Winter 12-2009

Crush Testing, Characterizing, and Modeling the Crashworthiness of Composite Laminates

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CRUSH TESTING, CHARACTERIZING, AND MODELING THE CRASHWORTHINESS OF COMPOSITE LAMINATES

by

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A dissertation submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Department of Mechanical Engineering

The University of Utah

December 2009

THE UNIVERSITY OF UTAH GRADUATE SCHOOL

SUPERVISORY COMMITTEE APPROVAL

of a dissertation submitted by

David Michael Garner Jr.

This dissertation has been read by each member of the following supervisory committee and by majority vote has been found to be satisfactory.

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To the Graduate Council of the University of Utah:

I have read the dissertation of David Michael Garner Jr. in its final form and have found that (1) its format, citations, and bibliographic style are consistent and acceptable; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the supervisory committee and is ready for submission to The Graduate School.

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ABSTRACT

Research in the field of crashworthiness of composite materials is presented. A new crush test method was produced to characterize the crush behavior of composite laminates. In addition, a model of the crush behavior and a method for rank ordering the energy absorption capability of various laminates were developed.

The new crush test method was used for evaluating the crush behavior of flat carbon/epoxy composite specimens at quasi-static and dynamic rates. The University of Utah crush test fixture was designed to support the flat specimen against catastrophic buckling. A gap, where the specimen is unsupported, allowed unhindered crushing of the specimen. In addition, the specimen's failure modes could be clearly observed during crush testing.

Extensive crush testing was conducted wherein the crush force and displacement data were collected to calculate the energy absorption, and high speed video was captured during dynamic testing. Crush tests were also performed over a range of fixture gap heights. The basic failure modes were buckling, crack growth, and fracture. Gap height variations resulted in poorly, properly, and overly constrained specimens. In addition, guidelines for designing a composite laminate for crashworthiness were developed.

Modeling of the crush behavior consisted of the delamination and fracture of a single ply or group of like plies during crushing. Delamination crack extension was modeled using the mode I energy release rate, G_{Ic}, where an elastica approach was used to obtain the strain energy. Variations in G_{Ic} were briefly explored with double cantilever beam tests wherein crack extension occurred along a multidirectional ply interface. The model correctly predicted the failure modes for most of the test cases, and offered insight into how the input parameters affect the model.

The ranking method related coefficients of the laminate and sublaminate stiffness matrices, the ply locations within the laminate, and the laminate thickness. The ranking method correctly ordered the laminates tested in this study with respect to their energy absorption.

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ACKNOWLEDGMENTS

I wish to give special thanks to Dr. Dan Adams, my advisory committee chair, for being the source of so many opportunities and ideas, for providing sound and timely advice, encouragement, and for introducing me to the professional composites community. Thanks also to my committee members who contributed to this work and my professional development by providing valuable feedback and insights along the way. Thanks to Brian Shelby, my dedicated research assistant, who effectively doubled my efforts through his countless hours making test specimens and collecting data – even staying late on Friday afternoons. I also want to thank Jeff Kessler for his laboratory support during the experimentation, for patiently answering my many questions, and for his timely, practical advice. Thanks also to Tom Slowik for allowing me to use the machine shop and for giving me valuable guidance and instruction when needed.

Thanks to the senior faculty of the Department of Engineering Mechanics at the US Air Force Academy for the privilege to pursue this dream. Thanks to Hexcel for donating the high quality composite material used throughout this study. I would also like to thanks Graham Barnes and Richard Roberts of Engenuity Ltd for sharing their time and experience, and for inspiring key aspects of this research.

I especially want to recognize and thank my wife and my children for their unwavering support, patience, and enthusiasm through these years of study. And thanks to my extended family for the many prayers and encouragement. Finally, my eternal thanks to the One who is the fullness of wisdom, knowledge, and understanding.

The views expressed in this article are mine and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

TEST METHODS FOR COMPOSITES CRASHWORTHINESS: A REVIEW

Introduction

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

Crashworthiness and Vehicle Safety

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

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

Although metals have been used extensively, the high specific strength and stiffness of composites make them excellent alternatives for crashworthy structures [11]. Energy absorbed in the crushing of metals comes primarily through plastic deformation after yield [12]. For composites, however, energy is absorbed through a combination of crack growth, fiber-matrix debonding, fiber pullout, microfragmentation, brittle fracture of the fibers and matrix, friction, as well as plastic yield [1,12-15]. High energy absorption per unit mass is possible if the proper failure mechanisms are initiated and maintained during the crash event [16]. The particular failure mode, owing to the nonhomogeneity and anisotropy that are characteristic of composites, depends on a complex interaction between many variables, which include the fiber volume fraction, fiber orientations, laminate stacking sequence, specimen thickness, the behavior of the fiber-matrix interface, the properties of the constituent materials, the geometry of the specimen, crush initiating device, the crushing surface's roughness, temperature, and load application rate [13,17,18].

Crashworthiness Crush Testing

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

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

Behavior of the Crush Test Specimen

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

Czaplicki et al. [19] described the fundamental sequence of the crushing process. First, the crush load must be supported by one of a number of structural elements in the specimen. When this element fails, another element must take over in order to prevent catastrophic, nonenergy absorbing collapse. Thus, the serrated region of the load-displacement curve is evidence of the passing of the primary load support from one structural

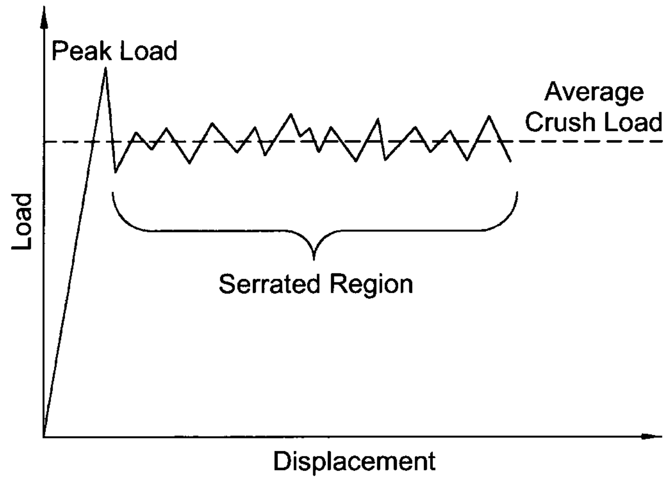

Figure 1. Notional crushing response as represented in a load-displacement plot for a typical crashworthiness crush test.

element to another. According to Hull [13], the initial slope of a single serration represents an essentially elastic material response and depends on the stiffness of the specimen, the crush zone, the test fixture, and the test machine. As the test proceeds, the stress in the crush zone becomes sufficiently high to initiate further crushing. Crushing stops when the load becomes less than is required to propagate cracking in the crush zone. This sequence is repeated continuously for the duration of the test. Thus, the serrated region exists because the stress required to initiate crack growth is higher than that needed to propagate it. Lavoie and Kellas [11] observed that a sharply serrated curve indicates many fracture events during crushing, whereas a smoother curve is characteristic of failure dominated by delamination.

Observed Crushing Failure Modes

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

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

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

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

Figure 2d shows the local buckling failure mode, which occurs through localized plastic deformation of the reinforcing fibers or the matrix material, or both. In addition, fiber splitting may occur and local delamination may take

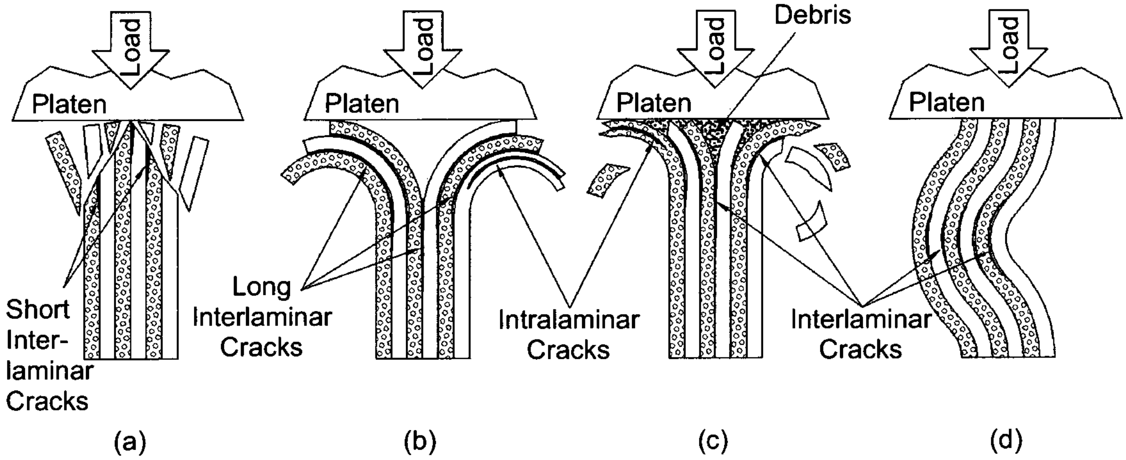

Figure 2. Crush failure modes adapted from Farley and Jones [14]: (a) transverse shearing, (b) lamina bending, (c) brittle fracture, (d) local buckling.

place between laminae. Generally, a locally buckled specimen remains intact and therefore maintains some level of beneficial postcrush integrity [14].

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

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

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

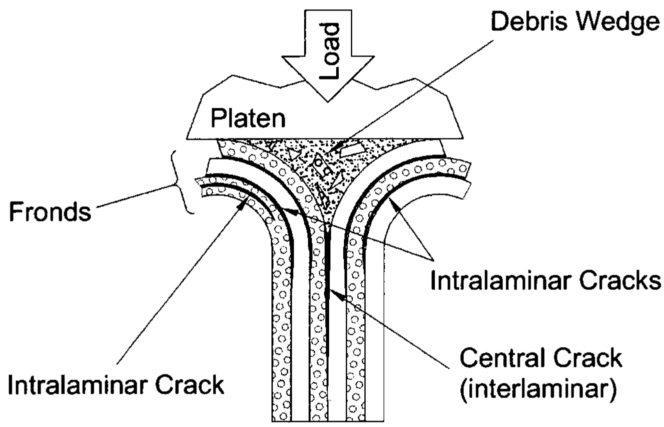

Figure 3. Splaying crushing mode adapted from Hull [13].

characteristic of composites with high interlaminar and intralaminar shear strengths.

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

Important Quantities for Crashworthiness

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

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

$$\text{SEA} = \frac{E}{\rho A \delta} = \frac{\int_0^{\delta} F d\delta}{\rho A \delta} \tag{1}$$

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

$$\text{SSCS} = \frac{\bar{F}}{\rho A}\frac{\delta}{\delta} = \frac{\bar{\sigma}}{\rho}. \tag{2}$$

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

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

Test Machines for Crush Testing

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

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

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