- The brittle fracturing crushing mode is a combination of fragmentation and splaying crushing modes. Please see Figure 4 on page 70.
- This crushing mode is exhibited by brittle fiber reinforcement tubes
- The main energy absorption mechanism is fracturing of lamina bundles.
- When brittle fracturing occurs, the lengths of the interlaminar cracks are between 1 and 10 laminate thickness.

4. Local Buckling or Progressive Folding

- The progressive folding mode is characterized by the formation of local buckles. Please see Figure 5 on page 71.
- This mode is exhibited by both brittle and ductile fiber reinforced composite material.
- Mechanisms like plastic yielding of the fiber and/or matrix control the crushing process for progressive folding.

CALCULATION OF SPECIFIC ENERGY ABSORPTION E_S

Specific energy absorption, E_S, is defined as the energy absorbed per unit mass of material. Figure 6 on page 72 is a typical load displacement curve obtained from progressive crushing of a composite tube specimen. The area under the load-displacement curve is

$$W = \int_{0}^{S_b} P dS \tag{2}$$

where W is the total energy absorbed in crushing of the composite tube specimen. A more characteristic property of progressive crushing mode is

$$W = \int_{S_i}^{S_b} P dS = \overline{P}\,(S_b - S_i) \tag{3}$$

where S_b and S_i are the crush distances as indicated in figure 6 and $\overline{P}$ is the mean crush load. The specific energy absorption capability, E_S, of a composite material defined as the energy absorbed per unit mass of material is given by

$$E_S = \frac{W}{m} \tag{4}$$

where m is the mass of the composite material.

Combining the above two equations we get

$$E_S = \frac{W}{m} = \frac{\overline{P}(S_b - S_i)}{V\rho} \tag{5}$$

where V is the volume of the crushed portion of the composite tube specimen and ρ is the density of the composite material. We can also write

$$E_S = \frac{W}{m} = \frac{\overline{P}(S_b - S_i)}{V\rho} = \frac{\overline{P}(S_b - S_i)}{AL\rho} \tag{6}$$

where A and L are the cross sectional area and length of the crushed portion of the composite tube specimen respectively.

$$E_S = \frac{\overline{P}(S_b - S_i)}{AL\rho} = \frac{\overline{P}S_b}{AL\rho} \qquad (7)$$

if S_i is much less than S_b. The ratio (S_b / L) = K is a measure of the collapsibility of the composite tube. Substituting (S_b / L) = K in the above equation we have

$$E_S = \frac{\overline{P}K}{A\rho} = \frac{\bar{\sigma}K}{\rho} \qquad (8)$$

where $\bar{\sigma}$ is the mean crush stress. In the case of polymer composites some times it is rather difficult to determine a specific value for the mean crush load, $\overline{P}$, from the load displacement curve because of the erratic changes in the magnitude of the load with displacement. One does not get the typical load displacement curve obtained from progressive crushing of a composite tube as shown in Figure 6. In that case an alternative procedure followed for calculating the energy absorbed, W, is to just determine the area under the whole load displacement curve.

LITERATURE SURVEY

Many researchers have conducted research on the energy absorption capability of composite materials. Axi-symmetrical tubes, because they are easy to fabricate and close to the geometry of the actual crashworthy structures, have been used to carry out much of the experimental work on the energy absorption of composite materials. More over composite tubes can be easily designed for stable crushing. They can be designed to absorb impact energy in a controlled manner by providing a trigger to initiate progressive crushing. This paper focuses on the experimental work conducted on axi-symmetric tubes.

The energy absorption characteristics of a crashworthy composite structure can be tailored by controlling various parameters like fiber type, matrix type, fiber architecture, specimen geometry, process conditions, fiber volume fraction and testing speed. In this paper care has been taken to group the various research activities that have been conducted to understand the effect of a particular parameter on the energy absorption capability of a composite material.

Table 2 on pages 53 to 56 provides a summary view of the range of E_S and G_{IC} values for materials that have been tested. Table 2 ranges over many parameters namely fiber type, matrix type, fiber orientation, specimen dimension, fiber volume fraction, processing conditions, test speed and trigger. Hence the range of values for the specific energy absorption, E_S, and interlaminar fracture toughness, G_{IC}. An exhaustively designed set of experiments to determine the effect of one parameter upon another for a particular composite material would be the square of the number of parameters. Considerable work needs to be done to meet this requirement.

Table 3 on pages 57 to 58 provides a summary view of the various composite materials that have been researched to understand the effect of a particular parameter on its energy absorption capability. One can see from Table 3 that the energy absorption capabilities of carbon, glass and Kevlar fibers have been investigated the most. Epoxy, polyetheretherkeetone, polyester and vinylester are the matrices whose energy absorption capability has been most extensively studied. The succeeding paragraphs report the detailed findings of the various individual studies.

The Effect of Reinforcing Fiber on the Energy Absorption Capability of a Composite Material

The type of reinforcing fiber used in a composite material determines to a very large extent its energy absorption characteristics. The important findings are:

a) Decrease in the density of fiber causes an increase in specific energy absorption capability of the fiber-reinforced tubes.

b) Higher the strain to failure of the fiber, greater the energy absorption capabilities of the fiber reinforced tubes.

c) When the fiber reinforced tubes crush in similar modes, changes in the fiber stiffness affect the energy absorption capability less than fiber failure strain.

Farley [4, 5, 6, 7, 8], **Thornton** and **Edwards** [9] and **Hull** [3, 10] observed that glass and carbon fiber reinforced thermoset tubes progressively crush in fragmentation and splaying modes. Aramid (Kevlar and Dyneema) fiber reinforced thermoset tubes, on the other hand, crush by a progressive folding mode [4, 11]. Similar results were got when **Schmuesser** and **Wickliffe** [12] performed impact and static compression tests on graphite/epoxy, Kevlar/epoxy and glass/epoxy composite tube specimens respectively. The graphite/epoxy and glass/epoxy angle-ply tubes exhibited brittle failure modes consisting of fiber splitting and ply delamination, whereas the Kevlar/epoxy angle-ply tubes collapsed in an accordion buckling mode. The lower strain to failure of the glass and carbon fibers, which fail at about 1% strain, compared to aramid fibers, which fail at about 8% strain attributes to this difference in behavior. Results of static crushing tests of graphite reinforced composite tubes conducted by **Farley** [7] to study the effects of fiber and matrix strain failure on energy absorption helped in drawing the following conclusion: "To obtain the maximum energy absorption from a particular fiber, the matrix material in the composite must have a greater strain at failure than the fiber". The graphite/epoxy tubes had specific energy absorption values greater than that of Kevlar/epoxy and glass/epoxy tubes having similar ply constructions. This is attributed to the lower density of carbon fibers compared to glass and Kevlar fibers. The theoretical density of carbon is 2.1 g/cm^3. But the actual density of carbon fibers ranges from 1.3 g/cm^3 to 1.9 g/cm^3, which is lower than the theoretical value. This is because in the act of creating the fiber, voids are also generated which causes a decrease in the density of the fibers. Since the difference in energy absorption and crush morphology are attributed to the differences in fiber properties **Hamada**, **Ramakrishna**, **Sato** and **Maekawa** [13] investigated PEEK matrix composite tubes reinforced with AS4 carbon fiber, IM7 carbon fiber and S2 glass fiber respectively. The fibers were aligned parallel to tube axis, i.e. $\theta = 0^o$. The tubes crushed progressively by the splaying mode. The S2/PEEK tubes displayed approximately 20% lower specific energy absorption than the AS4/PEEK and IM7/PEEK tubes though the mean crush stress of S2/PEEK tubes is comparable to that of AS4/PEEK and IM7/PEEK tubes. This is a direct result of the lower density of carbon fiber reinforced materials than the glass reinforced material, since the specific energy absorption is defined as the ratio of the mean crush stress and density of the composite. Despite AS4 carbon fibers being more ductile than the IM7 carbon fibers, both AS4/PEEK and IM7/PEEK tubes displayed similar specific energies. Hence they concluded, unlike the thermoset tubes, the fiber failure strain has little effect on the energy absorption of the thermoplastic tubes, as the fiber failure strain is much smaller than that of the thermoplastic matrix. Epoxy composite tubes reinforced with low failure strain Thornel-300 carbon fibers and intermediate failure strain Hercules AS-4 carbon fibers was investigated by **Farley** [4]. He observed that the tubes having greater energy absorption properties were the ones reinforced with fibers having higher strain to failure. **Farley** and **Jones** [14] established the modes of crushing and the controlling mechanisms on continuous fiber-reinforced composite tubes. They suggested that the crushing response of the composite tubes could be categorized into three basic modes: transverse shearing, lamina bending, and local buckling. The mechanical properties of the constituent materials and the structure of the specimen influence the mechanisms that control these different crushing modes. In addition, they presented an analysis procedure that can be used to determine the qualitative change in the sustained crushing load due to a change in specimen material properties or geometry. The analysis procedure is similar in form to the equation of buckling load of a column on an elastic foundation. This procedure will be useful in preliminary design and in providing an insight in to the crushing behavior of composite tubes. A finite element analysis was also conducted to model the crushing process of continuous-fiber-reinforced tubes by **Farley** et al [15]. The analysis is compared with experiments on graphite/epoxy and Kevlar/epoxy tubes. The method is based upon a phenomenological mode of the crushing process and obtained a reasonable agreement between the analysis and the experiment. **Thornton** et al [16] examined the energy absorption capability in graphite/epoxy, Kevlar/epoxy and glass/epoxy composite tubes. The composite tubes collapsed by fracture and folding mechanisms. The load/compression curves for the graphite/epoxy and the glass/epoxy tubes had similar characteristics but the Kevlar/epoxy composite tubes collapsed by buckling. For Kevlar composites, the collapse started progressively under essentially a constant load until the collapse was complete, apart from a fine serrated structure superimposed upon the load curve. In addition, they showed that changes in the lay-up that increased the modulus increased the energy absorption of the tube. These tubes made from, or including Kevlar fiber, tended to collapse in an unstable mode by buckling rather than by fracture, which led to low values for specific energy absorption. The fracture collapse mechanism depends upon the geometry. **Farley** [6] demonstrated that graphite/epoxy tubes which failed in a brittle mode had negligible post crush integrity, where as Kevlar/epoxy tubes which failed in an accordion buckling mode similar to aluminum tubes exhibited post crush integrity. This characteristic of the Kevlar/epoxy tubes can be attributed to fiber splitting and fiber plasticity affects. He observed that longitudinally oriented graphite fibers absorb more energy than longitudinally oriented Kevlar or glass fibers. Static crushing tests were conducted by **Chiu** et al [17] on 3-D carbon/epoxy and Kevlar/epoxy braided composite square tubes to investigate the energy absorption capabilities of these materials. The 3-D carbon braided composite tube displayed higher specific energy absorption than the Kevlar tubes. This revealed that carbon tubes in crush tests are capable of absorbing more energy. However, the Kevlar tubes demonstrated good post-crush structural integrity. Another study by **Chiu** et al [18] revealed similar results as above where the specific energy absorption of the 3-D braided carbon/epoxy composite square tube was 24% higher than that of the 3- braided Kevlar/epoxy composite square tube.

To visualize how much of specific energy absorption, E_S, is really attributable to fiber type, please refer to Table 4 on page 59.

The Effect of the Matrix on the Energy Absorption Capability of a Composite Material

The following comments tell us about what was found with respect to matrix type:

a) Higher interlaminar fracture toughness, G_{IC}, of the thermoplastic matrix material causes an increase in energy absorption capability of the composite material.

b) An increase in matrix failure strain causes greater energy absorption capabilities in brittle fiber reinforcements. Conversely, the energy absorption in ductile fiber reinforcements decreases with increasing matrix failure strain.

c) Changes in matrix stiffness have very little effect on the energy absorption capability of composite materials with ductile fiber reinforcement.

d) Further studies are essential to understand clearly the role of thermosetting resin matrices in the energy absorption capability of the composite material.

Carbon fiber reinforced composite tubes with different kinds of thermoplastic matrices were studied by **Ramakrishna** et al [19]. Among all types of tubes investigated carbon fiber/PEEK tubes exhibited the highest specific energy owing to its higher fracture toughness (1.6 ~ 2.4 kJ/m^2). These were in comparison to that of carbon fiber/PEI (1.0 ~ 1.2 kJ/m^2) and carbon fiber/PI (1.0 ~ 1.2 kJ/m^2) composite materials [20, 21]. The carbon fiber/PAS tubes displayed the lowest energy absorption capability. The specific energy of thermoplastic tubes follow the order PAS< PI< PEI< PEEK. In a similar study **Satoh** et al [22] investigated the energy absorption of carbon/polyetherimide (C/PEI), carbon/polyimide (C/PI), carbon/polyarylsulfone (C/PAS), carbon/polyetheretherkeetone (C/PEEK), and compared it with that carbon /epoxy and glass/polyester. Carbon/thermoplastic tubes demonstrated superior energy absorbing capabilities (E_S = 128 ~ 194 kJ/kg) than carbon/epoxy (E_S = 110 kJ/kg) or glass/polyester (E_S = 80 kJ/kg) structures. Carbon/PEEK crushed progressively and recorded a specific energy absorption value of 194 kJ/kg. The energy absorption capability of carbon/epoxy and carbon/PEEK composite tubes made from unidirectional prepreg materials was investigated by **Hamada** et al [23] by conducting axial compressive tests on them. The superior energy absorption capability of carbon fiber/PEEK tubes (180 kJ/ Kg) is attributed to the higher interlaminar fracture toughness (G_{IC}) of the thermoplastic PEEK matrix composite (1.56 to 2.4 kJ/m^2). The carbon/epoxy tube having an interlaminar fracture toughness in the range 0.12 to 0.18 kJ/m^2 absorbed only 53 kJ/Kg specific energy. **Farley** [8] based upon observation and a general understanding of the crushing process concluded the following: The energy absorption of materials that fail by transverse shearing or brittle fracturing is little affected by matrix stiffness. However, materials that fail by lamina bending can be more significantly affected by matrix stiffness. A change in matrix stiffness can cause brittle fiber composites to fail in a different mode. However, changes in matrix stiffness have very little effect on the energy absorption of ductile fiber reinforcements.

To visualize how much of specific energy absorption, E_S, and interlaminar fracture toughness, G_{IC}, is really assignable to matrix type, please refer to Table 5 and Table 6 respectively on page 60 and page 61 respectively.

The Effect of Fiber Architecture on the Energy Absorption Capability of a Composite Material

The following comments tell us what was found with respect to fiber orientation.

The fiber orientations that enhance the energy absorption capability of the composite material requires them to:

a) Increase the number of fractured fibers.

b) Increase the material deformation.

c) Increase the axial stiffness of the composite material.

d) Increase the lateral support to the axial fibers.

Work by **Farley** [4] on glass/epoxy, carbon/epoxy and Kevlar/epoxy composite tubes with fiber architecture $[0\pm\theta]_4$, where θ varied from 0^o to 90^o, showed significant differences in the energy absorption trends for these materials. The difference in trends can be explained by examination of crushing modes. The specific energy of the glass/epoxy and Kevlar/epoxy tubes remained constant with increasing θ up to 45^o and above this value it increased. This trend is not consistent with the general mechanical response of composites. The glass/epoxy and Kevlar/epoxy specimen crushed in a lamina bending and local buckling mode respectively. This increase in energy is attributed to the increased lateral support to the axial fibers with increasing θ. On the other hand, the specific energy of the carbon/epoxy tubes initially decreased with increasing θ up to 45^o and then remained constant. The carbon/epoxy specimens crushed in brittle fracturing mode. This initial decrease in the energy absorption is attributed to the reduction in axial stiffness of the composite material with increasing θ. **Farley** and

Jones [24] in a later study quasi-statically crushed carbon/epoxy and glass/epoxy tube specimens with fiber architecture $[0 \pm \theta]_S$, to determine the influence of ply orientation on the energy absorption capability. As θ increases, the energy absorption capability of the carbon/epoxy tube decreases nonlinearly. The crushing mode is primarily brittle fracture. The energy absorption capability of the glass/epoxy tube increases nonlinearly with θ. The crushing mode of the glass/epoxy tube is lamina bending. **Hull** [3, 25] studied the effect of fiber arrangement on progressive crushing in carbon fiber/epoxy unidirectional laminate tubes, woven glass cloth/epoxy tubes, filament-wound angle ply glass fiber/polyester tubes and in plane random chopped glass fiber polyester tubes. The filament wound glass/polyester tubes were made by conventional filament winding with winding angles ϕ between $\pm 35^o$ and 90^o. Here ϕ is the angle between the direction and the longitudinal axis of the tube. The tube had 4 layers of fibers and the volume fraction of the fibers was about 0.45. These tubes were 50 mm in diameter and the wall thickness was about 3-4 mm. All tests were conducted at a crushing speed of 0.2 mm/s with a servo-hydraulic testing machine having a maximum static loading capacity of 180 kN. A 300 mm stroke was used for all the compression tests. The specific energy increased with increasing ϕ up to $\pm 65^o$ and after that it decreased. Hence the maximum value of specific energy occurred at $\phi = \pm 65^o$ and there was a systematic change in the load displacement curves and crush zone morphology with winding angle ϕ. These changes in crush zone morphology (when $\phi = \pm 35^o$ to $\pm 55^o$, tubes crush in splaying mode and when $\phi > \pm 65^o$, tubes crush in fragmentation mode) cause the changes in specific energy. The tube with axially aligned fibers showed very little progressive crushing before complete failure by the formation and growth of longitudinal cracks. **Hamada** et al [11] studied the effect of fiber architecture on the energy absorption capability of hybrid composite tubes reinforced with both carbon and dyneema (polyethylene) fibers. The resin fibers used were that of epoxy. It was seen that the energy absorption capability decreased with increasing fiber orientation with respect to the longitudinal axis of the tube. **Berry** [26] investigated woven glass fabric/polyester tubes by varying the angle of the lay-up. The energy absorption of the tubes with the warp and weft directions at 45^o to the tube axis is observed to be 30% less than that for similar tubes with warp and weft direction parallel to the axial (0^o) and hoop (90^o) directions respectively. This increase in the energy absorption is due to more material deformation and fracture in the case of the latter tubes. Carbon fiber reinforced composite tubes with different thermoplastic matrices: polyetheretherkeetone (PEEK), polyetherimide (PEI), polyimide (PI) and polyarylsulfone (PAS) were studied by **Ramakrishna** et al [19]. Fiber orientations of 0^o, $\pm5^o$, $\pm10^o$, $\pm15^o$, $\pm20^o$, $\pm25^o$ and $\pm30^o$ with respect to the axis of the tube were used. The specific energy absorption capability of the progressively crushed tubes was found to be a function of the θ value. In general, as θ increases, the length of the longitudinal cracks decrease. This is due to the increase of fracture toughness with increasing θ. This improved fracture toughness offers more resistance to the crack growth process, thus resulting in an increased specific energy absorption value for the composite material. Microfracture processes such as fiber fracture and frond splits were observed to increase with increasing θ. Hence it was concluded that this increase in microfracture processes is what causes an increase in the total energy absorbed.

To visualize how much of specific energy absorption, E_S, is really assignable to fiber architecture, please refer to Table 7 on page 62.

The Effect of Geometry of the Specimen on the Energy Absorption Capability of a Composite Material

The important findings are:

a) It is crush zone fracture mechanisms that determine the overall energy absorption capability of a composite material and tube dimensions largely influence these fracture mechanisms.

b) The specific energy absorption, E_S, follows the order: circular> square> rectangle, for a given fiber lay up and tube geometry.

Thornton and **Edwards** [9] conducted a study investigating the geometrical effects in energy absorption of circular, square, and rectangular cross section tubes. Although the range of geometrical parameters was large, the actual number of test conditions was limited. The limited number of tests made it difficult to precisely define certain trends. They concluded that for a given fiber lay up and tube geometry, the specific energy follow the order, circular > square > rectangle. Specimens were fabricated with graphite, Kevlar, glass, and hybrid combinations of these reinforcements in an epoxy matrix. Tape and fabric prepregs were utilized to fabricate tubes with ply orientations of [±45] and [0/90]. The tubes made from glass or graphite fibers collapsed by fracture mode. Stable collapse with high-energy absorption occurred over a critical range of tube geometry. Kevlar and Kevlar hybrid composites were found to generally be unsuitable energy absorbers because of unstable crushing behavior, resulting in large undulations in the crushing load. These results are in contrast with results for crushable beams reported by **Farley** [27]. **Farley** found Kevlar reinforced beams to consistently crush in a stable manner and graphite tubes of reference [9] exhibited combined brittle fracturing and lamina bending crushing modes. Crushing loads of glass and graphite composite tubes were more uniform than the crushing loads for the Kevlar reinforced composite tubes. **Farley** [5] investigated the geometrical scalability of graphite/epoxy (Gr/E) and Kevlar/epoxy (K/E) $[\pm 45]_N$ tubes by quasi-statically crush testing them. This ply orientation is used in typical subfloor beam structures. In that study, the tube inside diameter varied between 1.27 cm to 10.16 cm, the number of plies (N) varied between 2 and 24 and the tube inside diameter to wall thickness ratio (D/t) varied between 1.4 and 125. All circular cross section graphite/epoxy tubes exhibited a progressive brittle fracturing mode. All Kevlar/epoxy tubes when crushed exhibited the characteristic local buckling crushing mode. The buckle wavelength varied with tube diameter. Tube inside diameter to wall thickness ratio (D/t) was determined to significantly affect the energy absorption capability of the composite materials. Energy absorption was found to be a decreasing nonlinear function of tube D/t ratio. That is, a reduction in D/t ratio results in an increase in the specific energy. This increase is due to reduction in interlaminar cracking in the crush region of the tube. Kevlar/epoxy tubes are reported to exhibit similar trends. Their energy absorption capability is geometrically scalable but that of graphite/epoxy tubes are not. **Farley** and **Jones** [28] reported carbon/epoxy and Kevlar/epoxy tubes with elliptical cross section to also exhibit similar trends. When statically crushed, the energy absorption capability was determined to be a decreasing nonlinear function of the ratio of tube internal diameter to wall thickness (D/t). **Thornton** et al [29] studied the effect of tube dimensions. It was found that carbon/epoxy exhibited large changes in their energy absorption characteristics with a range of values of tube diameter (D), tube wall thickness (t) and (D/t) ratio. Relative density, defined as the ratio of the volume of the tube to that of a solid of the same external dimensions, was varied in the range 0.01 to 1.0. The tube crush length is unstable and the critical size of the tube is dependent on the fiber type and fiber architecture, below a relative density value of 0.025 for carbon/epoxy and 0.045 for glass/epoxy. The specific energy is essentially independent of tube dimensions for the tubes that crushed in a stable manner. A total of 28 graphite/epoxy flat plate specimens and 6 graphite/epoxy tube specimens were crushed by **Dubey** and **Vizzini** [30] under quasi-static conditions to provide a basis for the comparison of the measured energy absorbency of these two geometry. The tube and flat plate specimens crushed in similar failure modes with the flat plates absorbing 12% less energy per unit mass. It is concluded that flat specimens can be used as a lower cost alternative to tube specimens or in test programs requiring simpler geometry. Glass cloth/epoxy tubes and carbon fiber/PEEK tubes with cross sectional shapes full circle, three quarter circle, half circle and quarter circle were investigated by **Hamada** et al [31]. Two types of glass cloth/epoxy composite tubes were tested. One type of tubes contained glass cloth treated with an aminosilane-coupling agent and the other type of tubes used glass cloth treated with acrylsilane-coupling agent. Quasi-static tests were performed by axial compression between two flat platens. All the specimens crushed progressively from the chamfered end. One of the important results of this study is that the mode of progressive crushing is independent of the cross sectional shape of the composite tubes. The constituent materials in the composite mainly determine it. The aminosilane-treated glass cloth/epoxy specimens, owing to the good interfacial bonding of its fiber to the resin matrix, crush by splaying mode whereas the acrylsilane-treated glass cloth/epoxy specimens, due to the presence of higher frictional forces in the crush zone, crush by fragmentation mode. The carbon/PEEK specimens crush progressively by the splaying mode, mainly due to the orientation of carbon fibers parallel to the tube axis. Another important result of this study was that the cross-sectional shape of the tube influences the specific energy absorption capability of composite tubes. In the case of the glass cloth/epoxy specimens, the specific energy decreased by 20% with the change in tube cross section from full circle to quarter circle. The specific energy of carbon fiber/PEEK tube specimens decreased by only 5% for the same change in cross sectional shape. Square tubes, circular tubes and circular cones made of glass fiber, polyester or vinylester resin were tested by **Mamalis** et al [32] under static and dynamic crushing conditions in a speed range of 18 - 24 m/sec. It was found that for specimens showing stable crushing, greater thickness tends to reduce the specific energy absorption, square tubes have less specific energy absorption than circular tubes, and greater cone angle results in lower specific energy absorption. **Fairfull** [33] and **Fairfull** and **Hull** [34] studied the effects of specimen dimensions on the specific energy of glass cloth/epoxy tubes. Five sets of tubes with D ranging from 16 mm to 50 mm were studied. The specific energy decreased with increasing D. The specific energy, for a given D, initially increased with decreasing D/t ratio up to 5 below which, it decreased. It was concluded that there could not be a universal relationship to predict energy absorption capability because the reason for this variation of energy could not be clearly identified. Static crushing tests were conducted by **Farley** [35] on graphite/epoxy and Kevlar/epoxy square cross section tubes to study the influence of specimen geometry on the energy absorption capability and scalability of composite materials. Tube ply orientations were $[\pm 45]_N$. The square cross section tube widths were between 1.27 cm and 7.62 cm. The width to wall thickness ratios (w/t) was between 6 and 125. These tube geometry and materials are representative of helicopter subfloor beam structure applications. The tube inside width to wall thickness ratio (w/t) was determined to affect the energy absorption capability of composite materials. The energy absorption capabilities of graphite/epoxy and Kevlar/epoxy tubes are non-linear functions of tube ratios (w/t). Energy absorption generally increased with decreasing w/t ratio. For graphite/epoxy tubes having w/t ratios in the range of 20 and 50, changes in crushing mode occurred, resulting in a decrease in energy absorption capability as w/t ratio decreased. Both graphite/epoxy tubes and Kevlar/epoxy tubes crushed in a progressive and stable manner. All graphite/epoxy tubes exhibited a lamina bending crushing mode while Kevlar/epoxy tubes exhibited a local buckling crushing mode. The test results suggest that Kevlar/epoxy tubes are geometrically scalable where as that of graphite/epoxy are not. **Hamada** and **Ramakrishna** [36] studied the crushing performance of carbon fiber/PEEK tubes with different thickness t and diameter D values. When t is in the range of 2mm and 3mm all the types of tube display their highest specific energies. With increasing t up to this critical range, the specific energy increased, above which it decreased. Changes in the crush zone morphology were the cause of specific energy variation. Microfracture processes in the crush zone varied with the thickness t though the tubes crushed progressively by splaying mode. With increasing t up to critical range both the frond splits and fractured fibers increased. It was confirmed after the above investigation that in the case of thermoplastic composite tubes, the energy absorption characteristics are mainly influenced by the absolute value of t rather than the (D/t) ratio. Static energy absorption tests were conducted on different geometry of 6 ply T300/934, graphite/epoxy sine web by **Hanagud** et al [37]. They reported that the sine web composite material exhibit good energy absorption capabilities when crushed in the web direction. They demonstrated that the energy absorption efficiency of the web specimens with 180^{o} included angle is equal to corresponding tube specimens. By reducing the included angle of the sine web from 90^{o}-60^{o}, the crushing mode changed abruptly from stable progressive crushing to unstable global buckling.

To visualize how much of specific energy absorption, E_S, is really assignable to specimen geometry, please refer to Table 8 on pages 63 to 64.

The Effect of Processing Conditions on the Energy Absorption Capability of a Composite Material

The following comments tell us what was found with respect to processing conditions:

a) The cause for variation in energy absorption capability with cooling rate is the cooling rate dependence of fracture toughness of semi-crystalline thermoplastic composite materials. Fracture toughness increases with an increase in cooling rate and hence causes an increase in the energy absorption capability of the thermoplastic composite material.

b) There has been no systematic study reported in the literature on the effect of processing conditions on the energy absorption characteristics of thermoset composite tubes.

Hamada et al [38] investigated the effect of processing conditions on the energy absorption capabilities of carbon fiber/PEEK composite tubes. The thermoplastic tubes having the carbon fibers aligned parallel to the tube axis were fabricated using a thermally expandable PTFE mandrel technique. Three cooling rates were used: rapid cooling by immersion in chilled water (95.5^{o}C/min.), gradual cooling in air (8.2^{o}C/min.) and slow cooling in the oven with heater switched off (0.7^{o}C/min). All the tubes crush progressively by splaying mode when quasi-statically crush tested. The rapidly cooled tubes have specific energy absorption of 226 kJ/kg, the highest recorded for any material, which is 15% higher than the 197 kJ/kg, the specific energy absorbed by the gradually and slow cooled tubes.

To visualize how much of specific energy absorption, E_S, is really assignable to processing conditions, please refer to Table 9 on page 65.

The Effect of Fiber Volume Fraction on the Energy Absorption Capability of a Composite Material

The following comments tell us what was found with respect to fiber volume fraction:

a) The effect of fiber volume fraction on the energy absorption has been less extensively studied.

b) It is not always true, as one would normally think that an increase in the fiber content would necessarily improve the specific energy absorption capability of a composite material. A possible explanation for the above statement is that as the fiber volume fraction increases, the volume of the matrix between the fibers decrease. This causes an increase in the matrix density. This further leads to a decrease in the interlaminar strength of the composite. As interlaminar strength decreases, interlaminar cracks form at lower loads, resulting in a reduction in the energy absorption capability. So the changes in the energy absorption trends with fiber content are determined by the crushing response of the composite material.

Ramakrishna and **Hull** [39] investigated the specific energy absorption capability of knitted carbon fiber-fabric/epoxy tubes tested under axial compressive load. Tubes with lower fiber content crushed irregularly where as progressive crushing took place in tubes having fiber content above 15%. The specific energy absorption capability increased with fiber content. **Ramakrishna** [40], a couple of years later, again investigated the effect of fiber content on the specific energy absorption capability of knitted carbon fiber fabric/epoxy and knitted glass fiber fabric/epoxy composite tubes. The specific energy of both types of composite tubes increased with increasing fiber content. One possible explanation for this is that a higher tube loading is associated with generation of larger surfaces due to fiber/matrix debonding which results in increased energy absorption capability. Contrary to the above finding, **Farley** [4] reported a decrease in specific energy of carbon fiber/epoxy composite material with the increase in fiber volume fraction from 40% to 70%. The decrease in specific energy is attributed to the decrease in interlaminar shear strength of the composite with increasing fiber content. In a later study **Farley** and **Jones** [24] again investigated carbon/epoxy composite tubes with fiber volume fractions in the range 40% to 55% to get similar results. They reported some specimens exhibit a large decrease in energy absorption capability with increasing fiber volume fraction, where as other specimens exhibit a slight decrease. Hence, it should be concluded that an increase in the fiber content might not always necessarily improve the specific energy absorption capability. The crushing response is what determines the energy absorption trends. Work by **Hull** and **Snowdon** [41] on sheet molding compounds based on polyester resins and glass fibers (SMC) showed an increase in specific energy with an increase in fiber volume fraction. The tube specimens made by hot press molding of SMC were subjected to axial compression at speeds up to 15 m/sec (33 mph). **Thornton** et al [42] investigated glass fiber/vinyl ester rods with fiber volume fraction in the range 10% to 50%. He reported an increase in specific energy with increase in fiber volume fraction.

The Effect of Testing Speed on the Energy Absorption Capability of a Composite Material

The important findings are:

a) The energy absorption capability is a function of testing speed when the mechanical response of the crushing mechanisms is a function of strain rate. The rate at which the structure is loaded has an effect on both the material's behavior and also the structural response of the target.

b) The strain energy absorbing capabilities of the fibers and the geometrical configuration of the target are very important factors that determine the impact resistance of composites at low rates of strain.

c) The strain energy absorbing capabilities of the fibers and the geometrical configuration of the structure is less important at very high rates of strain since the structure responds in a local mode. What is important is the magnitude of energy dissipated in delamination, debonding and fiber pull out.

Bannerman and **Kindervater** [43] while investigating carbon/epoxy and Kevlar/epoxy tubular and beam specimens reported an increase in energy absorption with crushing speed. **Thornton** [16] reported very little change in the specific energy absorption of 0/90 graphite/epoxy, Kevlar/epoxy and glass/epoxy composite tubes over a wide range of compression rates (10^{-1} to $2*10^{4}$ inches/min). **Thornton** [44] also investigated the energy absorption behavior of Pultruded glass/polyester and glass/vinyl ester tubes in the crushing speed range from 2.1 X 10^{-4} m/s to 15 m/s. He reported a 10% decrease with increasing test speed in the case of glass/vinyl ester tubes and a 20% increase in energy absorption in the case of glass/polyester tubes. This can be attributed to the higher tensile strength and modulus of the vinylester. **Thornton** et al [42] later investigated glass fiber/vinyl ester rods with testing speed in the range 0.13 to 2.54 mm/min. The specific energy was seen to increase essentially linearly with log (testing rate). **Farley** [6] investigated Kevlar/epoxy, carbon/epoxy, and glass/epoxy and composite tubes with fiber architecture $[0\pm\theta]_4$ at speeds of quasi-static and 7.6 m/sec impact and found specific energy to be independent of crushing speed. When **Farley** [45] investigated carbon/epoxy and Kevlar/epoxy tubes with $[\pm\theta]_3$ fiber architecture he found a 35% increase in specific energy with the change in the crushing condition from quasi-static to impact. The magnitude of effects of crushing speed on specific energy was determined to be a function of the mechanism that controls the crushing process. Static and dynamic crushing tests in a speed range of 18 – 24 m/sec were conducted by **Mamalis** et al [32] on three different composite materials. Two of the composite materials consisted of fiberglass and vinyl ester resins. The third was made up of fiber glass and polyester resin. The specimens under investigation had different geometry:

square, circular and circular cone. The specific energy of thin walled circular conical specimen made of polyester resin and random chopped strand mat of glass fiber were reduced by 35% under a crushing speed of about 21 m/sec. It was hence concluded that crush speed interacts with cone angle and wall thickness of the specimen. Reduction in specific energy caused by the increase of crush speed becomes more significant when wall thickness or cone angle is larger. However the crushing speed was not observed to have a significant effect on the specific energy absorption of thin walled circular or square tubes made of the three kinds of composite materials. In another investigation **Kindervater** [46] observed little difference between the quasi-static and dynamic energy absorption of Kevlar/epoxy tubes. **Schmueser** and **Wickliffe** [12] reported a decrease of up to 30% in energy absorption of impacted carbon/epoxy, glass/epoxy and Kevlar/epoxy tubes with fiber architecture $[0_2/\pm45]_s$, as compared to static test results. **Ramakrishna** [40] studied the effect of testing speed on the specific energy absorption capability of knitted glass fiber/epoxy and knitted carbon fiber fabric/epoxy composite tubes. The specific energy of both types of composite tubes decreased by 20% with change in testing condition from quasi-static to impact. This is attributed to the decrease in fracture toughness (G_{IC}) of composite materials with increasing test speeds. Decreased fracture toughness means less resistance to the longitudinal cracking of the tube wall and therefore lower energy absorption.

To visualize how much of specific energy absorption, E_S, is really assignable to testing speed, please refer to Table 10 on page 66. Note that of the two systems reported, the E_S for the glass/polyester system goes up with an increase in the testing speed while the E_S for the glass/vinyl ester goes down with a similar increase in testing speed.

SUMMARY OF FINDINGS

The effect of a particular parameter (such as fiber type, matrix type, fiber orientation, specimen geometry, processing conditions, fiber content, test speed and test temperature) on the energy absorption of a composite material is summarized below.

Fiber Type: The density of the reinforced fibers has a lot to do with the energy absorption characteristics of a composite material. As the density of the fiber decreased from a higher to a lower value, the specific energy of the fiber reinforced tubes increased from a lower to a higher value respectively. Tubes reinforced with fibers having higher strain to failure result in greater energy absorption properties. Changes in fiber stiffness affect energy absorption capability less than changes in fiber failure strain, provided the different materials crush in the same mode. **Matrix Type:** If one is restricted to discussing the energy absorption capability of a reinforced fiber thermoplastic matrix material it could be concluded that a higher interlaminar fracture toughness, G_{IC}, of the thermoplastic matrix material would increase the energy absorption capability of the composite material. Also an increase in matrix failure strain causes greater energy absorption capabilities in brittle fiber reinforcements. Conversely, the energy absorption in ductile fiber reinforcements decreases with increasing matrix failure strain. The role of thermosetting resin matrices in energy absorption is not clear and further studies are essential. **Fiber Orientation:** Regarding the effects of fiber orientation on the energy absorption capability of a composite material, the fiber orientations that enhance the energy absorption capability of the composite material requires them to:

a) Increase the number of fractured fibers.

b) Increase the material deformation.

c) Increase the axial stiffness of the composite material.

d) Increase the lateral support to the axial fibers.

Specimen Geometry: Studying the effect of tube dimensions it can be said that the crush zone fracture mechanisms are influenced by the tube dimensions and these fracture mechanisms determine the overall energy absorption capability of the composite tubes. For a given fiber lay up and tube geometry, the specific energy follows the order, circular> square> rectangle. **Processing Conditions:** The cooling rate dependence of fracture toughness of semi-crystalline thermoplastic composite materials is the cause for variation in energy absorption capability with cooling rate. Fracture toughness increases with increase in cooling rate and hence causes an increase in the energy absorption capability. There has been no systematic study reported in literature on the effect of processing conditions on the energy absorption characteristics of thermoset composite tubes. **Fiber Content:** There has been no systematic study reported in literature on the effect of fiber content on the energy absorption of composites. It should be noted that an increase in the fiber content might not always necessarily improve the specific energy absorption capability. As the fiber volume fraction increases, the volume of the matrix between the fibers decreases. This causes the interlaminar strength of the composite to decrease. As interlaminar strength decreases, interlaminar cracks form at lower loads, resulting in a reduction in the energy absorption capability. Also, as fiber volume fraction increases, the density of the composite increases which results in a lower energy absorption capability. **Test Speed:** Upon reviewing the literature there seems to be a lack of consensus about the influence of test speed on the energy absorption. However it is known that energy absorption capability is a function of testing speed when the mechanical response of the crushing mechanism is a function of strain rate. The rate at which the structure is loaded has an effect on both the material's behavior and also the structural response of the target. The strain energy absorbing capabilities of the fibers and the geometrical configuration of the target are very important to the impact resistance of composites at low rates of strain. However the strain energy absorbing capabilities of the fibers and the geometrical configuration of the structure is less important at very high rates of strain since the structure responds in a local mode. What is important is the magnitude of energy dissipated in delamination, debonding and fiber pull out.

THE MOST EFFICIENT CRASHWORTHY COMPOSITE MATERIAL

Carbon fiber reinforced tubes display higher strength than other fiber-reinforced tubes. Its superior specific energy absorption is a direct result of the lower density of carbon fiber reinforced materials, since energy absorption is defined as the ratio of mean crush stress and density of the composite. The energy absorption capability of the fiber reinforced thermoplastic PEEK tubes is higher than the other fiber reinforced matrix materials due to its superior interlaminar fracture toughness (1.56–2.4 kJ/m^2) compared to other matrix materials. Because of their high strains to failure, they are the only matrices presently available that allow the new intermediate modulus, high strength (and strain) carbon fibers to use this full strain potential in the composite. The PEEK resin in carbon/PEEK is believed to have three phases: an amorphous phase, a trans-crystalline growth from fiber surfaces and a sphere shaped crystal. The bond strength of the carbon fibers to the matrix is enhanced by this kind of crystallinity. Therefore one can conclude that the specific energy absorption (180 kJ/kg) of the semi crystalline 0^0 carbon fiber/PEEK tube should be much higher than other composite tubes [23]. The damages they incur while absorbing energy are in very small amounts. The superior performance of carbon fiber/PEEK tubes is attributed to mainly to:

a) Higher fracture toughness of PEEK matrix composites (Carbon fiber/PEEK composites exhibit excellent static and dynamic toughness).
b) Splitting of fronds.
c) Large number of fiber fractures.
d) The PEEK matrix allows rapid repair using fusion techniques. For example, if we adopt the hot press technique, simply treating the component to a temperature above the melting point of the matrix, reforming and cooling can reduce the impact damage.

The PEEK matrix leads to a much higher resistance to crack growth between the fibers. This ensures that the tube does not fail before the onset of progressive crushing mode. Measurements of the interlaminar Mode I fracture toughness, G_{IC}, parallel to the fibers of the unidirectional materials gave values of G_{IC} in the range 1.56 to 2.4 kJ/m^2 for carbon fiber/PEEK.

The success of the PEEK matrix as a superior energy absorbing material suggests the high potential in thermoplastic matrix materials to be good energy absorbers. The role of a thermoplastic resin matrix in energy absorption is extensively reported in the literature. However the same cannot be said with regard to thermosetting resin matrices. Their role in the energy absorption characteristics of composites is not yet clear. Considering the large number of cost efficient, low temperature processing methods available to industry more work towards understanding the energy absorption characteristics of these matrices is currently needed.

RATE EFFECTS

The ability of a structure to absorb impact energy and be survivable for the occupant is called the "crashworthiness" of the structure. From this definition it is understood that an ideal crashworthy material used in a car, in the event of a crash, must do the following. One, absorb the kinetic energy of the car and two, dissipate this energy over a time frame that ensures the deceleration of the car to be less than a critical value, above which the passengers will experience irreversible brain damage because of the relative movements of various parts of the brain within the skull cavity. So while testing specimens in the lab one needs to measure the magnitude of the energy that it is capable of absorbing and the length of time over which this energy will be absorbed. Both the magnitude and the rate of energy absorption is characteristic to a particular material. If there were two different types of materials with similar energy absorption capabilities, the material that dissipated this energy over a longer period of time would be considered more crashworthy. So in the course of evaluating the crashworthiness of a material, measurement of time is important. The magnitude of the energy absorbed by the crash elements in a car is the area under the load displacement curve where load is nothing but the product of the mass of the car and its deceleration after impact. The rate of energy absorption in the car is dependent on the constituent materials the car is made of and configuration of its structures.

Both quasi-static and impact testing can be carried out in the lab. Impact testing is a true simulation of the actual crash condition. The magnitude of energy absorbed by a material when impact tested and the rate at which this energy is dissipated can be used to accurately interpret the material behavior in the event of an actual crash. Here again the magnitude of energy absorbed by the specimen is the area under the load displacement curve where load is the product of the mass of the impactor and its deceleration after impact. The rate of energy transformation is solely a material property.

In quasi-static testing the tube specimen is crushed at a constant speed. Here the energy absorbed is the area under the load displacement curve. However load in this case is just the specimen's reaction to it being crushed. It does not have a deceleration term because the crushing process is taking place at a constant speed. The measurement of the time quantity is not worthwhile because one actually controls the rate of energy absorption rather than it being a material property as in the case of impact testing. Hence it is inferred that quasi-static testing is not a true simulation of the actual crash conditions. It can however be used to study the failure mechanisms that take place during the crushing of a tube.

One can conclude from the above thoughts the following: 1) While conducting impact tests on a composite material, it is equally important to determine the rate of energy transformation as it is to record the magnitude of the energy being absorbed by the specimen. 2) It is also important that when one reports the magnitude of energy absorbed by a particular material when quasi-statically or impact tested, the speed at which the testing was done be also reported. Many materials are rate sensitive and can absorb different magnitudes of energies at different testing speeds. 3) Quasi-static testing is not a true simulation of real crash conditions and is used to study the failure mechanisms that take place when composite tubes are crushed. However if a sample is progressively crushed, its load displacement curve is characterized by the load rising to some peak value followed by an initial failure and then a sustained crushing load (Mean Crush Load) that cycles about some average value suggested to be at least 75% of the peak load. Hence in this special case, the mean crush load is independent of the change in displacement and time. The magnitude of the specific energy absorbed will give a clear measure of its crashworthiness. Hence there is no need to calculate the rate of energy absorption. But not all materials when crush tested exhibit ideal progressive crushing. Therefore there is a need to measure the rate of energy absorption for these materials in addition to recording the magnitude of energy they absorb before determining their crashworthiness.

DESIGN FOR OPTIMUM WORK RATE DECAY

$$W_{Vehicle} + W_{Structure} = 0 \tag{9}$$

The above expression will always be true: The sum of the work done by the vehicle and work done by the structure is always zero. Here $W_{Vehicle}$ is the work done by the vehicle moving at a particular velocity ‘v’ having a kinetic energy of 0.5 m v^2. During the crash event the structure does work to absorb this kinetic energy. It will be desirable that this energy be absorbed over a large period of time rather than in a short time duration. That is, the rate of work done by the structure is as low as possible. This can be accomplished by optimum design of structure geometry or by coupling different material types while fabricating the structure.

Structure Geometry

Consider two specimens A and B having geometries as shown in Figure 7(a) and 7(b) respectively on page 73. Axial compression of specimen A and B will yield load displacement curves as shown in Figure 7(c) on page 73 when W1 is equal to W2. Since the deformation of the specimen is proportional to the time taken by it to absorb energy, the rate of energy absorption can be considered as the ratio of absorbed energy by deformation. From Figure 7(c) the following conclusions can be drawn:

$$\frac{Absorbed\ Energy\,(E2)}{Displacement\,(L+\Delta L)} < \frac{Absorbed\ Energy\,(E1)}{Displacement\,(L)}$$

$$\frac{Initial\ \ Absorbed\ Energy\,(\Delta E2)}{Initial\ Displacement\,(L1)} < \frac{Initial\ \ Absorbed\ Energy\,(\Delta E1)}{Initial\ \ Displacement\,(L1)}$$

Also obvious from Figure 7(c) is that the magnitude of energy absorbed by specimen B deformed over length L is less than that of specimen A deformed over the same length. Hence it can be concluded that the rate of energy absorption of specimen B is less than that of specimen A. Consider Figure 7(d) on page 73, which exhibits the rate of deformation experienced by specimens A and B when subjected to axial compression.

Now consider the case when the width of specimen B, W2, is greater than the width of Specimen A, W1. Please see Figure 8(a) and 8(b) on page 74. Axial compression of specimen A and B will yield load displacement curves shown in Figure 8(c) on page 74. The goal of crashworthiness is to absorb the kinetic energy possessed by the car, at the time of impact, over as large a time frame as possible to ensure passenger safety. It can been seen from Figure 8(c) that though F2 is greater than F1, the energy absorbed by specimen B when axially compressed has been stretched over a larger time frame thus improving the crashworthiness of the structure. Consider Figure 8(d) on page 74, which exhibits the rate of deformation experienced by specimens A and B when subjected to axial compression. From Figure 8(d) it can be seen that by setting W2>W1 one has decreased the rate of deformation of specimen B when axially compressed to a value less than that of specimen A when crushed in similar conditions. The above arguments indicate that altering specimen shape reduces the rate of deformation, thereby increasing the time frame over which energy is absorbed, hence on the whole contributing to improved crashworthiness.

Coupling

The load increases very rapidly in the initial stages of the load displacement curve for most materials undergoing crushing to some maximum value after which stable crushing takes place. Though these materials might be good energy absorbers, it is in the interest of passenger safety that the deceleration in this stage of the crash not exceed the critical range above which the passengers will experience irreversible brain damage because of the relative movements of various parts of the brain within the skull cavity. To safe guard the interest of the passengers but still use these high energy absorbing materials as crash elements they can be coupled with other materials that have a lower peak load but not necessarily a high energy absorption capability. Please see Figure 9 on page 75.

Consider two specimens C and D of width W and length L having geometries as shown in Figure 10(a) and 10(b) respectively on page 76. Depending on their material properties specimen C and D will generate load displacement curves as shown in Figure 10(c) on page 76. If these 2 materials are coupled together homogeneously to form specimen E having a geometry similar to that of specimen C and D, when axially compressed specimen E will yield a load displacement curve as shown in Figure 10(d) on page 76. Figure 10(d) also exhibits the load displacement curves of specimen C and D when axially compressed. This arrangement discussed above, as can be seen in Figure 10(d), lowers the initial peak load to a value that is well within the safe deceleration range that the passengers are allowed to experience at the time of impact. It should also be noted that the coupling of the material C with D resulted in the lowering of the magnitude of energy absorbed from E3 to E5. The specimen length of the coupled material E can be increased by ΔL in order to raise the magnitude of the energy absorbed from E5 to E3. Please refer to Figure 10(e) on page 76. Hence by increasing the length of specimen E the reduction in the magnitude of energy absorbed that resulted from coupling can be made up. Figure 10(e) also exhibits how by coupling material C with D, its initial peak load value can be lowered and the rate of energy absorption decreased by stretching it over a larger time frame, still not having to compromise on the magnitude of energy that may be absorbed during its crushing.

CONCLUSION

Many criterions, in addition to a material being crashworthy, have to be met before one can begin the use of a particular composite as a crash energy absorber in automobiles. The primary ones are low costs involved in its manufacture and the materials being readily available. Once a composite material is identified to meet the above necessary requirements, one ought to know the effect all the controllable parameters (like fiber arrangement, specimen geometry etc.) will have on its energy absorption capabilities, in an attempt to design the most crashworthy structure. Though in the past several researchers have investigated the energy absorption capabilities of composite materials, it is now time to have enough literature to understand the effect of all the parameters on the energy absorption characteristics of each candidate composite material. It will also be of interest to create a database on the specific energy of various composite materials for the designer's reference. A lot of this experimental data can be used to support the analytical modeling efforts being conducted by several U.S. national laboratories [47].

From Table 2 one sees a range of values for the specific energy absorption E_S and interlaminar fracture toughness G_{IC}. This is because Table 2 ranges over all the parameters namely fiber type, matrix type, fiber orientation, specimen dimensions, volume fraction, processing condition, test speed and trigger. Consider a matrix to help visualize how many experiments are needed to determine the effect of one parameter upon the other.

Para-meter	**First Exp.**	**Second Exp.**	**Third Exp.**	**Fourth Exp.**	**Fifth Exp.**	**Sixth Exp.**	**Seventh Exp.**	**Eighth Exp.**	**Ninth Exp.**
Fiber Type	Kevlar	Carbon	Kevlar	Kevlar	Kevlar	Kevlar	Kevlar	Kevlar	Kevlar
Matrix Type	Epoxy	Epoxy	PEEK	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy
Fiber Arch.	$[\pm 45^{o]}$	$[\pm 45^{o]}$	$[\pm 45^{o]}$	$[\pm 55^{o]}$	$[\pm 45^{o]}$	$[\pm 45^{o]}$	$[\pm 45^{o]}$	$[\pm 45^{o]}$	$[\pm 45^{o]}$
Volume Fraction	15.75%	15.75%	15.75%	15.75%	22.75%	15.75%	15.75%	15.75%	15.75%
Proc. Cond.	Slow cooled	Slow cooled	Slow cooled	Slow cooled	Slow cooled	Rapidly cooled	Slow cooled	Slow cooled	Slow cooled
Test Speed	10 m/sec	10 m/sec	10 m/sec	10 m/sec	10 m/sec	10 m/sec	15 m/sec	10 m/sec	10 m/sec

Trigger	Chamfer	Chamfer	Chamfer	Chamfer	Chamfer	Chamfer	Chamfer	Bevel	Chamfer
Spec. Dim.	D/t = 25	D/t = 25	D/t = 25	D/t = 25	D/t = 25	D/t = 25	D/t = 25	D/t = 25	D/t = 45
E_S (kJ/kg)	80	90	70	75	76	67	78	65	78
G_{IC} (J/m^2)	1130	1150	1230	1300	1430	1234	1342	1432	1236

An exhaustively designed set of experiments to determine the effect of each parameter on the energy absorption capability of the composite material would thus be the number of parameters plus one. The number of experiments required to explore the effect of one parameter upon another, would be the square of the number of parameters. This helps to show just how complicated the task is.

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Table 1. Definition of terms and parameters appearing in the report.

Parameter	**Details**
Fiber Type	Names the type of reinforcing fibers used. Their properties can be related directly to the atomic arrangement and the defect content of the reinforcement, which must be controlled in the manufacturing process.
Matrix Type	Matrix may be thermoset or thermoplastic. The choice of the matrix is related to the required properties, the intended application of the composite and the method of manufacture.
Fiber Orientation	A simple convention is often used when describing the stacking sequences. For example, the angle ply laminate [0/+60/-60/0] is abbreviated to $[0/\pm\theta]$ where $\theta = 60^o$.
Specimen Geometry and Dimensions	One of the variables, which affect the crushing behavior, is the geometry and dimensions of the specimen. The different cross sectional shapes of the specimen might be square, circular, or rectangular. 'D' refers to the tube diameter and 't' to the tube thickness.
Trigger	A trigger is a stress concentrator that causes failure to initiate at a specific location within the structure. From there on the failure, in a controlled predictable manner, progresses through the body at the loading speed.
Processing Conditions	Materials are known for their cooling rate dependency of mechanical properties. Fabrication can be done using three kinds of cooling rates: Rapid cooling by immersion in chilled water (95.5^oC/min), gradual cooling in air (8.2^oC/min) and slow cooling in the oven with heater switched off (0.7^oC/min).
Fiber Volume Fraction	Most calculations on composite materials are based on volume fractions of the constituents. $F = w\ \rho_f / (w\ \rho_f + w_m\ \rho_m)$ where w and w_m are the weight fractions and ρ_f, ρ_m are the densities of the fiber and the matrix respectively and F is the volume fraction of the fiber.
Test Speed	The response of composite tubes subjected to constant speed, quasi-static crush tests and impact crush tests where the speed decreases from the initial impact speed to rest have been studied.
E_S	Specific energy absorption defined as the energy absorbed per unit mass of material. $E_S = \sigma / \rho$ where ρ is the density of the composite material and σ is the mean crush stress
G_{IC}	Interlaminar fracture toughness defined as the measure of the damage tolerance of a material containing initial flaws or cracks. $G_{IC} = \pi\ K_{IC}^2/E$, where E is the Young's modulus and K_{IC} is the fracture toughness parameter.

Table 2. Specific Energy Absorption E_S, and Interlaminar Fracture Toughness G_{IC}, Values of Materials That Have Been Tested.

Material	Specific Energy Absorption E_S (kJ/kg)	Interlaminar Fracture Toughness G_{IC} (kJ/m^2)	Specifications
Carbon/PEEK	180 Ref. [23]	1.56 - 2.4 Ref. [23]	
Carbon/PEI		1.0 - 1.2 Ref. [20, 21]	
Carbon/PI		0.8 - 0.9 Ref. [20, 21]	
Unidirectional Graphite/ J polymer		2.02 Ref. [21]	
Unidirectional Graphite/Epoxy	53 Ref. [23]	0.21 - 0.26 Ref. [21]	
Unidirectional Graphite/Polyphenylene sulfide		1.37 Ref. [21]	
Unidirectional Graphite/Polysulfone		1.13 Ref. [21]	
Knitted Carbon Fiber Fabric/Epoxy	85 Ref. [39, 48, 40, 49, 50]		Carbon fiber volume fraction:22.5%
Braided Glass Fiber Fabric/Epoxy	70 Ref. [51]		Specimen has I cross section with fiber volume fraction 60%
Carbon Fiber/PEEK	226 Ref. [38]		Fibers aligned parallel to the tube axis, rapidly cooled
Carbon Fiber/PEEK	197 Ref. [38]		Fibers aligned parallel to the tube axis, gradually and slow cooled
S. M. C	39 Ref. [41]		13% fiber volume fraction
S. M. C	54 Ref. [41]		18% fiber volume fraction
Pultruded Glass Fiber Reinforced Vinyl ester Resin Tubes	58 Ref. [44]		Bevel trigger, 25*3.1 section size (mm) Initial Vel:0.00021 m/sec
Pultruded Glass Fiber Reinforced Polyester Resin Tubes	41 Ref. [44]		Bevel trigger, 25*3.1 section

			size (mm) Initial Vel:0.00021 m/sec
Pultruded Glass Fiber Reinforced Vinyl ester Resin Tubes	68 Ref. [44]		Tulip trigger, 25*3.1 section size (mm) Initial Vel:0.00021 m/sec
Pultruded Glass Fiber Reinforced Polyester Resin Tubes	39 Ref. [44]		Tulip trigger, 25*25*3.1 section size (mm) Initial Vel:0.00021 m/sec
Glass Fiber/Polyester Resin Tubes	50 Ref. [3]		Winding angle: 65^0 Crushed at 0.2 mm/sec
Carbon Fiber/Epoxy	110 Ref. [23]		Ratio of hoop to axial fibers of 1 to 3
Glass Fiber Reinforced Thermosetting Resin Composites	50 – 80 Ref. [23]		
Carbon/Epoxy	53 Ref. [23]		Fiber architecture: $\pm 45^0$
Carbon/PEEK	127 Ref. [23]		Fiber architecture: $\pm 30^0$
Graphite-Glass/Epoxy	44 Ref. [6]		Orientation: $[0_{Gr}/\pm 45_{Gl}]$, number of plies:6
Graphite-Kevlar/Epoxy	51 Ref. [6]		Orientation: $[0_{Gr}/\pm 45_{K}]$, number of plies:6
Kevlar-Graphite/Epoxy	35 Ref. [6]		Orientation: $[0_{K}/\pm 45_{Gr}]$, number of plies:6
6061 Aluminum	78 Ref. [6]		Diameter: 2.54 cm
6061 Aluminum	89 Ref. [6]		Diameter: 3.81cm
Glass/Epoxy	31 Ref. [6]		Orientation $[0/\pm\theta]$, $15^0<\theta<45^0$
Glass/Epoxy	47 Ref. [6]		Orientation $[0/\pm\theta]$, $60^0<\theta<90^0$
Kevlar/Epoxy	32		Orientation

	Ref. [6]		$[0/\pm\theta]$, $\theta=45^0$
Graphite/Epoxy	45 Ref. [6]		Orientation $[0/\pm\theta]$, $\theta=45^0$
Glass Cloth/Epoxy	60 Ref. [39]		Mandrel trigger
Glass Cloth/Epoxy	62 Ref. [39]		Chamfer trigger
Mono Layer Epoxy Composite Tube With Knitted Carbon Fiber Fabric Reinforcement	25 Ref. [39]		15.75 volume % of fibers. Warp tested tubes
Mono Layer Epoxy Composite Tube With Knitted Carbon Fiber Fabric Reinforcement	15 Ref. [39]		15.75 volume % of fibers. Weft tested tubes
Double Layer Epoxy Composite Tube With Knitted Carbon Fiber Fabric Reinforcement	85 Ref. [39]		22.5 volume % of fibers. Weft tested tubes
Graphite/Epoxy	80 Ref. [16]		0/90 orientation
Glass/Epoxy	60 Ref. [16]		0/90 orientation
Kevlar/Epoxy	63 Ref. [16]		45/45 orientation
Glass Fiber/Polyester Protrusion	38 Ref. [16]		Circular protrusion
Glass Fiber/Polyester Protrusion	20 Ref. [16]		Square protrusion
Graphite/Epoxy	65 Ref. [16]		At Temperature = $100\ ^0C$
Glass/Epoxy	40 Ref. [16]		At Temperature = $100\ ^0C$
Glass Fiber/Polyester Protrusion	25 Ref. [16]		At Temperature = $100\ ^0C$
Graphite/Epoxy	70 Ref. [16]		Compression Rate (10^4 inches/min) t/D = 0.035
Glass/Epoxy	55 Ref. [16]		Compression Rate (10^4 inches/min) t/D = 0.07
Kevlar/Epoxy	14 Ref. [16]		D/t ratio = 25 Inside tube diameter = 3.81 cm, orientation of the fiber $[\pm]_N$
Graphite/Epoxy	63 Ref. [45]		Crushing speed : 10

			m/sec Orientation $[\pm 75]_3$
Kevlar/Epoxy	38 Ref. [45]		Crushing speed : 10 m/sec Orientation $[\pm 75]_3$

Abbreviations used in the Table 2

- PEEK: polyetheretherkeetone.
- PEI: polyetherimide.
- PI: polyimide.
- J polymer: A semi-crystalline polyamide copolymer resin.
- SMC: Sheet-molding compounds based on polyester resins and glass fibers.
- Ref.: Reference.
- kJ: Unit of energy in kilo Joules.
- kg: Unit of mass in kilograms.
- m: Unit of length in meters.
- Vel.: Velocity.
- mm: millimeters.
- E_S: Specific energy absorption defined as the energy absorbed per unit mass of material.
- G_{IC}: Interlaminar fracture toughness.

Table 3. List of composite materials investigated.

Composite Studied	Fiber Type	Matrix Type	Fiber Orientation	Tube Geometry	Testing Speed	Cooling Rate	Fiber Volume Fraction
Kevlar/ Epoxy	X Ref. [12, 6, 7, 16 18]		X Ref. [4]	X Ref. [9, 5, 28, 27, 35]	X Ref. [6, 16, 43, 46]		
Carbon/ Epoxy	X Ref. [12, 4, 6, 7, 16, 17]	X Ref. [23, 22]	X Ref. [4, 3, 11, 24]	X Ref. [9, 5, 28, 27, 29, 37 35, 30]	X Ref. [6, 16, 45, 43, 40]		X Ref. [4, 39, 40, 24]
Glass/ Epoxy	X Ref. [12, 7, 16]		X Ref. [4, 3, 24]	X Ref. [9, 27, 29, 33, 34, 31, 32]	X Ref. [6, 16, 40]		X Ref. [40]
Carbon/ PEEK	X Ref. [13]	X Ref. [19, 23, 22]	X Ref. [19]	X Ref. [31,36]		X Ref. [38]	
Glass/ PEEK	X Ref. [13]						
Carbon/ PEI		X Ref. [19, 22]	X Ref. [19]				
Carbon/ PI		X Ref. [19, 22]	X Ref. [19]				
Carbon/ PAS		X Ref. [19, 22]	X Ref. [19]				
Glass/ Polyester		X Ref. [22]	X Ref. [3, 26]	X Ref. [32]	X Ref. [44, 48]		X Ref. [41]
Glass/ Vinyl ester				X Ref. [32]	X Ref. [44]		X Ref. [41]

Abbreviations used in the Table 3.

- PEEK: polyetheretherkeetone.
- PEI: polyetherimide.

- PI: polyimide.
- PAS: polyarylsulfone
- Ref.: Reference

Table 4. Effect of Fiber on Specific Energy Absorption E_S (kJ/kg).

Matrix Material: Polyetheretherkeetone, fibers are aligned parallel to the tube axis.

Fiber Material	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
AS4 Carbon	194	[13]
IM7 Carbon	202	[13]
S2 Glass	143	[13]

Table 5. Effect of Matrix on Specific Energy Absorption E_S (kJ/kg).

Fiber type: Carbon, axial compression at a constant rate of 1 mm/min, fiber orientation: 0^o to the axis of the tube.

Matrix Material	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
Polyetheretherkeetone	194	[22]
Polyetherimide	155	[22]
Polyimide	131	[22]
Polyarylsulfone	128	[22]
Epoxy	110	[22]

Table 6. Effect of Matrix on Inter-laminar Fracture toughness G_{IC} (kJ/m^2).

Fiber Type: Unidirectional carbon (AS-4) fiber, fiber volume fraction: 60%.

Matrix Material	**Inter-laminar Fracture Toughness G_{IC} (kJ/m^2)**	**Reference**
Polyetheretherkeetone	1.6	[20]
Polyphenylenesulfide	0.9	[20]
Polyetherimide	1.2	[20]
Epoxy	0.2	[20]

Table 7. Effect of Fiber architecture on Specific Energy Absorption E_S (kJ/kg).

Carbon fiber/polyetheretherkeetone tubes, outer diameter: 55 mm, wall thickness: 2.65 mm, length: 55 mm, trigger: 45^o chamfer.

Fiber Architecture	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
0^o	194.1	[19]
±5^o	205.3	[19]
±10^o	225.3	[19]
±15^o	226.8	[19]
±20^o	202.3	[19]
±25^o	181.1	[19]

Carbon fiber/polyetherimide tubes, outer diameter: 55 mm, wall thickness: 2.65 mm, length: 55 mm, trigger: 45^o chamfer.

Fiber Architecture	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
0^o	155.4	[19]
±5^o	162.4	[19]
±10^o	187.9	[19]
±15^o	167.5	[19]
±20^o	162.4	[19]
±25^o	135.6	[19]

Carbon fiber/polyimide tubes, outer diameter: 55 mm, wall thickness: 2.65 mm, length: 55 mm, trigger: 45^o chamfer.

Fiber Architecture	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
0^o	131.4	[19]
±5^o	151.1	[19]
±10^o	160.7	[19]
±15^o	162.3	[19]
±20^o	167.9	[19]

Carbon fiber/polyarylsulfone tubes, outer diameter: 55 mm, wall thickness: 2.65 mm, length: 55 mm, trigger: 45^o chamfer.

Fiber Architecture	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
0^o	128.1	[19]
±5^o	148.4	[19]
±10^o	147.2	[19]
±15^o	147.7	[19]

Table 8. Effect of specimen geometry on Specific Energy Absorption E_S (kJ/kg).

Aminosilane treated glass cloth/epoxy tubes, fiber volume fraction: 43%, internal diameter: 50 mm, wall thickness: 2.5 mm, trigger: 45^o chamfer.

Sectional shape	Specific Energy Absorption E_S (kJ/kg)	Reference
Full Circle	66.6	[31]
¾ Circle	60.6	[31]
½ Circle	60.1	[31]
¼ Circle	53.5	[31]

Acrylsilane treated glass cloth/epoxy tubes, fiber volume fraction: 43%, internal diameter: 50 mm, wall thickness: 2.5 mm, trigger: 45^o chamfer.

Sectional shape	Specific Energy Absorption E_S (kJ/kg)	Reference
Full Circle	53.0	[31]
¾ Circle	41.3	[31]
½ Circle	41.8	[31]
¼ Circle	40.7	[31]

Carbon fiber/polyetheretherkeetone, fiber volume fraction: 65%, outer diameter: 55 mm, wall thickness: 2.65 mm, length: 55 mm, trigger: 45^o chamfer.

Sectional shape	Specific Energy Absorption E_S (kJ/kg)	Reference
Full Circle	194.1	[31]
¾ Circle	192.9	[31]
½ Circle	190.6	[31]
¼ Circle	187.1	[31]

Carbon fiber/polyetheretherkeetone composite tubes.

Diameter D (mm)	Thickness t (mm)	t/D	Specific Energy Absorption E_S (kJ/kg)	Reference
35.5	0.80	0.023	171.7	[36]
35.5	1.04	0.029	172.3	[36]
35.5	2.20	0.062	205.9	[36]
35.5	3.44	0.097	207.1	[36]
35.5	4.58	0.130	154.9	[36]
35.5	6.33	0.178	140.6	[36]
55.0	1.09	0.020	189.0	[36]
55.0	2.09	0.038	218.4	[36]
55.0	2.66	0.048	228.3	[36]
55.0	5.27	0.096	186.7	[36]
55.0	6.43	0.117	186.0	[36]

55.0	10.47	0.190	113.7	[36]
96.0	1.64	0.017	194.0	[36]
96.0	1.91	0.020	215.2	[36]
96.0	2.14	0.022	195.6	[36]
96.0	5.68	0.059	156.9	[36]
96.0	10.54	0.110	147.8	[36]

Table 9. Effect of processing conditions on Specific Energy Absorption E_S (kJ/kg).

Carbon fiber/polyetheretherkeetone composite tube with fibers aligned parallel to the tube axis, tubes tested at a constant speed of 1 mm/min, outer diameter: 55 mm, wall thickness: 2.7 mm for rapidly cooled tubes and 2.8 mm for gradual and slow cooled tubes, trigger: 45^o chamfer.

Processing condition	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
Rapidly Cooled (95.5 ^{o}C/min)	226	[38]
Gradually Cooled (8.2 ^{o}C/min)	197	[38]
Slow Cooled (0.7 ^{o}C/min)	196	[38]

Table 10. Effect of testing speed on Specific Energy Absorption E_S (kJ/kg).

*Section size of the test specimen: 25 mm * 3.1 mm.*

Composite	**Initial Velocity**	**Specific Energy Absorption E_S (kJ/kg)**	**Reference**
Pultruded Glass fiber Reinforced Vinyl ester Resin Tube	$2.1 * 10^{-4}$ m/sec	57.5	[44]
	12 m/sec	53.5	
Pultruded Glass Fiber Reinforced Polyester Resin Tube	$2.1 * 10^{-4}$ m/sec	40.5	[44]
	12 m/sec	47.5	

Figure 1. Graph Of Amount Of Crashworthy Material Required To Rate Of Work Decay.

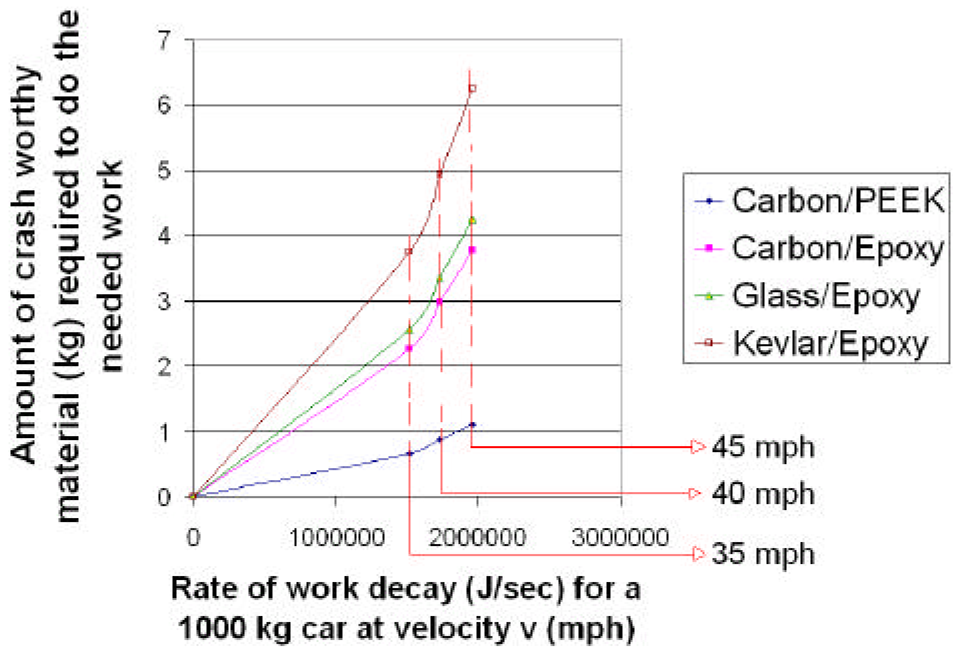

Figure 2. Fragmentation Crushing Mode [52].

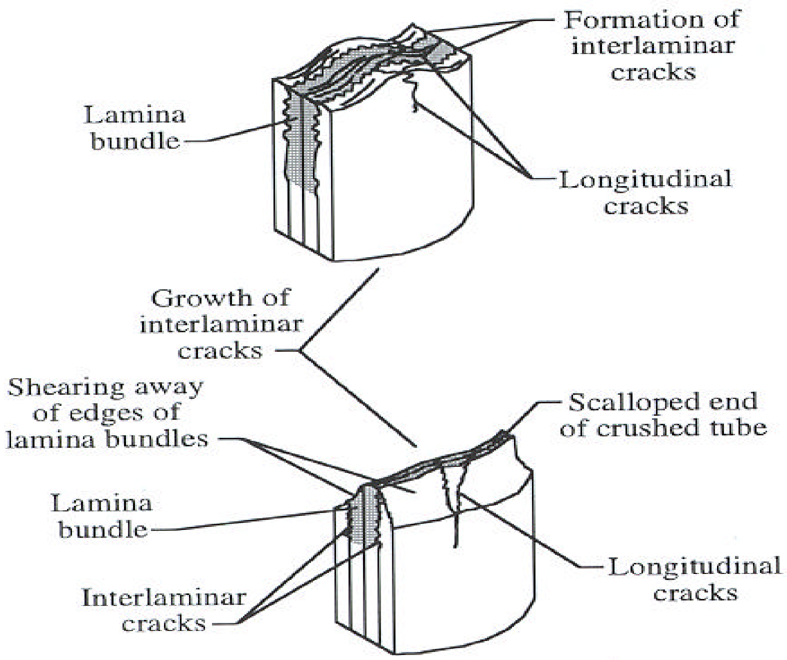

Figure 3. Splaying Crushing Mode [52].

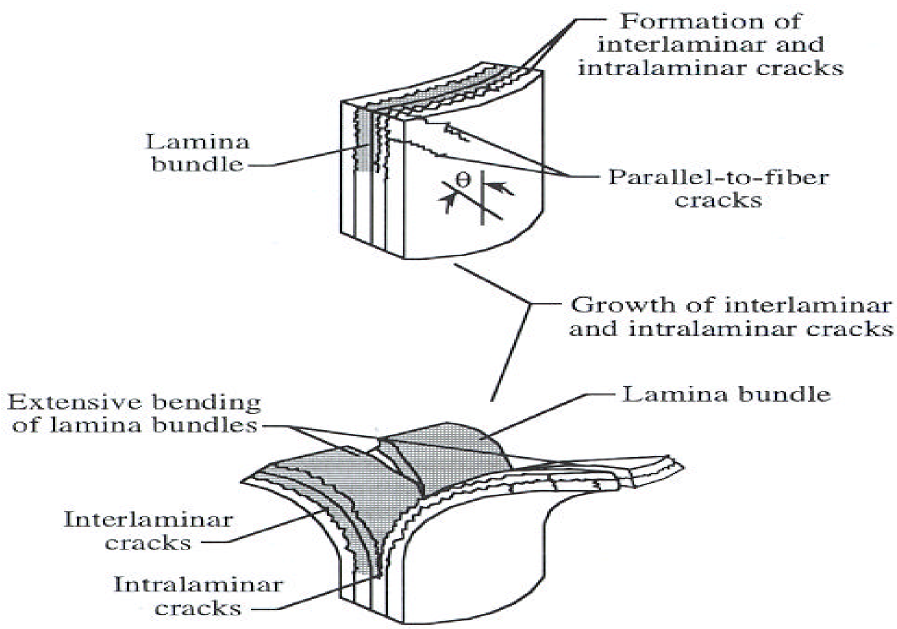

Figure 4. Brittle Fracturing Crushing Mode [52].

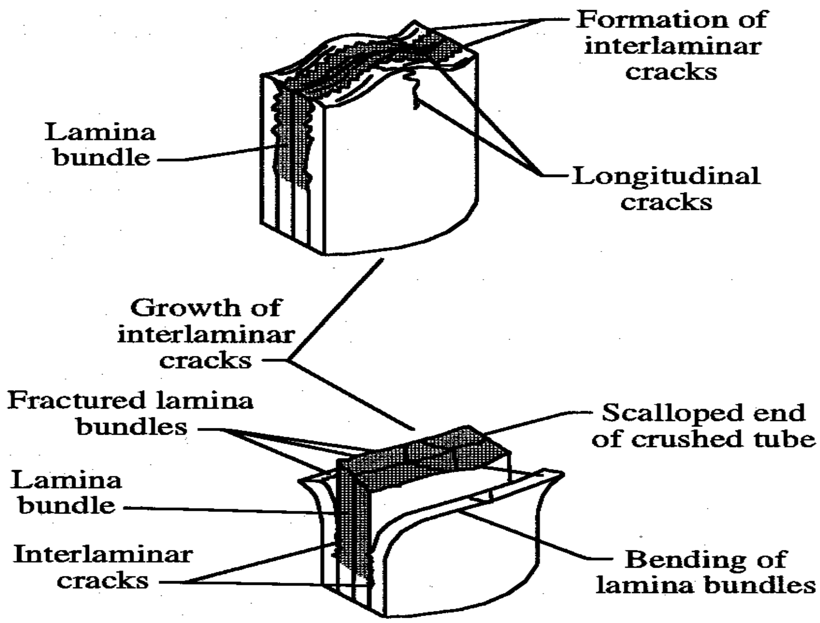

Figure 5. Progressive Folding Crushing Mode [52].

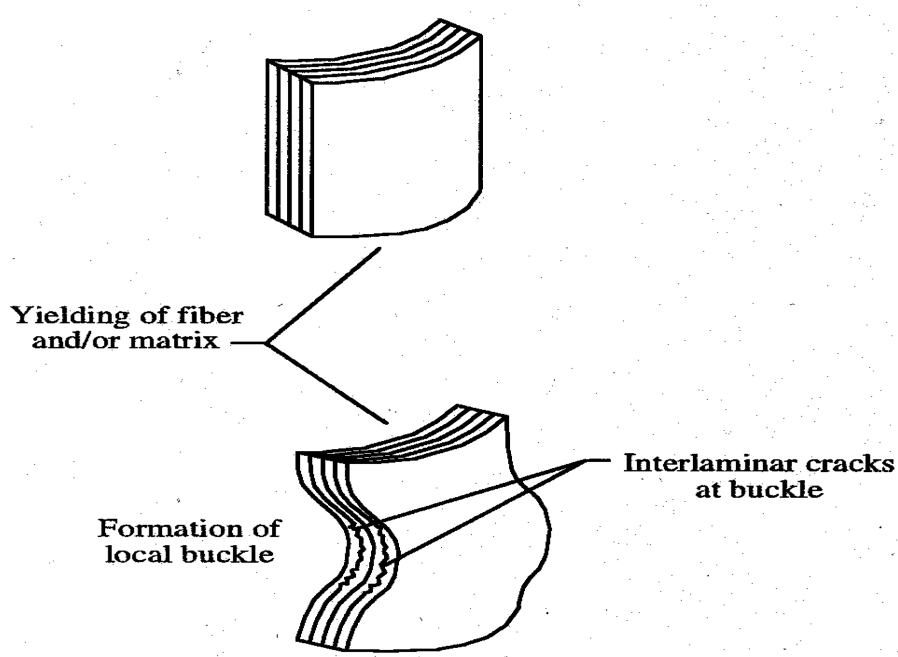

Figure 6. Typical Load Displacement Curve for a Progressively Crushed Composite Tube [36].

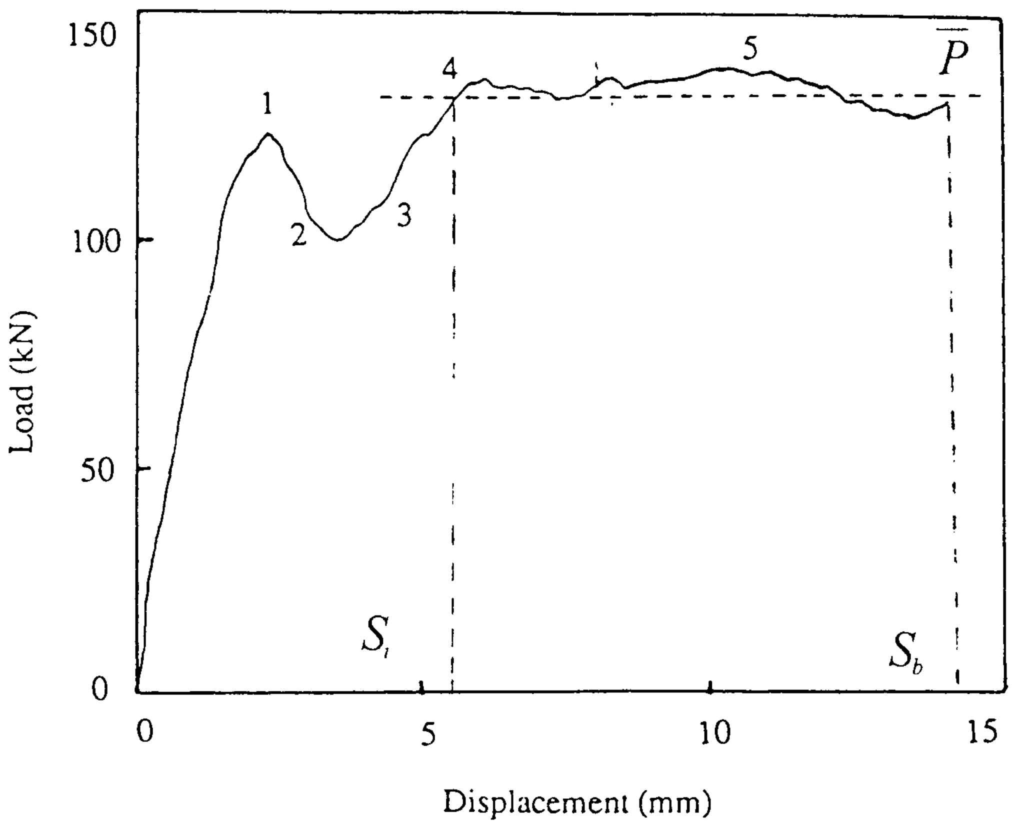

Figure 7. Design For Optimum Work Rate Decay-1.

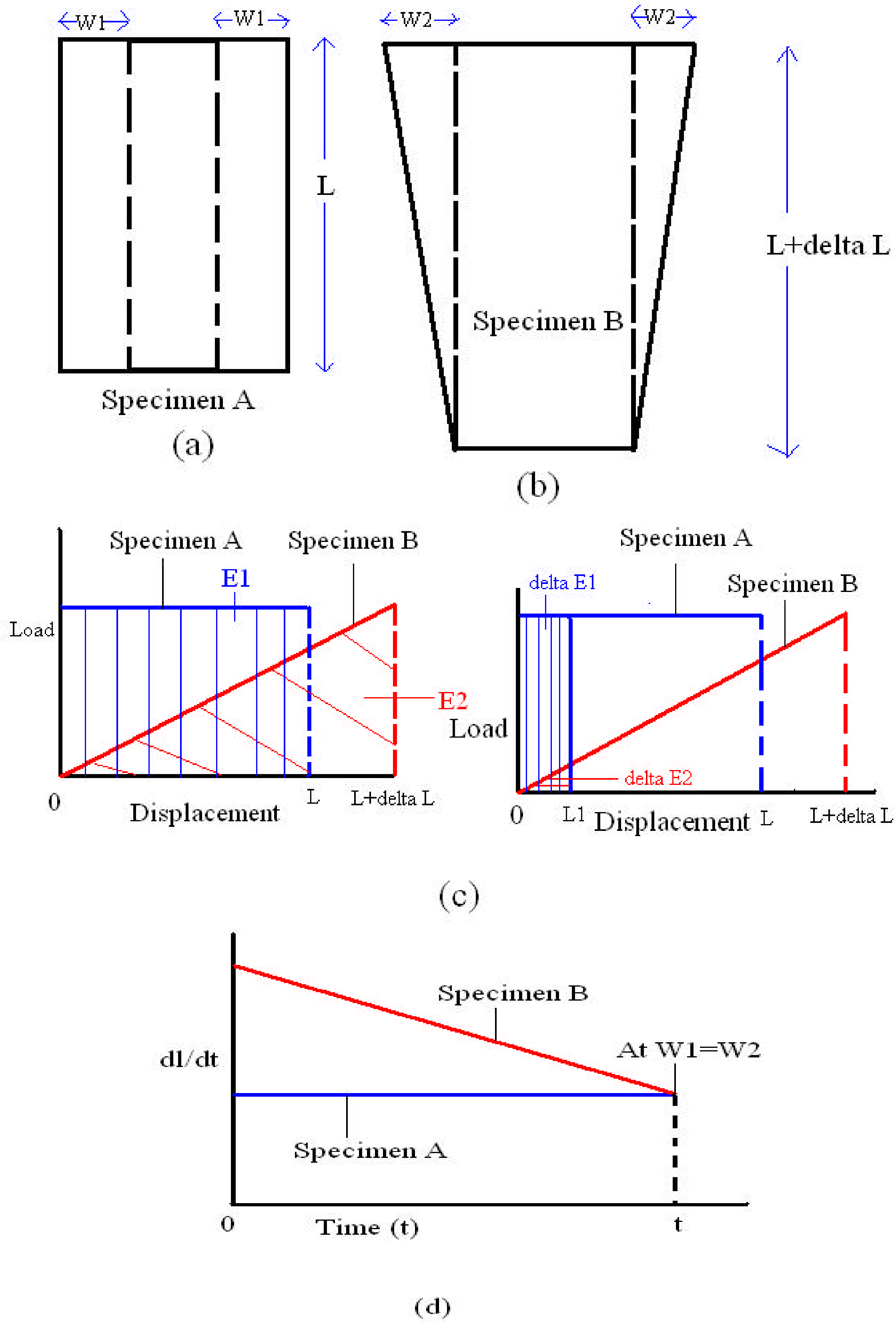

Figure 8. Design for Optimum Work Rate Decay-2.

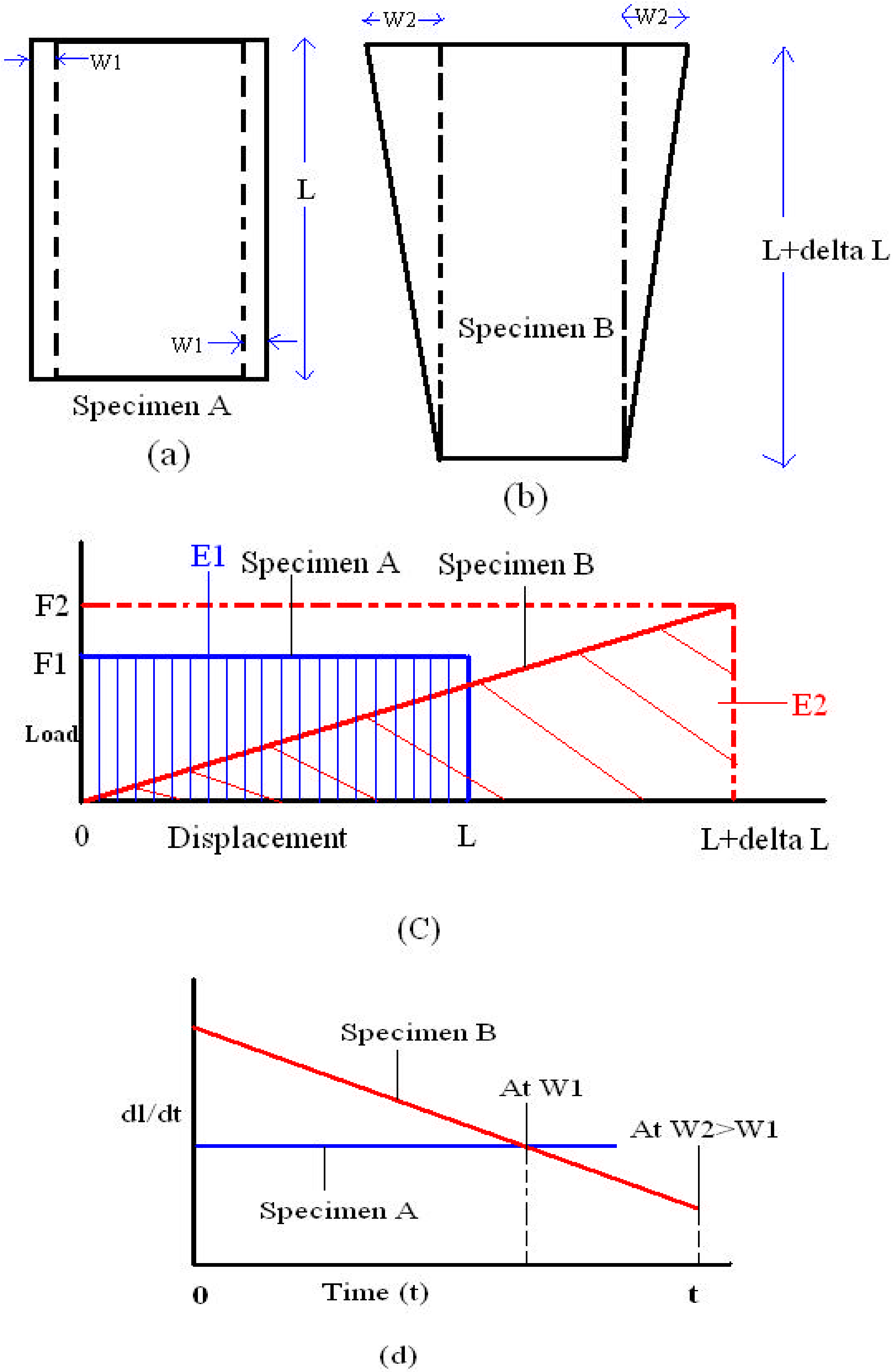

Figure 9. Design For Optimum Work Rate Decay-3.

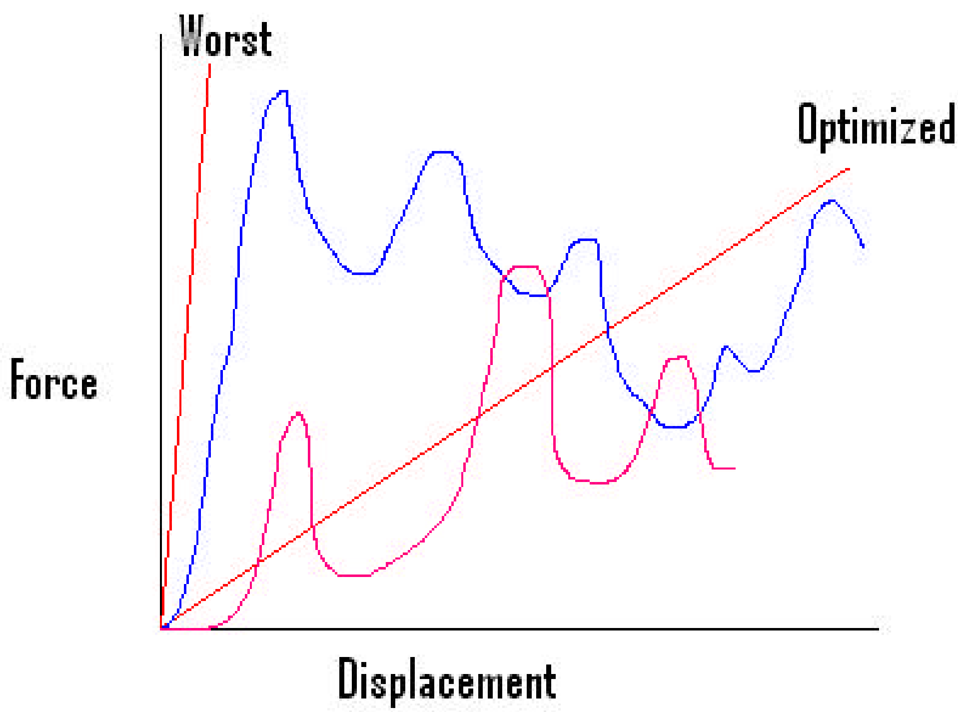

Figure 10. Design for Optimum Work Rate Decay-4.