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U.S. Army helicopters are designed to dissipate prescribed levels of crash impact kinetic energy without compromising the integrity of the fuselage. Because of the complexity of the energy-absorption process, it is imperative for designers of energy-absorbing structures to develop an in-depth understanding of how and why composite structures absorb energy. A description of the crushing modes and mechanisms of energy absorption for composite tubes and beams is presented. Three primary crushing modes of composite structure including transverse shearing, lamina bending, and local buckling are described. The experimental data presented show that fiber and matrix mechanical properties and laminate stiffness and strength mechanical properties cannot reliably predict the energy-absorption response of composite tubes.

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Abstract

U.S. Army helicopters are designed to dissipate prescribed levels of crash impact kinetic energy without compromising the integrity of the fuselage. Because of the complexity of the energy-absorption process, it is imperative for designers of energy-absorbing structures to develop an in-depth understanding of how and why composite structures absorb energy. A description of the crushing modes and mechanisms of energy absorption for composite tubes and beams is presented. Three primary crushing modes of composite structure including transverse shearing, lamina bending, and local buckling are described. The experimental data presented show that fiber and matrix mechanical properties and laminate stiffness and strength mechanical properties cannot reliably predict the energy-absorption response of composite tubes.

Introduction

U.S. Army helicopters are designed to a prescribed level of crashworthiness. One of the crashworthiness requirements is the ability to dissipate crash kinetic energy without compromising the integrity of the fuselage. Since future military helicopters, such as the U.S. Army's RAH-66 Commanche, will make extensive use of composite materials in the fuselage and rotor blade structure, an in-depth understanding of the crushing response of composite structures is imperative.

Approximately one-half of the kinetic energy dissipated in a helicopter crash is absorbed by the subfloor fuselage structure (ref. 1), which is depicted in figure 1. In spite of the typical brittle failure characteristics of composite materials, efficient energy-absorbing structures have been developed (ref. 2). Kevlar[1]-epoxy, carbon-epoxy, and aluminum integral stiffened beams were evaluated in reference 2. The energy-absorption capability of the integrally stiffened Kevlar-epoxy and carbon-epoxy beams was equal or superior to that of comparable aluminum beams with similar geometry, as shown in figure 2.

Composite structures can exhibit multiple energy-absorption mechanisms (refs. 2 and 3). Each energy-absorption response mechanism is a function of the mechanical properties of the constituent materials and the architecture of the energy-absorbing structure (refs. 2 and 3). Furthermore, not all composite structures will progressively crush and absorb energy; some fail catastrophically. Because of the complexity of the energy-absorption process, it is imperative for designers of energy-absorbing structures to develop an in-depth understanding of how and why composite structures absorb energy.

The present paper describes the fundamental mechanics of the energy-absorption process associated with the crushing of composite materials and structures. Unique crushing modes and mechanisms of composite materials and structures are described for composite material systems. The data presented show why mechanical-property trends of composite materials cannot be used reliably to predict the energy-absorption trends of composite structures. The experimental data contained in this paper summarize the data presented in references 2 and 3.

Crushing Modes and Mechanisms

Starting the crushing of fiber-reinforced composite tubes usually requires an initiator at one end of the tube, such as the chamfered end depicted in figure 3. When a load is applied to the edge of the crushing initiator, a local failure of material occurs and small interlaminar and intralaminar cracks are formed. The length of the interlaminar and intralaminar cracks and the integrity of the lamina bundles (i.e., a group of laminae between adjacent interlaminar cracks) determine whether the resulting crushing is characterized by transverse shearing, lamina bending, or a combination of these modes (brittle fracturing).

For ductile fiber-reinforced composite materials and certain brittle fiber-reinforced composite materials, the material in the region of the crushing initiator plastically deforms and the tube crushes in a local buckling mode. Tubes exhibiting the four characteristic crushing modes are shown in figure 4. This

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[1] Kevlar: Trademark of E. I. du Pont de Nemours & Co., Inc.

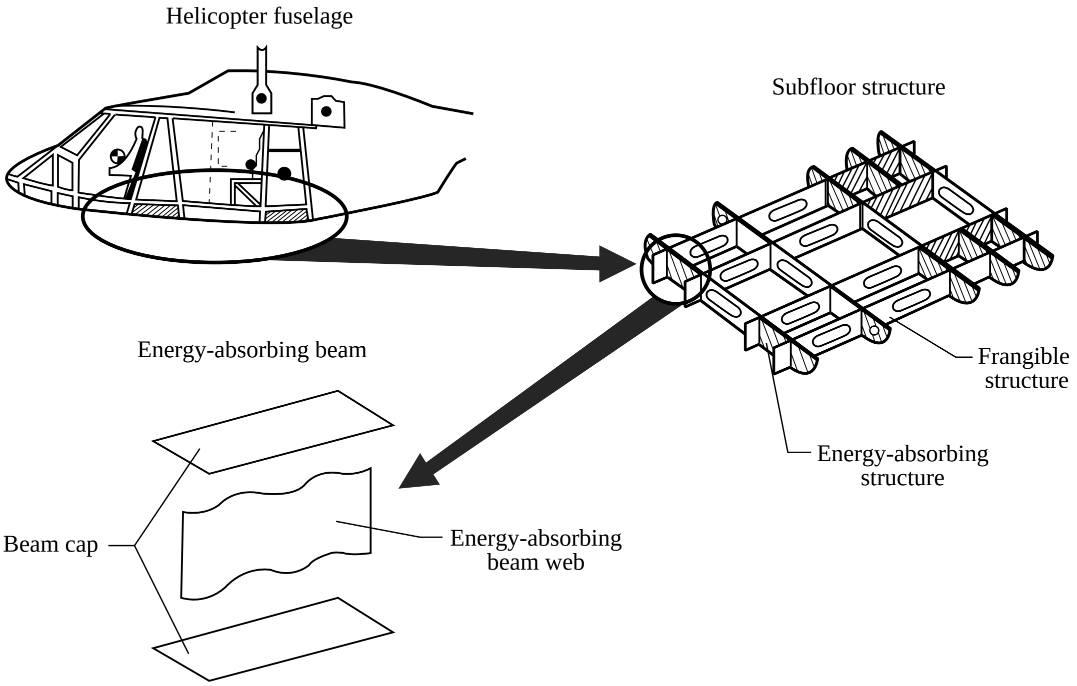

Figure 1. Energy-absorbing subfloor structure of helicopter.

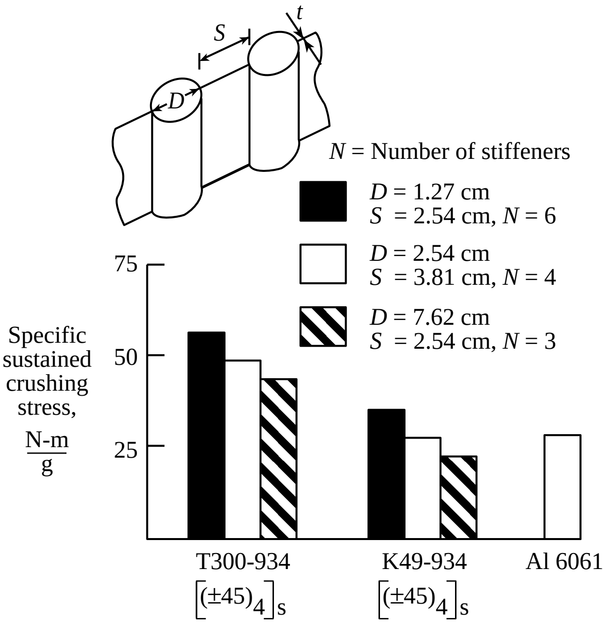

Figure 2. Energy-absorption capability of circular-tube stiffened beams.

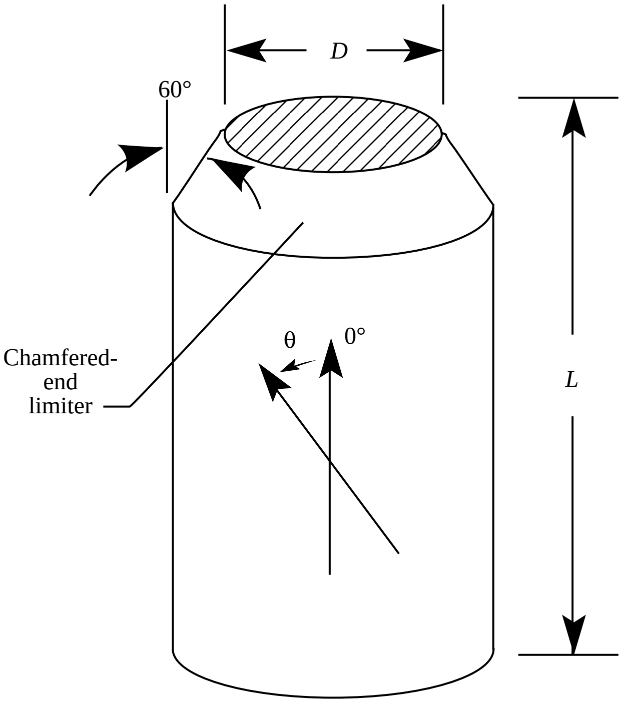

Figure 3. Typical chamfered region of tube specimen.

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Figure 4. Four characteristic crushing modes of composite tubes.

crushing process for continuous fiber-reinforced composite tubes is schematically presented in figure 5.

Not all composite tubes will crush progressively. The crushing process depends upon the mechanical properties of the fiber and matrix, fiber volume fraction, laminate stacking sequence, fiber architecture, and geometry of the tube. The mechanisms that can prohibit progressive crushing and cause catastrophic tube failures are depicted in figure 5. For example, if the interlaminar cracks are shorter than a ply thickness and the lamina bundles do not appreciably bend or fracture, a tube composed of brittle-fiber reinforcement can fail catastrophically. Catastrophic failure without significant energy absorption is also possible when unstable interlaminar or intralaminar crack growth occurs. Furthermore, thin-wall tubes can fail because of a column or shell instability mode, and they can also fail in a circumferential tension failure mode making it impossible to initiate a progressive crushing mode.

Energy-absorbing composite structures that exhibit transverse shearing, lamina bending, and local buckling crushing modes are suitable for decelerating an object, such as a human, in an impact event or a crash. Structures that produce catastrophic failures are generally not suitable for decelerating an object through energy absorption in an impact event or crash. Catastrophic failure of structure, as a mechanism for absorbing energy in a crash, usually occurs at load levels that are excessively high for preventing injury to occupants. A structure that has been designed to crush in a progressive manner can limit high-impact loads. In addition, a fuselage structure designed to react the loads produced by energy-absorbing elements that fail catastrophically is much heavier than a fuselage structure designed to

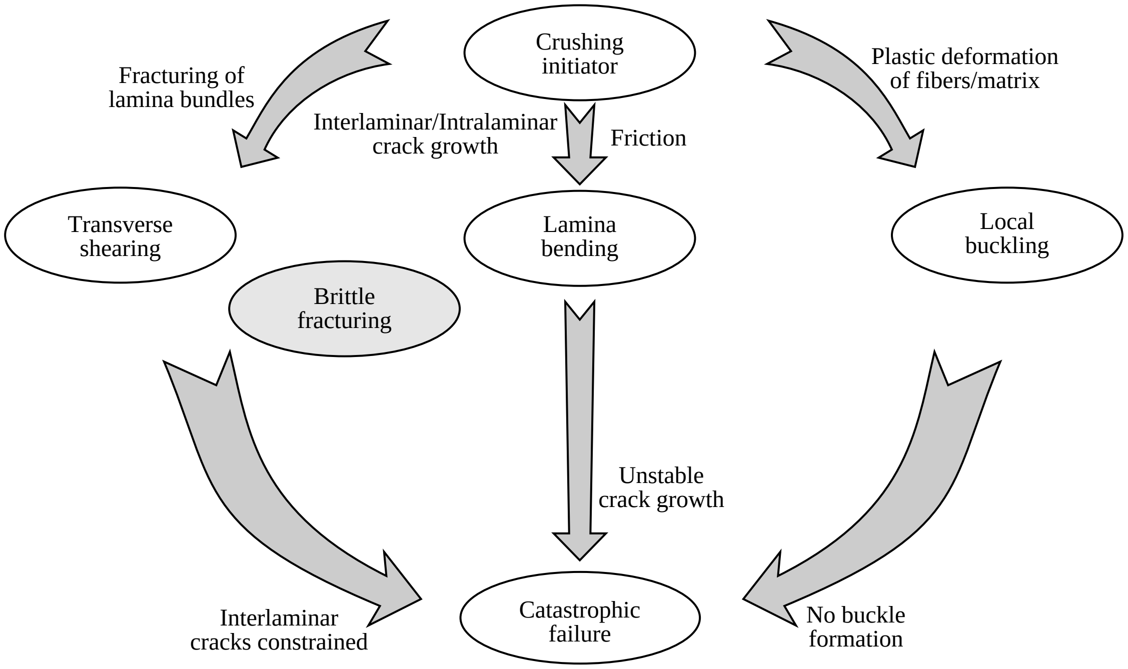

Figure 5. Crushing process of continuous fiber-reinforced composite tubes.

react loads produced by energy-absorbing elements that progressively crush. Therefore, these catastrophic failure modes are not normally of interest in a practical design and will not be discussed further.

The transverse shearing and lamina bending crushing modes are exhibited exclusively by brittle-fiber-reinforced composite materials and never by ductile-fiber-reinforced composite materials. However, both ductile- and brittle-fiber-reinforced composite materials can exhibit the local buckling crushing mode. Most brittle-fiber-reinforced composite tubes exhibit a combination of the transverse shearing and lamina bending crushing modes (brittle fracturing). Each mode is described below.

Transverse Shearing

The transverse shearing crushing mode is characterized by a wedge-shaped laminate cross section with one or multiple short interlaminar and longitudinal cracks that form partial lamina bundles, as illustrated in figure 6. Tubes that crush in the transverse shearing mode have been described for high-modulus, low-failure-strain, graphite-epoxy tubes (refs. 2 and 3) and for 90° graphite-epoxy and glass-epoxy tubes (ref. 4). Only tubes fabricated from brittle fiber reinforcements can exhibit the transverse shearing crushing mode. The crushing surface of the tube is scalloped such that load is not transferred uniformly across the crushing surface of the tube. The principal energy-absorption mechanism is fracturing of the lamina bundles as depicted in figure 6. The number, location, and length of the cracks are functions of the tube geometry and constituent material properties. The lengths of the interlaminar and longitudinal cracks are typically less than the thickness of the laminate. The interlaminar and longitudinal cracks form lamina bundles composed of a single lamina or multiple laminae. The lamina bundles act as columns that resist the applied load. As the load is applied, the interlaminar cracks grow until the edges of the column are fractured so as to form a wedge-shaped cross section as shown in figure 6.

Two crushing mechanisms control the crushing process for transverse shearing. These mechanisms are interlaminar crack growth and lamina bundle fracture. Interlaminar crack growth is controlled by the mechanical properties of the matrix, fiber orientation of the laminate, and extensional stiffness and failure strain of fibers oriented in the circumferential direction. Interlaminar cracks can grow in either a Mode I (opening) or Mode II (forward shear) failure mode. The ability for a crack to grow in either mode is a function of the "toughness" of the matrix and, to a lesser degree, the ply orientation of the lamina bundles through which the crack is attempting to grow.

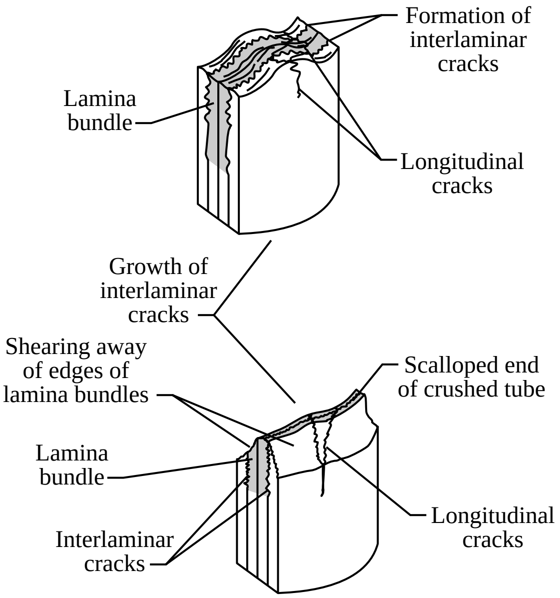

Figure 6. Crushing characteristics of transverse shearing crushing mode.

Circumferentially oriented fibers can have a major influence on interlaminar crack growth by restricting a Mode I crack opening. An increase in the stiffness and failure strain of the circumferentially oriented fibers can reduce the interlaminar crack length that decreases lamina bundle length and increases energy-absorption capability (ref. 2).

Fracturing of the lamina bundles is the principal contributor to the energy absorption of the crushing process in tubes that exhibit the transverse shear crushing mode. The lamina bundles are subjected to a transverse bending force that creates a bending moment at the base of the lamina bundle. When the stress on the tensile side of the lamina bundle exceeds the strength of the material, the lamina bundle fractures.

Strain rate and, therefore, crushing speed can influence the mechanical properties of the fiber and matrix. Therefore, crushing speed can influence the energy-absorption capability if the mechanical properties of fiber and matrix are strain rate sensitive. To determine whether a crushing mechanism is influenced by crushing speed, the degree of rate sensitivity of the mechanical property of the fiber or matrix that controls the crushing mechanism must be determined. The energy-absorption mechanisms associated with tubes that crush in the transverse shearing mode are interlaminar crack growth and fracturing of lamina bundles.

Matrix stiffness and failure strain can be a function of strain rate. For example, if the matrix controls the interlaminar growth and if the failure strain of the matrix decreases with increasing strain rate, the interlaminar crack length increases as crushing speed increases. When interlaminar crack length increases, the length of the lamina bundles increases and causes a decrease in energy-absorption capability.

The second mechanism of energy absorption is the fracturing of the lamina bundles. The fracture strength of a lamina bundle is principally a function of the stiffness and failure strain of the reinforcement fiber. If the mechanical properties of the fiber are a function of strain rate, the fracturing of lamina bundles can also be a function of crushing speed. The mechanical properties of these fibers are generally insensitive to strain rate, and the fracturing of the lamina bundles generally is not a function of crushing speed.

Lamina Bending

The lamina bending crushing mode is characterized by very long interlaminar, intralaminar, and parallel-to-fiber cracks, as shown in figures 4 and 7, but the lamina bundles do not fracture. Many researchers (refs. 2–10) have evaluated materials that exhibit exclusively or partially a lamina bending crushing mode. The principal energy-absorption mechanism for this mode is matrix crack growth. Although the interlaminar cracks form and grow at the interface of adjacent layers, the intralaminar cracks form and grow within individual layers. The parallel-to-fiber cracks propagate parallel to the fiber direction within a ply or within several adjacent laminas that have common fiber orientations. The lamina bundles exhibit significant bending deformation, but they do not fracture.

Two secondary energy-absorption mechanisms related to friction occur in specimens that exhibit the lamina bending crushing mode (refs. 10–12). As the lamina bundles bend, they slide along the face of the loading surface. Another friction-related energy-absorption mechanism is due to the relative motion between adjacent lamina bundles that slide against each other. The magnitude of these frictional effects has yet to be fully quantified.

The mechanisms that control the crushing process in the lamina bending crushing mode are interlaminar, intralaminar, and parallel-to-fiber crack growth and friction. The crack propagation experienced in the lamina bending mode is similar to that of the transverse shearing mode except

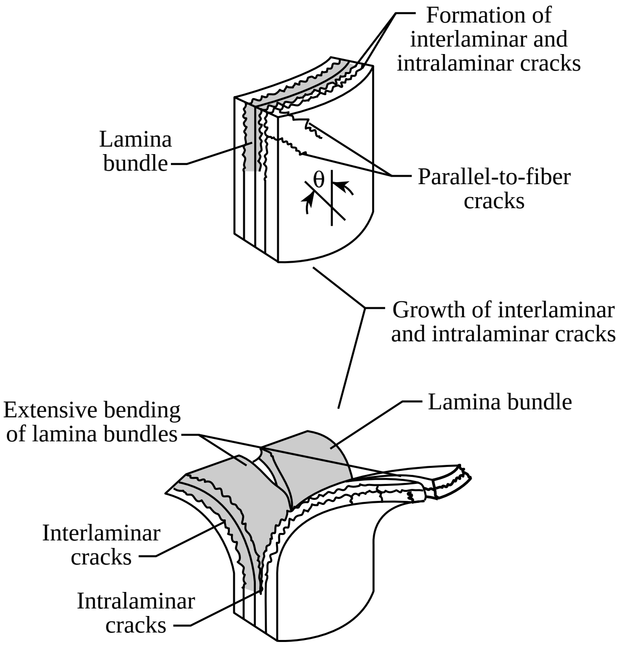

Figure 7. Crushing characteristics of lamina bending crushing mode.

that the length of the cracks is at least one order of magnitude greater. In the lamina bending crushing mode, the lamina bundles do not fracture; they just bend against the crushing surface. Interlaminar crack growth and the effect of crushing speed are controlled in the same manner as that described in the transverse shearing section. The coefficient of friction between the composite and crushing surface and between adjacent lamina bundles can be a function of crushing speed. Therefore, energy-absorption capability can be influenced by changes in crushing speed.

Brittle Fracturing

The brittle fracturing crushing mode is a combination of the transverse shearing and lamina bending crushing modes. The majority of the reported crushing results are for brittle-fiber-reinforced composite tubes that exhibit the brittle fracturing crushing mode (refs. 2-12). The similarities between the modes are (1) interlaminar and longitudinal cracks, (2) scalloped crushing surface, and (3) the principal energy-absorption mechanism (failure of the lamina bundles), as depicted in figures 4 and 8. The lengths of the interlaminar cracks in the brittle fracturing crushing mode are between 1 and 10 laminate thicknesses. Lamina bundles in the brittle fracturing mode exhibit some bending and can fracture near the base of the lamina bundle. When a lamina bundle fractures, the load is redistributed within the specimen, and the cyclic process of crack growth and lamina bundle bending and fracturing is repeated.

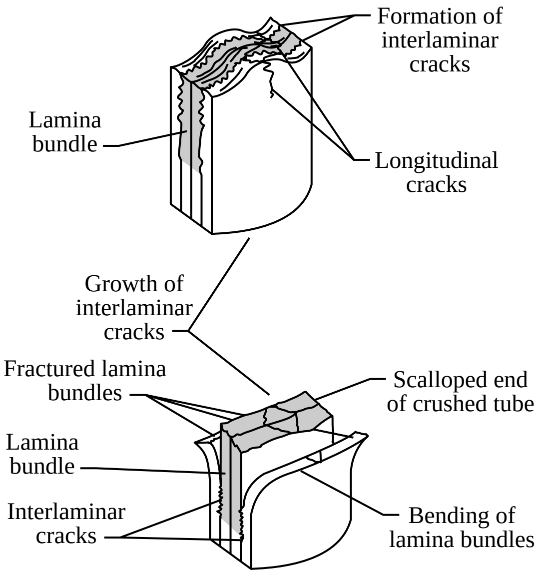

Figure 8. Crushing characteristics of brittle fracturing crushing mode.

Local Buckling

The local buckling mode exhibited by both brittle- and ductile-fiber-reinforced composite materials is similar to that exhibited by ductile metals. The crushing mode consists of the formation of local buckles, as depicted in figures 4 and 9, by means of plastic deformation of the material. Ductile-fiber-reinforced composite materials (such as Kevlar) plastically deform at the buckle site along the compression side of the buckled fibers (refs. 2–5, 7, 8, and 13–16). The fibers can also split along the tension side of the buckled fibers, and local delaminations between plies can occur. Ductile-fiber-reinforced composites remain intact after being crushed and thereby demonstrate postcrushing integrity. The postcrushing integrity of ductile-fiber-reinforced composites is a result of fiber and matrix plasticity (i.e., a significant deformation without fracture) and fiber splitting.

Brittle-fiber-reinforced composite materials exhibit the local buckling crushing mode only when (1) the interlaminar stresses are small relative to the strength of the matrix, (2) the matrix has a higher failure strain than the fiber, and (3) the matrix exhibits plastic deformation under high stress (ref. 2). Brittle fibers, by definition, do not have plastic

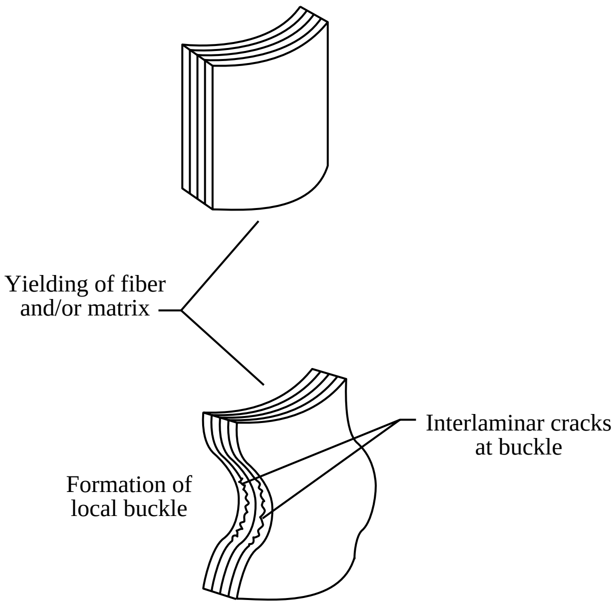

Figure 9. Crushing characteristics of local buckling crushing mode.

stress-strain response. The high-failure-strain matrix reduces interlaminar cracks or prevents them from occurring in the crushing process. If the interlaminar cracks are eliminated, the tube may fail in a catastrophic manner or it will crush in the local buckling mode. If the tube crushes in the local buckling mode, interlaminar cracks can form locally at the inflection points of the buckles, as depicted in figure 9. Typically, the local interlaminar cracks do not extend to adjacent buckles.

Two mechanisms control the crushing process: plastic yielding of the fiber and/or the matrix. Ductile-fiber-reinforced composite materials that crush in the local buckling mode can exhibit yielding of both the fibers and matrix. Brittle-fiber-reinforced composite materials crush in the local buckling mode only if the matrix yields. If the mechanical properties of fibers or matrix are a function of strain rate, then the energy-absorption capability of the composite tube can be influenced by changes in crushing speed.

Energy-Absorption Trends

As a method of explaining energy-absorption trends, one should attempt to correlate energy-absorption trends with changes in the mechanical properties of the constituent materials. A limited correlation between energy-absorption trends and mechanical properties has been achieved because the energy-absorption and mechanical-property response mechanisms are generally different. Experimental data are presented to demonstrate why care must be taken in defining the energy-absorption response mechanisms and to illustrate why mechanical-property trends of materials cannot be reliably used to explain energy-absorption trends. The variables used in the examples are ply orientation, fiber stiffness, fiber volume fraction, stacking sequence, and crushing speed. All energy-absorption tests were conducted using tubular specimens with one end chamfered to initate the crushing process.

All energy-absorption data presented herein are defined in terms of the specific sustained crushing stress. The specific sustained crushing stress σ/ρ is given by

$$\sigma/\rho = P/A\rho \tag{1}$$

where P is the sustained crushing force, as depicted in figure 10, A is the cross-sectional area of the tube, ρ is the density of the tube, and σ is the sustained crushing stress. The data presented represent the average of three tests. The data range is less than the symbol size unless otherwise noted.

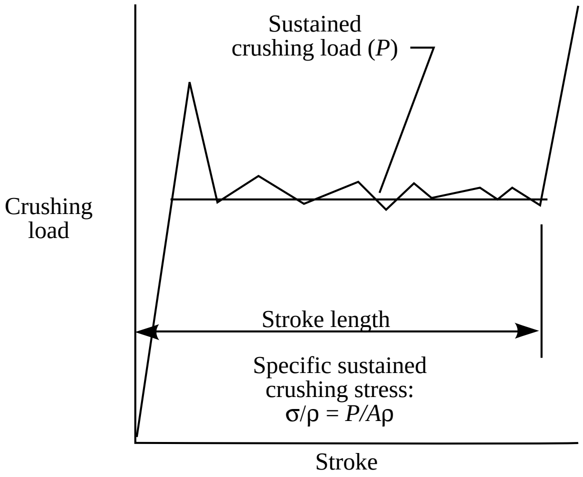

Figure 10. Typical load-stroke curve showing stroke length.

Ply Orientation

Carbon-epoxy and glass-epoxy tube specimens with ply orientations of $[0/\pm\theta]_s$ were quasi-statically crushed to determine the influence of ply orientation on energy-absorption capability (ref. 2). Energy-absorption capability of the carbon-epoxy tubes is plotted as a function of ply orientation. Results for the carbon-epoxy tubes indicate that the energy-absorption capability decreases, as depicted in figure 11, as ply orientation angle θ increases similar to the trends of material stiffness or strength as a function of ply orientation. That is, when θ is approximately equal to 0, the highest energy-absorption

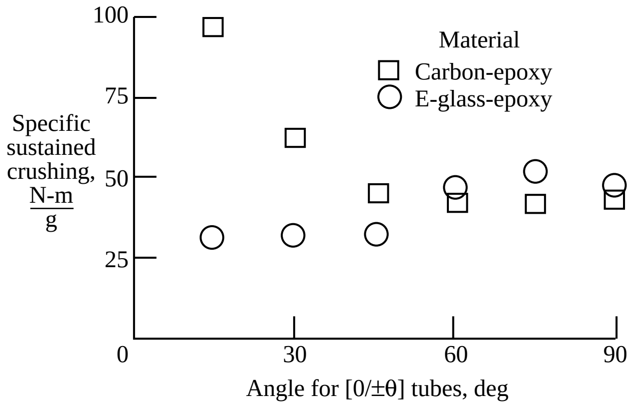

Figure 11. Energy-absorption capability of $[0/\pm\theta]$ tubes.

capability is achieved. As θ increases, the energy-absorption capability decreases nonlinearly. The crushing mode is primarily brittle fracture; therefore, the energy-absorption response mechanism is primarily related to fiber stiffness and fiber failure strain, which is the reason that the energy-absorption trends follow the material-property trends as a function of ply orientation.

The energy-absorption trend is different for glass-epoxy tubes and carbon-epoxy tubes, as shown in figure 11. When θ is approximately 0°, the energy-absorption capability of the glass-epoxy tubes is small compared with the energy-absorption capability of the carbon-epoxy tubes. The crushing mode of the glass-epoxy tubes is lamina bending, a matrix-controlled energy-absorption response.

As θ increases, the energy-absorption capability increases until θ becomes approximately 75°. As θ increases, the laminate stiffness and strength in the circumferential direction increase because of the increase in off-axis fiber angle. Also, the observed amount of brittle fracture increases as θ increases and results in an increase in energy-absorption capability. However, the predominate crushing mode is lamina bending, which is a matrix-controlled crushing mode; hence, the energy-absorption trend does not follow the expected decrease in stiffness as ply orientation θ increases. As θ increases from 75° to 90°, the energy-absorption capability decreases slightly. With angles of θ between 75° and 90°, the energy-absorption trends for the glass-epoxy tubes resemble the material stiffness or strength trends. For tubes with angles of θ between 75° and 90°, the energy-absorption response mechanisms are controlled by the fiber stiffness and failure strain of the 0° plies.

Fiber Stiffness

The influence of fiber stiffness on energy-absorption capability was investigated using six different fibers: E-glass, T300, AS4, AS6, P55S, and P75S carbon fiber in a common 934 epoxy matrix (ref. 2). The fiber stiffness for these fibers ranges from 75 to 525 GPa. Tubes were fabricated from these materials and quasi-statically crushed. Tube ply orientations are $[0/\pm\theta]_2$ and $[\pm\theta]_2$ where θ is 15°, 45°, and 75°. The energy-absorption capability of these tubes is presented in figure 12.

For the materials and ply orientations investigated, no obvious or consistent trends were associated with the variation in fiber stiffness. In some instances, as fiber stiffness increases, energy-absorption capability decreases, whereas the opposite is true for other materials. However, an understanding of the energy-absorption trends can be developed through identification of the response mechanisms and through examination of the crushing modes.

The energy-absorption capability increases as tube fiber stiffness increases between 75 and 210 GPa. For all ply orientations investigated, these materials exhibit predominately lamina bending and secondarily brittle fracturing crushing modes. As fiber stiffness increases, the force required to bend the lamina bundles and create interlaminar crack growth increases and results in an increase in energy-absorption capability.

As θ increases to 75°, energy-absorption capability is relatively constant for specimens whose fiber stiffnesses are between 75 and 210 GPa. The crushing mode changes from predominately lamina bending to predominately brittle fracturing. The increase in the circumferential component of laminate stiffness and strength due to the off-axis fiber orientation contributes significantly to the change in crushing mode.

For laminates having a fiber stiffness between 210 and 525 GPa, energy-absorption capability significantly decreases. The crushing mode changes from predominately brittle fracturing to transverse shearing. The energy-absorption capability of specimens that crush in the transverse shearing mode is related to the compression strength of the material. Since compression strength is a function of fiber stiffness and failure strain, it is reasonable to expect a change in energy-absorption capability with respect to change in fiber stiffness. The compression strength of the P55S and P75S fibers is less than that of the other carbon fibers. Although the fiber stiffness of the P75S fiber is approximately 40 percent greater than that of the P55S fiber, the energy-absorption

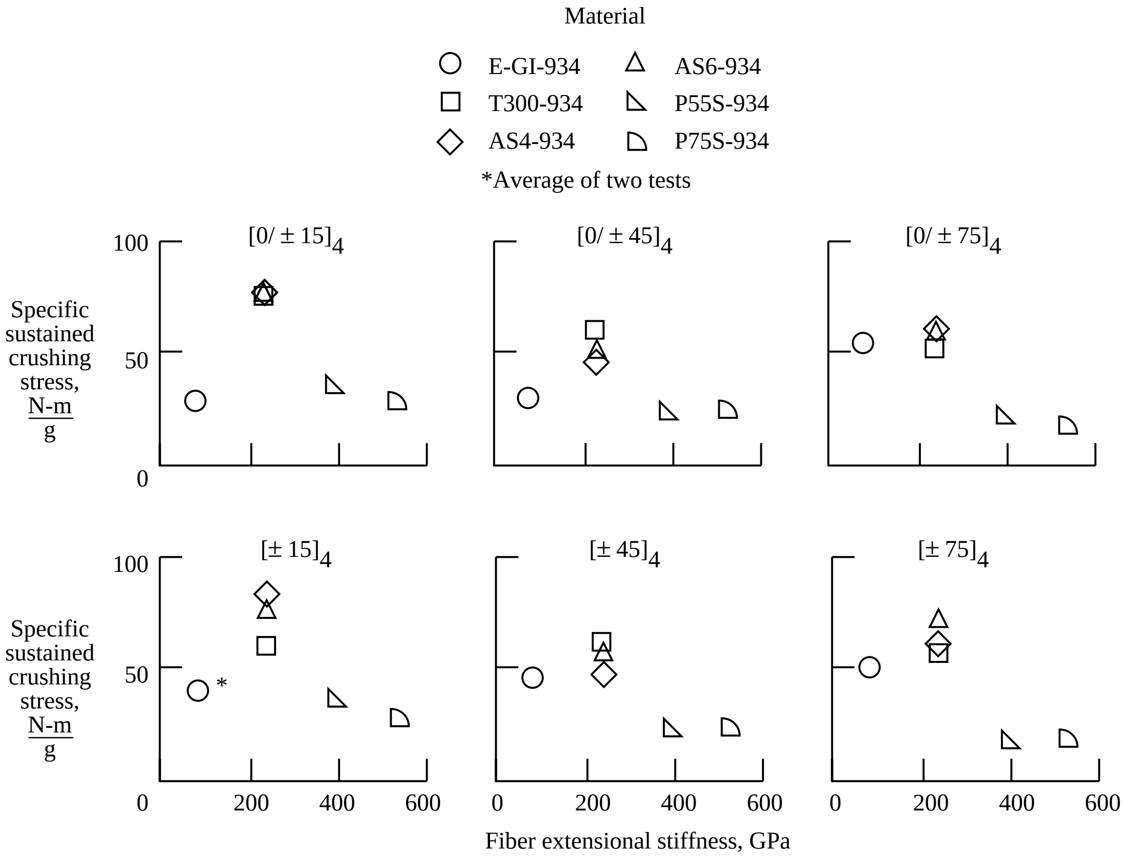

Figure 12. Effect of fiber stiffness on energy-absorption capability. All symbols represent an average of three tests unless otherwise noted.

capability is approximately the same for tubes fabricated from these two fibers. The energy-absorption capability is similar because both materials have similar compression strengths.

Fiber Volume Fraction

Although fiber volume fraction is rarely used in tailoring the response of composite structures, it is still an important parameter whose influence on mechanical response must be understood. The longitudinal stiffness and strength of a material are directly proportional to fiber volume fraction. To understand the influence of fiber volume fraction on energy-absorption capability, tube specimens have been fabricated from T300-934 composite material having fiber volume fractions between 40 and 55 percent (ref. 2). The ply orientations of the tube laminates are $[\pm 45]_6$, $[0/\pm 15]_4$, and $[0/\pm 75]_4$.

Based upon the energy-absorption results depicted in figure 13, some specimens exhibit a decrease in energy-absorption capability with increasing fiber volume fraction, whereas other specimens exhibit a slight increase. To explain these energy-absorption trends, identifying the crushing response mechanisms is necessary.

The decrease in energy-absorption capability as fiber volume fraction increases as exhibited by the $[\pm 45]_6$ and $[0/\pm 15]_4$ tubes is due to the reduced interlaminar strength of the specimens. As fiber volume fraction increases, the volume of matrix in the specimen reduces fiber spacing. The close fiber spacing results in higher interlaminar stresses and, consequently, lower interlaminar strength. The $[0/\pm 15]_4$ specimens exhibit predominately a lamina bending crushing mode, and the $[\pm 45]_6$ specimens exhibit a combination of lamina bending and brittle fracturing. The energy-absorption capability of specimens that crush in either the lamina bending or brittle fracturing crushing modes is significantly influenced by the interlaminar strength of the material.

The $[0/\pm 75]_4$ tubes exhibit a slight increase in energy-absorption capability as fiber volume fraction increases. The crushing mode of these tubes is

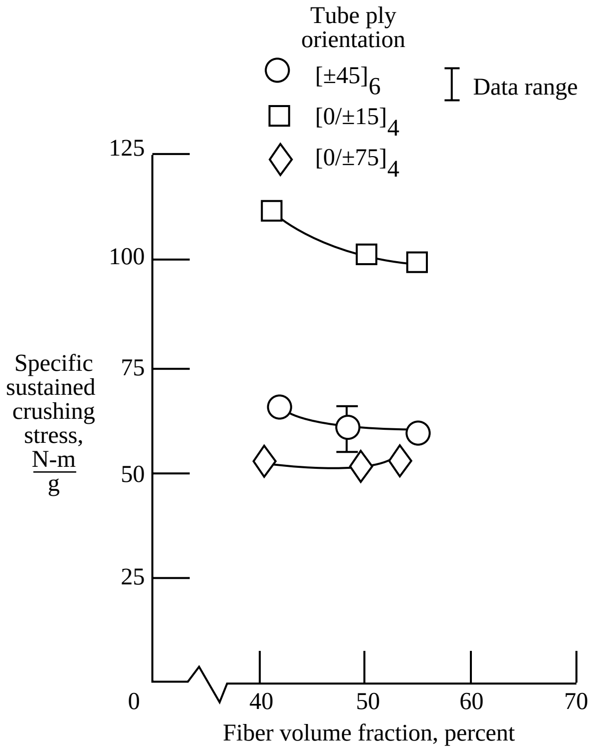

Figure 13. Effect of fiber volume fraction on energy-absorption capability of T300-934 composite tubes.

predominately brittle fracturing. The circumferential fibers provide lateral support to stabilize the 0° fibers instead of the matrix and control interlaminar crack growth. Therefore, changing the volume of the matrix in the specimen has little influence on energy-absorption capability. The slight increase in energy-absorption capability is due to increased laminate strength and is achieved in spite of the approximate 4-percent decrease in laminate density associated with the increase in fiber volume fraction.

Stacking Sequence

Laminate stacking sequence is used to tailor in-plane and bending stiffnesses and damage tolerance of a structure. Positioning 0° layers on the exterior of the stacking sequence increases bending stiffness. However, when damage tolerance is important, the 0° layers are typically positioned in the interior of the stacking sequence. In the design of energy-absorbing structures, laminate stacking sequence can also influence energy-absorption capability.

Two sets of tubes were fabricated to demonstrate the influence of stacking sequence on energy-absorption capability (ref. 2). The first set consists of T300-934 carbon-epoxy composite tubes of $[\pm 45]_6$ and $[\pm 45]_{3s}$ and K49-934 Kevlar-epoxy composite tubes of $[\pm 45]_6$, $[\pm 45]_{3s}$, and $[+45_6/-45_6]$. The second set consists of $[+45^{H}_{F}/0_{10}{}^{Gr}_{T}/-45^{H}_{F}]$ and $[0_5{}^{Gr}_{T}/\pm 45^{H}_{F}/0_5{}^{Gr}_{T}]$ tubes where H, F, Gr, and T refer to hybrid, fabric, carbon, and unidirectional tape, respectively. The unidirectional material is a T300-934 carbon-epoxy material, and the hybrid fabric is a plain-weave T300-K-934 carbon- and Kevlar-epoxy hybrid material.

The energy-absorption capability of the [±45] composite tubes is shown in figure 14. Changes in stacking sequence result in a variation in energy absorption between 5 and 25 percent, depending on the composite material system. The stacking sequence that produced the lowest energy-absorption capability is the $[+45_6/-45_6]$ Kevlar-epoxy tubes. This stacking sequence segregates common ply orientations together and, based on conventional design practice, is the least likely of the three stacking sequences to be used in a structure.

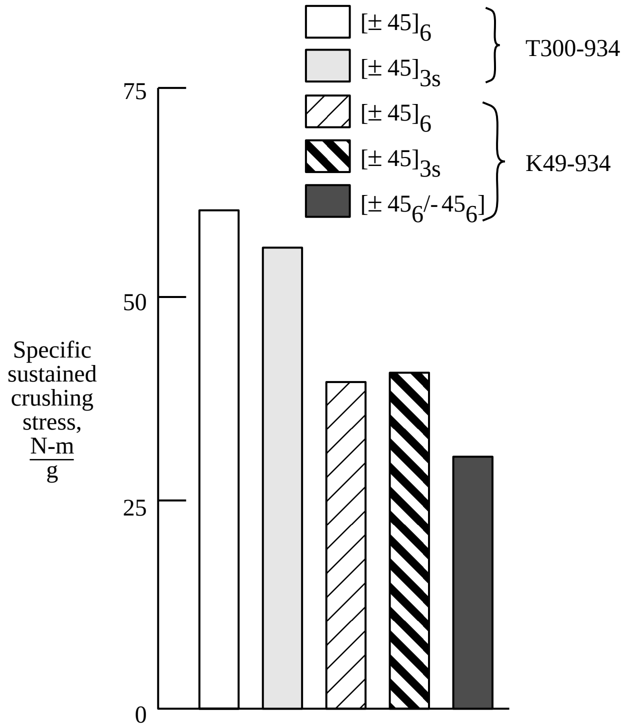

Figure 14. Effect of stacking sequence on energy-absorption capability of [+45] composite tubes.

If the objective is to maximize energy-absorption capability, the effects of stacking sequence can be significant, as shown in figure 15 for the hybrid tubes. In this example, the 0° layers of material are either on the exterior or interior of the laminate stacking sequence. When the 0° layers are on the exterior of the stacking sequence, which increases bending stiffness, the energy-absorption capability is less than

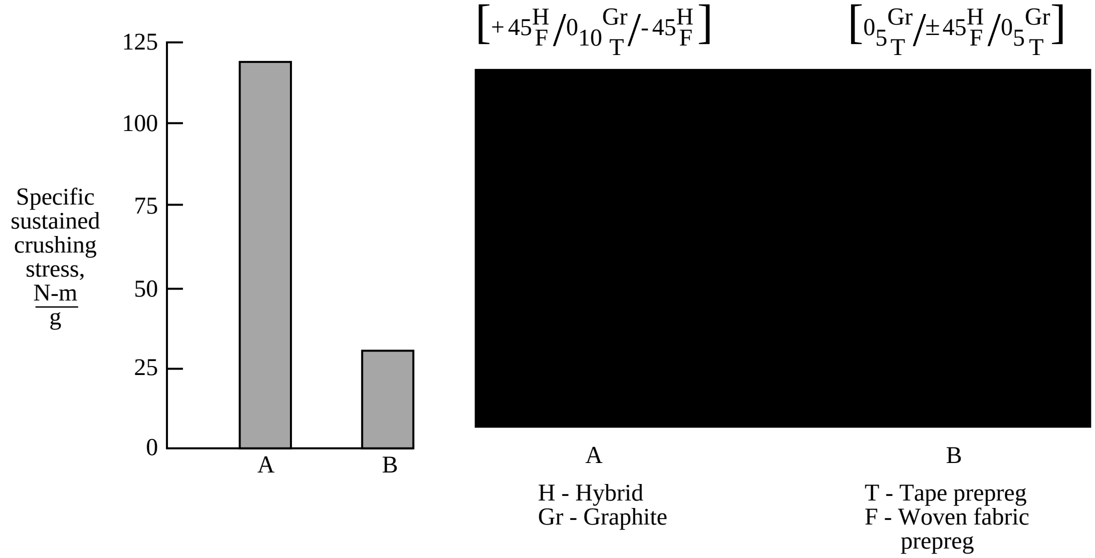

Figure 15. Effect of stacking sequence on energy absorption.

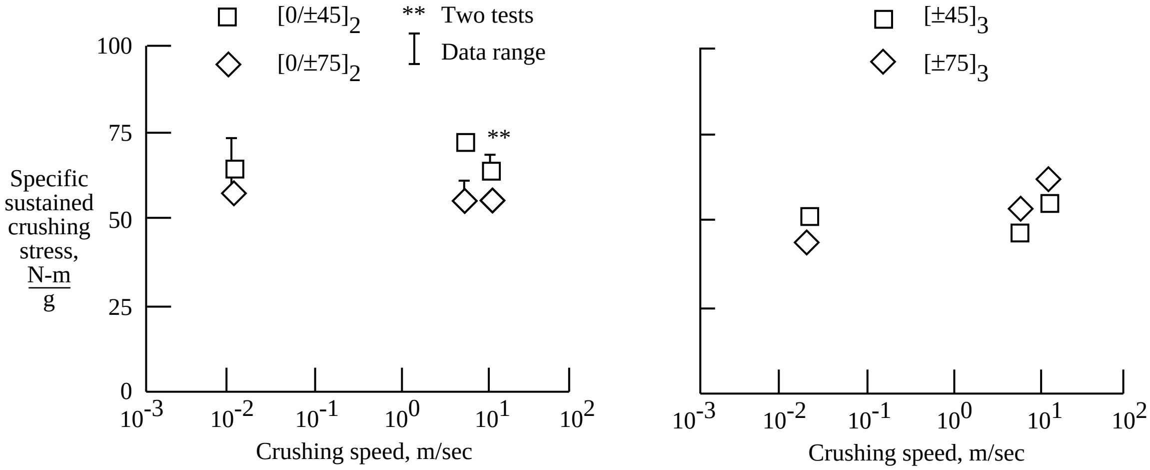

Figure 16. Effects of crushing speed on Gr-E tubes. All symbols represent an average of three tests unless otherwise noted.

20 percent of the case in which the 0° layers are on the interior of the stacking sequence, which is a more damage-tolerant laminate. When the 0° layers are on the interior of the stacking sequence, the 0° layers crush in a transverse shearing mode, which is an efficient energy-absorption crushing mode. The 0° layers on the exterior of the stacking sequence tend to crush in an inefficient lamina bending mode.

Crushing Speed

The strength and stiffness of composite materials can be a function of strain rate. However, the mechanical properties of some materials are insensitive to strain rate. Since the crash of a helicopter is a dynamic event, the influence of crushing speed on the crushing process must be understood. Tubes were fabricated from T300-934 carbon-epoxy composite material with ply orientations of $[0/\pm\theta]_2$ and $[\pm\theta]_3$, where θ is 45° and 75° (ref. 2). The tubes were crushed at rates between 0.01 and 13 m/sec.

The energy-absorption capability of the $[0/\pm\theta]_2$ tubes is not a function of crushing speed, but the energy-absorption capability of the $[\pm\theta]_3$ tubes is a function of crushing speed as shown in figure 16. All tubes crushed in the brittle fracturing mode. To understand why tubes of the same material exhibit different energy-absorption characteristics, one must examine the mechanisms that control the crushing process.

For the $[0/\pm\theta]_2$ tubes, the mechanical properties of the fibers control the crushing process. The off-axis fibers provide foundation support for the lamina bundles and control the interlaminar crack growth. The 0° fibers in the lamina bundles react the axial crushing load. Since the response mechanisms are controlled primarily by the mechanical properties of the fibers, which are not strain rate sensitive, the energy-absorption capability of these tubes should not be a function of crushing speed, as is the case.

For the $[\pm\theta]_3$ tubes, the mechanical properties of the matrix control the crushing process. The matrix provides the foundation support for the lamina bundles and controls interlaminar crack growth. The matrix significantly contributes to the longitudinal stiffness of the lamina bundles. Since the mechanical properties of the matrix are a function of strain rate, the energy-absorption capability of $[\pm\theta]_3$ tubes should be a function of crushing speed.

Concluding Remarks

A description of the crushing modes and mechanisms of composite tubes is presented to illustrate how various factors can influence the energy-absorption process. Three different crushing modes (transverse shearing, lamina bending, and local buckling) have been identified and their crushing response mechanisms have been described. The data show that changes in laminate extensional stiffness or strength cannot be correlated directly to changes in energy-absorption capability. However, once the response mechanisms have been identified, relating the crushing response to fiber and matrix properties, laminate stacking sequence, and fiber volume fraction becomes possible. A good understanding of the crushing response mechanisms is shown to be necessary to interpret energy-absorption trends.

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