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ENERGY-ABSORBING STRUCTURES MAY HELP HELICOPTER CREWS SURVIVE CRASHES

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Hanagud - 3040
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Aerospace engineers at the Georgia Institute of Technology believe helicopters should be designed for crashes, so they have developed special structural components which would give the crew and passengers of future lightweight helicopters a better chance of surviving low altitude accidents.

The components, similar in shape to the corrugated materials used for shipping boxes, could also improve the crash safety of automobiles and fixed-wing aircraft, said Dr. Sathya Hanagud, professor in Georgia Tech's School of Aerospace Engineering.

Because of their strength and lower weight, composites are increasingly being used to replace heavier metal parts, and new helicopters on the drawing boards will be made almost entirely of composites. But despite their strength, composites are brittle and may provide less crash protection than the metal components they replace.

As a result, aerospace engineers are looking at ways to improve safety and meet new U.S. Army crew protection regulations.

"In a crash situation, the velocity of the rotorcraft suddenly goes to zero," explained Hanagud. "How fast you bring the velocity of the occupants to zero determines the forces in the crash. What we would like to do in a crash situation is bring the velocity to zero relatively slowly in occupant areas by absorbing the kinetic energy outside the occupant space."

Using sophisticated computer analysis and data acquisition techniques, the Georgia Tech researchers are studying energy-absorbing "sine web" composite structures which could be located beneath a rotorcraft's cabin floor. In a crash, the structures would be crushed by the forces of impact -- absorbing energy and reducing the amount of force transferred to occupant areas.

Like
having
a lot
of
padding
under
the floor.

"You translate this crash energy into breaking up the structure," he explained. "Because it is breaking in a controlled fashion, it absorbs energy."

- more -

...for simulating the crashes

To control the breaking, the researchers are developing mechanisms for initiating destruction of the structure under the high loads of a crash. These include beveling the edges of the structures, or introducing precisely designed defects at strategic locations. These initiator mechanisms do not affect the structure during normal operations.

The sine web material consists of curved pieces of graphite-resin composite materials. The curves provide the necessary strength and control over crushing, while enabling the structure to be packed into a relatively small space. At the same time, they allow routine inspection of the aircraft.

Tech researchers experimented with different variations of curved webs and found that angles between 90 and 180 degrees produced the best energy absorption.

Tests in metal aircraft have shown that relatively simple energy-absorbing metal structures can reduce impact forces by approximately one-third, Hanagud said. He believes the sine web materials should do even better -- but would only be effective as part of an overall crash-resistant design strategy.

"You have to start with a systems approach to the process," said Dr. James Craig, professor of aerospace engineering who collaborated on the effort. "You have to look at the structural integrity of the space within which the occupants are located."

In a crash, he noted, impact forces might first be absorbed by the helicopter's landing gear, then by the structures to which the gear is attached. Sine wave web structures in the cabin sub-floor would absorb more energy, while the crew seats and restraint mechanisms provide a final measure of protection. Engineers must also make the cockpit area strong enough to prevent collapse -- and keep other components like engines from entering the occupant areas, Craig said.

"It doesn't really do any good to come up with solutions to any one of these problems if the others are deficient," he added. "It's a combination of things, and the best overall performance is obtained when they all work together."

Designing for crashes is particularly important for helicopters, which often operate at treetop level in dangerous environments. For military helicopters, enemy fire poses an additional hazard.

Craig and Hanagud believe engineers should look beyond traditional design requirements -- what the helicopter must do to fulfill its mission -- and consider accidents as part of the likely operating conditions.

"Designers should take into account the fact that helicopter crashes do occur," Hanagud said. "When we design an aircraft, we look at all the loads that must be encountered. This is one of the loads that we must plan for."

The research was sponsored in part by the U.S. Army Research Office, through Georgia Tech's Center for Excellence in Rotary Wing Aircraft Technology. Results of the research were published in the <u>Journal of Composite Materials.</u>

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Energy Absorption Behavior of Graphite Epoxy Composite Sine Webs

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ABSTRACT: The static energy absorption behavior of graphite epoxy composite corrugated (sine wave) webs loaded in axial compression is reported in this paper. Tests have been conducted to study the effects of various geometric parameters of the web specimen including width and gross thickness. The importance of the failure initiator and its effect on energy absorption are described along with other observed energy absorption trends. Comparisons are made with published tube specimen behavior where appropriate. The existence of a stability boundary within which efficient crushing occurs is shown in the case of gross thickness variation of the web.

INTRODUCTION

CRASHWORTHY DESIGN HAS become a standard feature of many vehicle design processes subsequent to the realization of the potential savings attainable with relatively minor additions to the basic structure. Standard requirements like MIL-STD-1290 [1] provide design criteria for crashworthy performance. The additional weight penalties introduced by such considerations are often offset by the inclusion of light weight composite assemblies. Most composites also provide the ability to tailor material properties to match specific design requirements. This enables efficient designs. With reference to the energy absorption capabilities mandated by crashworthiness requirements, the relatively brittle nature of many of the modern composite materials can be used successfully to absorb energy by using various innovative concepts [2–5]. Such studies have shown the enhanced capabilities attainable using composite structures in comparison with metallic structures when a selected mode of energy absorption (brittle fracture) is used.

One of the important methods of achieving high energy absorption performance with brittle materials like graphite epoxy composites is the triggering and stabilization of an efficient failure mode. For example, consider the composite beam web shown in Figure 1. Compressive loading of such a web results in a mid span fracture as shown in the figure and the load-end shortening curve shows a radical loss of load carrying ability as illustrated by curve "a" in Figure 2. Inclu-

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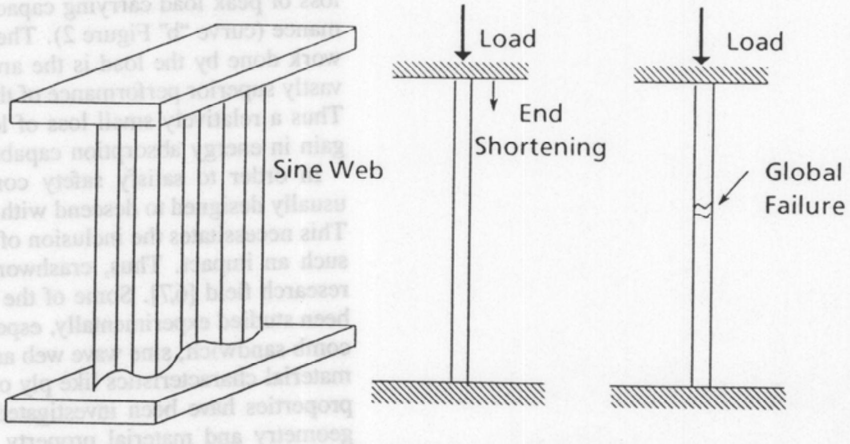

Figure 1. *Composite beam and sine web.*

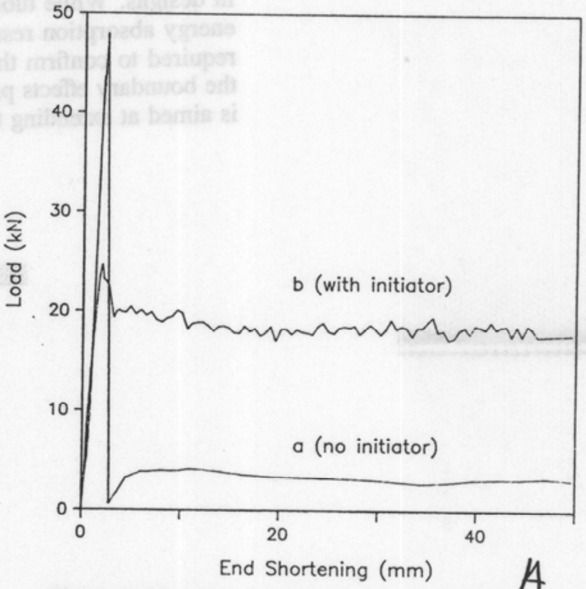

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Figure 2. *Energy absorption due to failure initiator.*

sion of a load limiting failure initiator at one of the ends (Figure 3) results in a loss of peak load carrying capacity but greatly enhances the post failure performance (curve "b" Figure 2). The energy absorption of the structure which is the work done by the load is the area under the load-end shortening curve and the vastly superior performance of the initiated failure design is evident in the figure. Thus a relatively small loss of load carrying capacity can be traded for a large gain in energy absorption capability.

In order to satisfy safety considerations, a rotorcraft under power loss is usually designed to descend with a maximum vertical velocity of about 15 m/sec. This necessitates the inclusion of crashworthy structures capable of withstanding such an impact. Thus, crashworthy design of rotorcraft has become an active research field [6,7]. Some of the energy absorbing structural concepts that have been studied experimentally, especially for this application include [8–11] honeycomb sandwich, sine wave web and foam filled stiffened beam. Effects of various material characteristics like ply orientation, stacking sequence, fiber and matrix properties have been investigated and reported. To a limited extent, specimen geometry and material property effects have also been reported [3–5, 12–14], with the axially loaded tube as the primary structural configuration.

The sine wave web (or corrugated web) has been chosen as the structural member in this study since it represents a realistic configuration directly usable in designs. While tubes can be tested under well controlled conditions and the energy absorption results used as material properties in designs, web testing is required to confirm the validity of this extrapolation process. Further, some of the boundary effects present in web structures are not seen in tubes. This paper is aimed at extending the experimental data base of sine web energy absorption

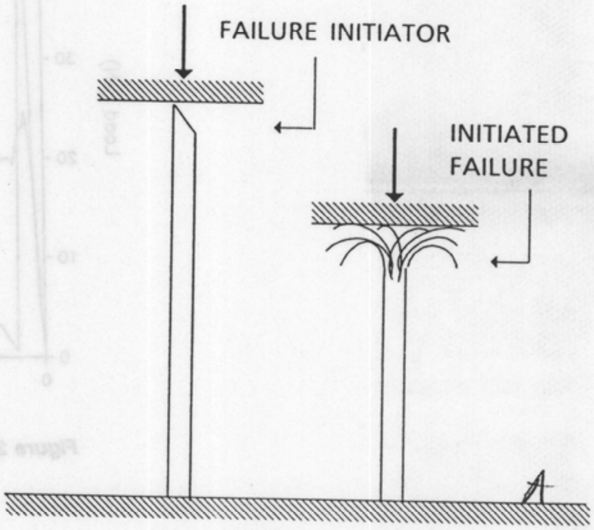

Figure 3. Initiated failure mode.

behavior, specifically with respect to graphite epoxy webs under quasi-static loading including a study of some of the geometric effects. In particular, a comparison will be made with semicircular webs which have energy absorption capability nearly that of tubular specimens while retaining ease of construction and space efficiency.

SPECIMEN DESIGN AND FABRICATION

All test specimens were fabricated using 6 plies of Fiberite T300/934 graphite epoxy unidirectional pre-preg tape. The specimen cross section geometry was composed of tangentially joined circular arc segments as shown in Figure 4. Such specimens have been usually called sine wave web specimens. The arc radius was 9.5 mm (.375″) and included angles of 180°, 150°, 120°, 90°, 60° and 0° were used. Ply orientation sequences were mostly $(\pm 45°/0°)_s$, with some $(\pm 45)_3$ and $(\pm 45°/0°/90°/\pm 45°)$ specimens for comparison [12]. Failure initiators were incorporated on one end of each web specimen using one of three techniques—a full width ply drop off where the two mid plies were made shorter than the outer plies, an end chamfer or a machined notch (Figure 5). The ply drop off can be directly incorporated in actual load bearing structural assemblies. The end chamfer has been used mainly for comparison with published energy absorption results [8–14]. The machined notch has been used since it could be reproduced with high precision.

The web configuration was chosen since it is an arrangement that can be used directly in airframe structures as a part of a built up assembly. The idea was to study specimens under laboratory conditions while retaining similarity to actual structures. The circular tube under axial compression is an abstraction and may not always represent a practical airframe crashworthy structure. The sine web geometry is closer to the web of a practical structure and thus, web tests bridge the gap between tube or coupon testing and subassembly testing. In order to accurately predict the behavior of the full scale airframe structure under field con-

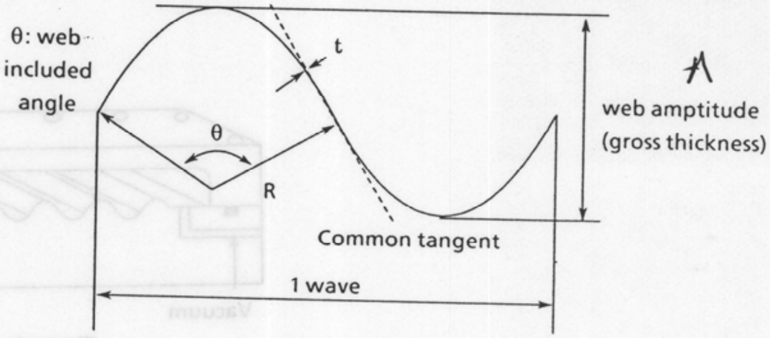

Figure 4. *Sine web terminology.*

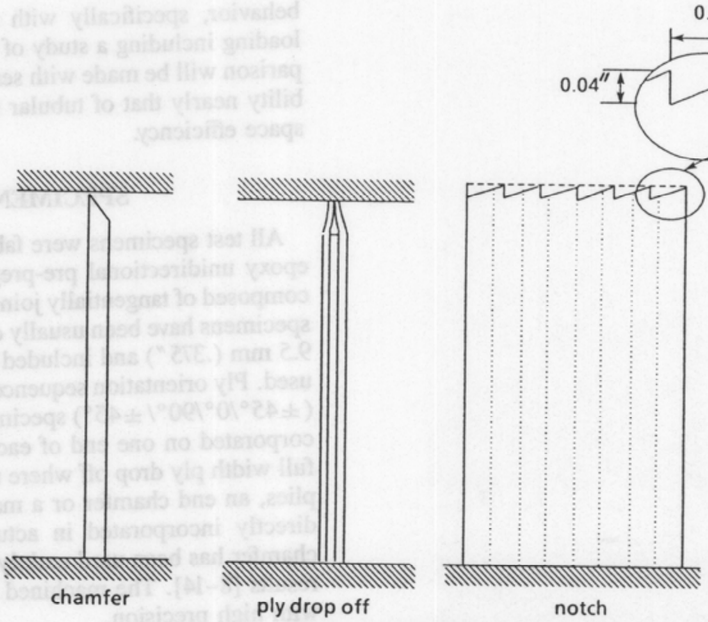

***Figure 5.** Initiator types.*

ditions, the interaction between components and the complete structural assembly has to be studied in addition to the component behavior type studies reported here.

As discussed previously, the failure (crush) initiator (or load limiter) facilitates the initiation of the crushing process and reduces the magnitude of the initial peak load. In the absence of a load limiter, global buckling followed by catastrophic failure could occur. Various size initiators were used. The specimens were nominally 89 mm (3.5 inch) high and 1, 2 or 3 waves wide.

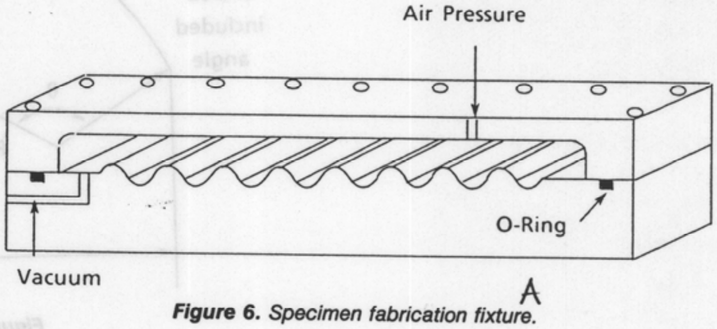

***Figure 6.** Specimen fabrication fixture.*

The specimens were laid up by hand and cured in a special plate curing autoclave described in detail elsewhere [15]. A cross-sectional view of the fixture is shown in Figure 6. The two halves are bolted together with an O-ring seal in between to form the pressure box. The specimen was laid up on the interchangeable contour plate and the whole assembly was placed in an oven and cured according to the pre-preg tape manufacturer's recommendations. Sine webs of up to 280 mm width and 185 mm height can be fabricated in this fashion. The cured web sections were trimmed and cut to required size. The hand lay up process limited the precision with which the ply drop off could be created and this type of failure initiator has subsequently been abandoned. The chamfer was also difficult to fabricate and the notch has since become the preferred initiator. The influence of the type of the initiator used has been discussed subsequently.

TEST PROCEDURE

The static tests utilized a conventional approach in which the specimens were placed in a 534 kN (120 kip) screw jack Baldwin universal testing machine and loaded in a quasi-static manner at a uniform rate. The load rate was approximately .18 mm/min (.007 inch/min) until crushing was initiated and 2 mm/min (.08 inch/min) thereafter. Based on previous experience and information in the literature [3,4], this difference in loading rate has little effect on the measured behavior. The web specimens were compressed to a little over 50% stroke. A personal computer based automatic data logger was used to collect, analyze and reduce the test data. Replica tests (up to 5) were performed as necessary to increase the confidence level in the test results.

A simple transducer was fabricated to measure the end shortening. A taut wire attached to the loading cross head passes over a pulley on the shaft of a 10-turn precision potentiometer. Use of various pulley sizes gives control over range and sensitivity. This transducer is simpler, less expensive and easier to use than bulky long stroke LVDTs.

All energy absorption data have been reduced to Specific Sustained Crush Stress [4] (SSCS) for comparison purposes. The SSCS is defined as the ratio of the sustained crush stress to the material density. The sustained crush stress in turn is based on the average load during crushing and the cross-sectional area of the specimen. Writing the density of the specimen as the ratio of specimen mass to the product of its cross-sectional area and length, the SSCS can simply be expressed as the sustained load divided by the mass per unit length of the specimen. This is the form in which it has been calculated for the results reported in this paper.

TEST RESULTS AND DISCUSSION

Effect of Initiator Type and Size

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Three types of failure initiators, namely full width ply drop off, notched or chamfered ends have been used. The ply drop off length varied between 3.2 mm

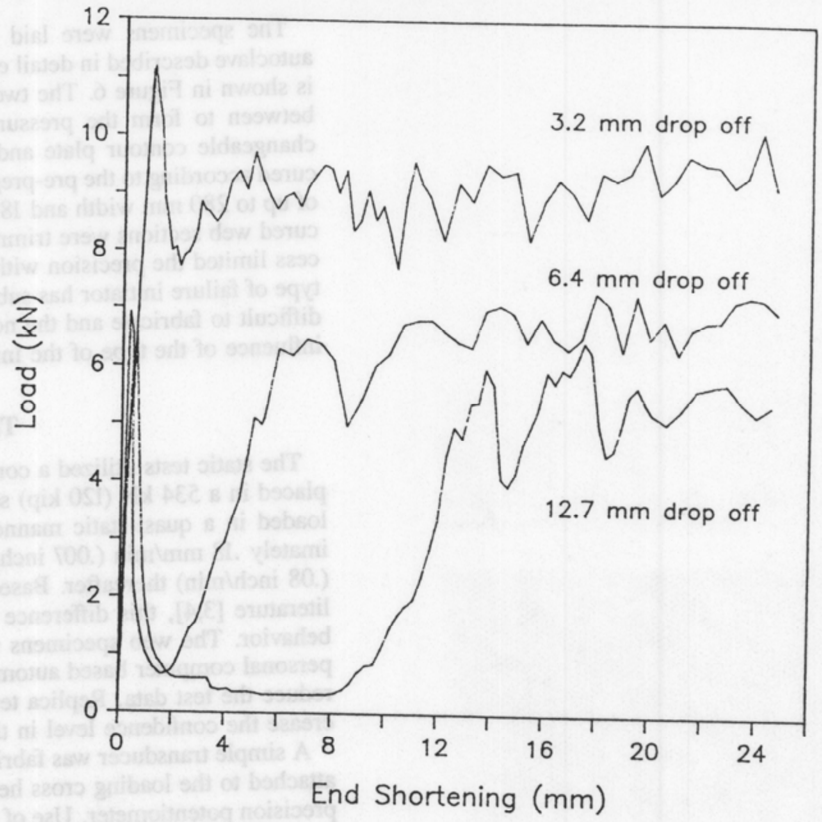

Figure 7*. Effect of initiator size.*

(.125 inch) and 12.7 mm (.5 inch). Single wave wide, 180°, 150° and 120° included angle, $(\pm 45°/0°)_s$ ply orientation specimens were used for this exploratory study. The objectives were to find a failure initiator that could be produced consistently and to study the effect of various initiators. A total of 12 specimens were tested with various size initiators. In the case of chamfered end or notched end initiators, only a single initiator size was used. The load versus end shortening curves of specimens with three different ply drop off lengths are shown in Figure 7. The curves clearly indicate a loss of energy absorption capability as the initiator size increases. It can be observed that the sustained crush load is attained only after the entire initiator has been crushed i.e. the 3.2 mm initiator specimen attains a sustained crush state only after about 3.2 mm stroke. Further, the larger initiator leads to a reduced sustained crush load and hence reduced energy absorption (SSCS). The load-stroke curves in Figure 7 are typical of the behavior of all of the specimens tested in this group.

Table 1. Average energy absorption of graphite epoxy specimen.

Specimen Type	Initiator	SSCS kN-m/kg
$(\pm 45°/0°)_S$ 1 wave web	12.7 mm ply drop off	43.12
$(\pm 45°/0°)_S$ 1 wave web	6.4 mm ply drop off	74.32
$(\pm 45°/0°)_S$ 1 wave web	3.2 mm ply drop off	94.62
$(\pm 45°/0°)_S$ 1 wave web	2.54 mm chamfer	94.53
$(\pm 45°/0°)_S$ 1 wave web	1.0 mm notch	94.34
$(\pm 45°)_3$ 1–3 waves (average)	3.2 mm chamfer	59.26
$(\pm 45°)_N$ tube (Reference [12])	0.3–0.8 mm chamfer	50–60
$(\pm 45°/0°)_4$ tube (Reference [8,15])	3.8 mm chamfer	50–60

The observed energy absorption is presented in Table 1 along with some comparative published data. These results show that the small initiator specimens exhibit high energy absorption independent of the nature of the initiator while the larger initiator specimens show a loss of energy absorption capability. Thus a small defect initiates and promotes efficient failure modes, but overdoing the initiation can lead to rapid loss of performance. In practical applications an optimization study is important. There were no visible differences in the failure modes of the various specimens used in this study. It is believed that the differences in energy absorption are related to the micro mechanical effects of the initiator on the failure mode leading to failure mode differences at the micro mechanical level. This aspect of the problem requires further study. Scanning electron micrography of the failure surfaces is being undertaken in order to identify any differences in the failure modes.

Wave Count (Specimen Width) Effects

As stated previously, the energy absorption of a tube in axial compression has been widely studied. The sine web specimen is a realistic load bearing structure and exhibits certain features which have no corresponding entities in equivalent tube specimens. The width of the web is one such feature. While a web with large width is unlikely to be affected by the presence of the unloaded sides (edges), a web of relatively low width can suffer boundary effects due to these edges. As long as the failure mode is uniform throughout the width, the web can be considered equivalent to a tube. Tests have been conducted to examine this phenomenon. One, two and three wave specimens with ply lay up sequences $(\pm 45°)_3$, $(\pm 45°/0°/90°/\pm 45°)$ and $(\pm 45°/0°)_S$ and with chamfered or notched end failure initiators were tested. The specimen cross-sectional geometry is shown in Figure 8. The edge offset for all specimens in this group was zero. The effect of width is summarized in Figure 9 which contains the averaged results from tests on 41 specimens of various configurations as stated above. Though the actual energy absorption of various layups differ, the width effect can be seen to be similar for all, namely, a slight (less than 10%) reduction in energy absorption

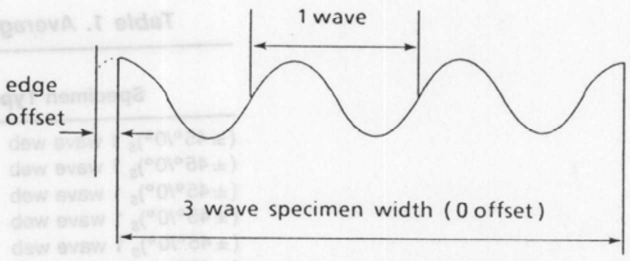

Figure 8. Sine web specimen geometry.

capability as width is varied by a factor of 3. The small observed decrease can be attributed to boundary effects of the stress free sides. This observation is in agreement with reported behavior [8]. It should be remembered, however, that specimens of different material and geometry may exhibit width dependent energy absorption characteristics.

Edge Effects

The tube cross section is of closed geometric form and does not have any load-free edges. The sine web, being of open cross section, has free edges. In

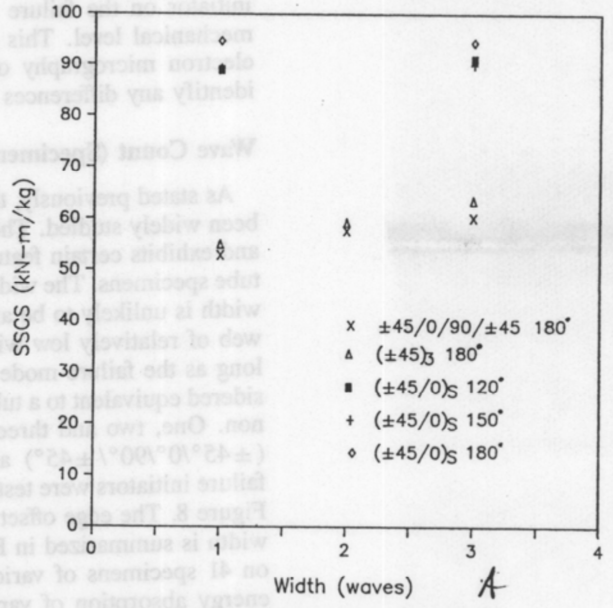

Figure 9. Ply orientation and width effects.

a built up structure, these edges are likely to be connected to adjacent structural members and thus are not free edges but edges with some prescribed boundary conditions. Nevertheless, it is of interest to investigate the effect of the location of these edges. The location is characterized by the edge offset as shown in Figure 8. From the definition of the edge offset, it is evident that edge offsets in the range +.5 to −.5 of the wave length cover all cases. Further, a positive offset at one edge produces the same negative offset at the other edge and thus only positive (or negative) offsets need be tested, i.e., offset range to be tested is zero to one- half wavelength. In addition, the specimen geometry is symmetric with respect to .25 wavelength offset in the sense that an offset of .25 − x at one edge is equivalent to an offset of .25 + x at the other edge. Thus, edge offsets between zero and one-quarter wavelength cover all possible cases.

Four specimens with edge offsets of 0, 0.0625, 0.125 and 0.1875 wavelength have been tested. All four were 150° included angle, 3-wave specimens with $(\pm 45°/0°)_s$ ply lay up. The energy absorption (SSCS) of these differed by less than 3% and the failure modes were essentially identical. Considering this result and the small variation of SSCS with width reduction, for the specimen configurations tested, the width and free edges have only minor effects on the performance of the web.

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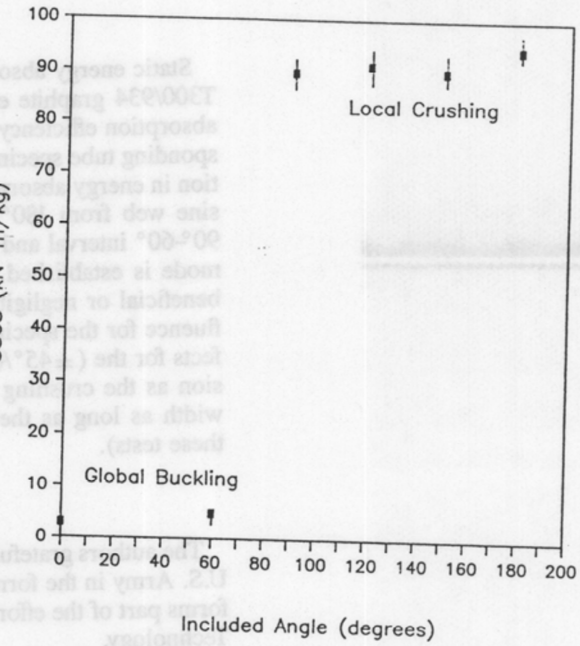

Figure 10. *Included angle (gross thickness) effect.*

Included Angle (Effective Amplitude) Effects

The effective amplitude of the web is an important geometric parameter since it defines the gross width to thickness ratio of the web. The flat plate geometry can be considered to be one extreme, with a zero amplitude and the 180° included angle specimen is another extreme. It has been established that tube type specimens exhibit high energy absorption and the 180° included angle specimens behave in an equivalent manner [8,9].

Tests have been conducted on $(\pm 45°/0°)_s$ specimens to establish energy absorption trends for included angle variations. The flat plate specimen failed in a global buckling (wide column) mode resulting in almost zero energy absorption. The energy absorption characteristics for 180°, 150°, 120°, 90°, 60° and 0° included angle specimens were obtained through tests on 3 to 5 specimens of each type. The SSCS results from these tests are summarized in Figure 10. It is interesting to note that there is no significant loss of energy absorption performance when the included angle of the web is varied from 180° to 90°. The 60° specimens exhibit a dramatic departure from this trend and the energy absorption capability is almost negligible. The failure mode is global and of the same type as has been observed in the flat plate. This suggests the existence of a stability boundary, for these studies, in the range of 60°–90° included angle, where the failure mode switches from efficient crushing to inefficient global failure. This result is important in a design process in order to avoid inefficient energy absorption performance.

CONCLUSIONS

Static energy absorption tests were conducted on different geometries of 6 ply T300/934 graphite epoxy sine webs. These tests have demonstrated the energy absorption efficiency of the 180° included angle specimens being equal to corresponding tube specimens. For the study performed, there was only a small variation in energy absorption performance with reduction in the included angle of the sine web from 180° to 90°. However, a stability boundary is detected in the 90°–60° interval and an abrupt transition from local crushing to global buckling mode is established. The effect of failure initiators is shown to be not always beneficial or negligible. The role of width is shown to be only a secondary influence for the specimen geometries concerned, implying minimal boundary effects for the $(\pm 45°/0°)_s$ webs used in the tests. This is not a surprising conclusion as the crushing is a local failure mode and should be independent of the width as long as the failure mode remains unchanged (which was the case in these tests).

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