Impact Properties of Three-Dimensional Braided Graphite/Epoxy Composites

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ABSTRACT: An experimental study of the response and damage of three-dimensional braided graphite/epoxy composite due to sub-perforation velocity impact was carried out in this research. Simply supported square plates were impacted with an instrumented impact pendulum and also a projectile fired by a gas gun. Hemispherical nose impactors of two different diameters, 12.7 mm and 25.4 mm, were used in the pendulum tests. In addition, static flexure tests were performed. Impact damage was assessed using X-radiography, and compression after impact tests. Damages involved in impacted braided panel are matrix cracking in resin pockets, separation of fiber tows, and fiber tow breakage, mostly in fiber bundle crimp areas. A quasi-isotropic laminate was impact tested with pendulum for comparison of impact tolerance between the two composite systems.

KEY WORDS: gas gun impact, instrumented pendulum impact, 3-D braided composites, graphite/epoxy composite, impact damage modes.

INTRODUCTION

MATRIX CRACKING AND delamination have long been found as major damage modes for laminated composites subjected to sub-perforation impact. The invisible delamination damage may severely impair the load carrying capacity of laminated composites, particularly in compression mode, and lead to catastrophic failure. Previous studies in this area have concentrated on predicting impact response, finding the relationship between the impact energy and damage, and assessing the impact damage tolerance. A comprehensive treatise on the low velocity impact of laminated composites can be found in [1]. Innovative methods

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aiming at improving the impact resistance of laminated composite structures have been investigated in the past decade. Improvement in impact resistance of laminated structures have been reported with through-the-thickness stitching [2], interleaving [3], and by employing tough or toughened resins [4].

Recent developments in textile technology have given rise to novel methods of weaving and braiding fibers to fabricate desired three-dimensional structural shapes. These dry preforms can then be impregnated with suitable matrix materials to manufacture three-dimensional objects. These materials are expected to have higher impact damage tolerance, because there is no plane of lamination in the structure. Fabrication of braided composites, and material characterization have been the subject of several studies [5,6].

Impact properties of braided composites have been reported in [5,7,8]. Drop tower impact tests were performed in these studies. The general conclusion was that the braided composite is more capable in containing the impact damage than the laminated composites. In the present study the impact response and damage of three-dimensional braided graphite/epoxy composites have been determined in tests conducted with an impact pendulum and a gas gun. Damages were assessed using X-radiography, and quantified by measuring residual compressive strength. Impact response was compared to that of the quasi-static plate flexure test.

MATERIAL

Braided preforms with high strength, high modulus PAN based Celion 12K (12000 filaments in a single fiber tow) graphite fibers were purchased from Atlantic Research Corporation and then impregnated with Hercules 3501-6 epoxy resin at Douglas Aircraft Company. The apparent braid angle was 20°, and the braided pattern was designated as $1 \times 1 \times 1$. The nominal panel size was 0.127×1.0 meter. Thickness of an impregnated braided panel varied from 5.8 mm, along the edges, to 4.8 mm, in the middle section. Fiber volume fraction reported was about 60%, with 2% void content.

A photomicrograph of braided composite is given in Figure 1. This photomicrograph depicts sizable resin pockets and shows that the braided composite is a highly inhomogeneous material. The resin pockets appear more or less irregularly on the surfaces or inside the braid. Resin pockets represent areas that do not have fiber reinforcement and constitute areas of weakness. Though a three-dimensional braided composite is not a layered structure, it contains many oblique small size fiber tow interfaces. Interfaces exist between fiber tows and resin pockets as well.

EXPERIMENTS AND RESULTS

Static Tests

Tests [9] on low-velocity impact of laminated graphite/epoxy composites have shown that, for large mass impactors at low velocities, a static test gives essentially the same results as a low-velocity impact test. To make a similar study for braided composite, plates of size 127×127 mm with four edges simply-

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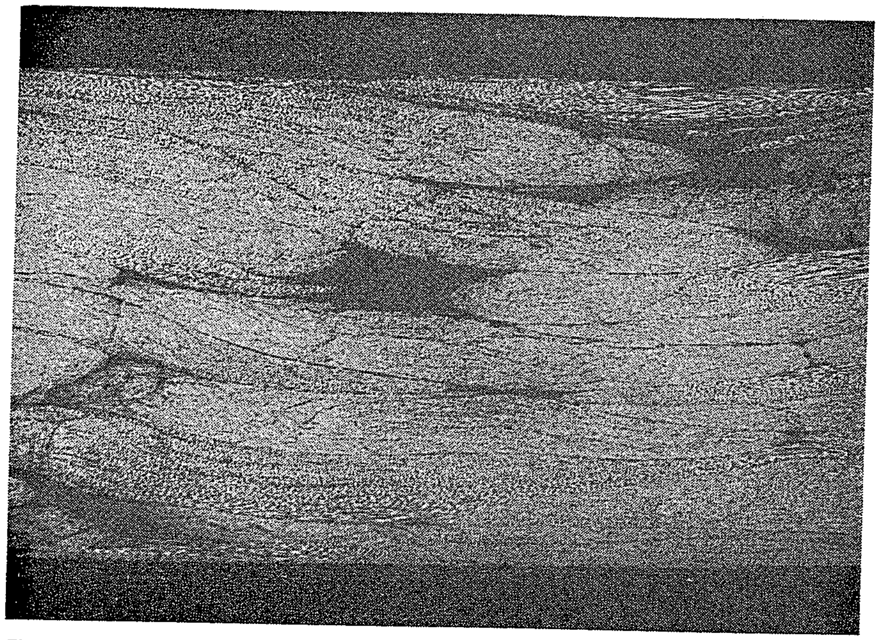

Figure 1. *Photomicrograph (×27) of a three-dimensional braided composite sample sectioned perpendicular to the braiding direction.*

supported on a 102 × 102 mm square ridge were used in pendulum, gas gun impact tests, and static plate flexure tests. Center deflection of static plate flexure test was measured at the bottom surface with a linear variable differential transformer (LVDT) and recorded with a Nicolet digital oscilloscope. Bending deflection as measured did not include indentation due to contact force. Simultaneous measurement of center deflection and contact indentation with two sets of LVDT showed that indentation is two orders smaller than bending deflection [10], hence it is assumed to be negligible in the present situation. Contact behavior of hemispherical steel indenters and 3-D braided composite was also investigated in [10]. Contact stiffness was found higher when the indentation test was performed on top of a fiber tow compared to that on a resin pocket.

Load–center deflection curves of two plates, loaded to failure with 25.4 mm and 12.7 mm diameter indenters, respectively, are given in Figure 2. An early load drop is apparent at approximately 2 KN for most of the plates tested; thereafter, the load-deflection curves become inelastic and nonlinear.

Impact Tests

An impact test should be designed, in addition to ease of modeling and analysis, to simulate foreign object impact that may happen to a composite structure in service. Bird-strike on propellers, tool or tool box drop on the skins of wing or control surfaces, and runway debris hit on the lower part of fuselage or wing skin are common foreign object impacts for aircraft structural members. In this study an instrumented pendulum with tup mass up to 15 Kg and impact velocity ranging from 0.5 m/s to 5 m/s was used to simulate tool or tool box drop. A gas gun was used to propel cylindrical projectiles of mass 14.5 gm up to a velocity of 95 m/s. Details of the pendulum and gas gun setup can be found in References [9,11].

Braided composite plates tested were 127 × 127 mm and with four edges simply-supported on a 102 × 102 mm square ridge. Two hemispherical nose impact tups, 25.4 mm and 12.7 mm in diameter, were used in the pendulum impact. Impactor mass of 13.84 Kg was used for all the pendulum impact tests. Figure 3 is the impact force versus time curves of specimens B42 and B43. Impact force history is important for obtaining information about the impact response and damage of the impact tested specimen. The impactor-target contact duration, the threshold impact force, and information about the impact damage tolerance are all revealed in an impact load versus time curve. From Figure 3 it shows that specimen B42 was only slightly damaged, while B43 was severely damaged. After the pronounced load drop in the curve of B43 the specimen became less strong, however was able to sustain a relative high impact load for a period of time. Results from a pendulum impact are impact velocity (V_I), rebound velocity (V_R), impact energy (E_I), energy loss (E_L), impact force history, and the maxi-

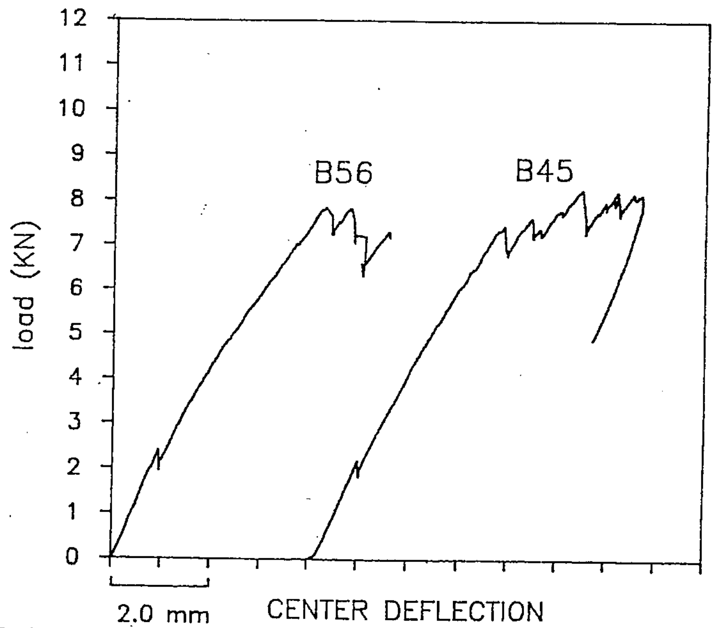

Figure 2. Load-deflection curves for two plates in static flexure test with the 25.4 mm (B56) and 12.7 mm (B45) indenters.

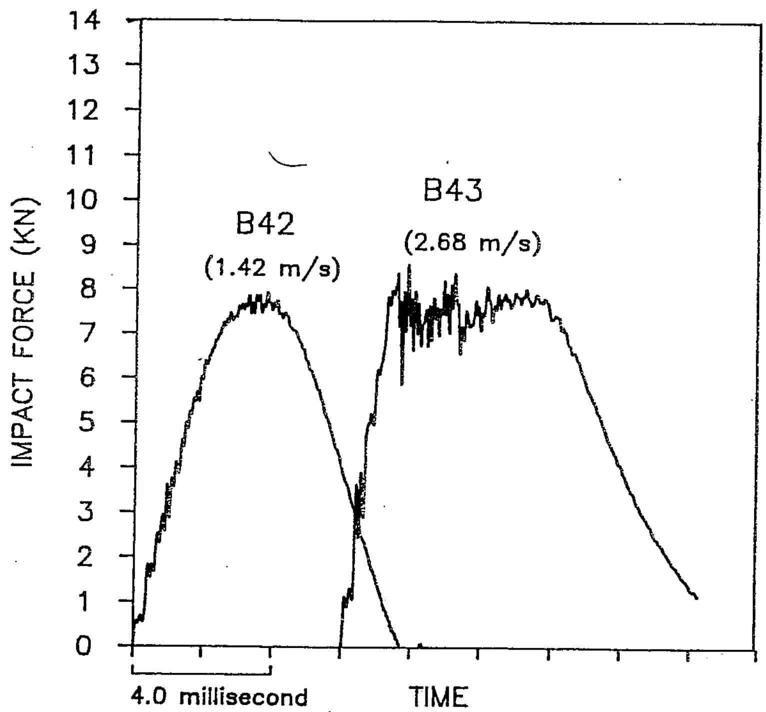

Figure 3. *Impact force-time curves of pendulum impact tests for specimens B42 and B43.*

mum impact force (F). Energy loss was calculated from impactor impact energy and rebound energy. Energy loss, although it may also include vibration dissipation energy, was used as a parameter indicating energy absorbed by the plate in the course of damage. Energy loss fraction versus the impact energy are plotted in Figure 4.

A steel cylindrical impactor (9.5 mm in dia.) with a 12.7 mm diameter spherical end was used in the gas gun impact test. The plate size and support conditions were the same as those of the pendulum impact tests. Nominal impactor mass was 14.5 g. In the gas gun impact test the impact force was not measured.

After the impact test the specimens were first photographed on both the impacted (front) and the nonimpacted (back) faces. The impacted plates were then X-rayed with the aid of an X-ray enhancement liquid named Conray-43 (Iothalamate Meglumine). Figures 5a, b, and c show the photographs and the X-ray picture of specimen B34.

The damages visually noticed in a low velocity impacted braided composite plate were surface matrix cracking in resin pockets, separation of fiber tows, fiber tow breaking, and debonding of matrix and fiber filament within broken fiber tow. Almost all broken fiber bundles broke in fiber crimp areas. Whether there exists tow splitting or transverse crack within unbroken fiber bundles needs further microscopic study.

Damages were assessed further with dye-penetrant enhanced X-radiography. In respect of damage severity one is able to mark the damage as a two-zone area. The first damage zone looks darker in X-radiographs. Within this damage zone matrix cracking in the resin pockets and/or fiber-tow breakage exist commonly as noticed in visual observation of damaged specimens. In the second damage zone the damage is mainly separation of fiber tows. Separation of fiber tows appeared as a tiny trace in X-radiography and was shown more extensive in X-ray than from naked eye examination. It is believed that separation of fiber tows may exist not only on the surface but also within the braid. In order to compare the severity of damage from specimen to specimen, efforts were directed to estimate the areas of these two damage zones. An example on differentiating the two damage zones is shown in Figure 5c. Area of first damage zone (A_1) and the total damage area (A_T) for all specimens tested are included in Table 1. Figure 6 depicts total damage area as related to impact energy. Damage areas of static plate flexure tests are shown on the ordinates.

A compressive test fixture developed at NASA Langley [12] was modified to conduct a residual compressive strength study. Due to capacity of the testing

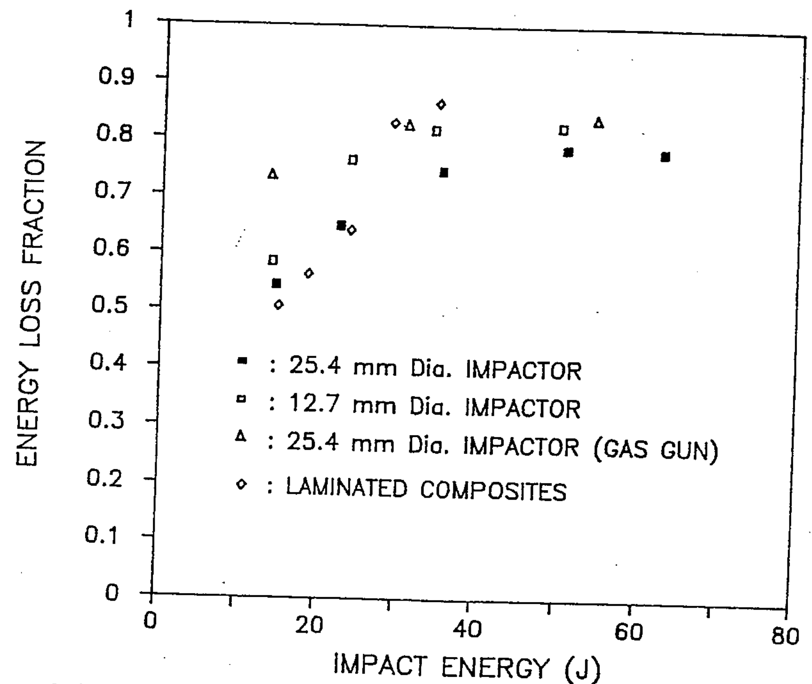

Figure 4. *Impact energy loss fraction for impacted braided and laminated panels as related to impact energy.*

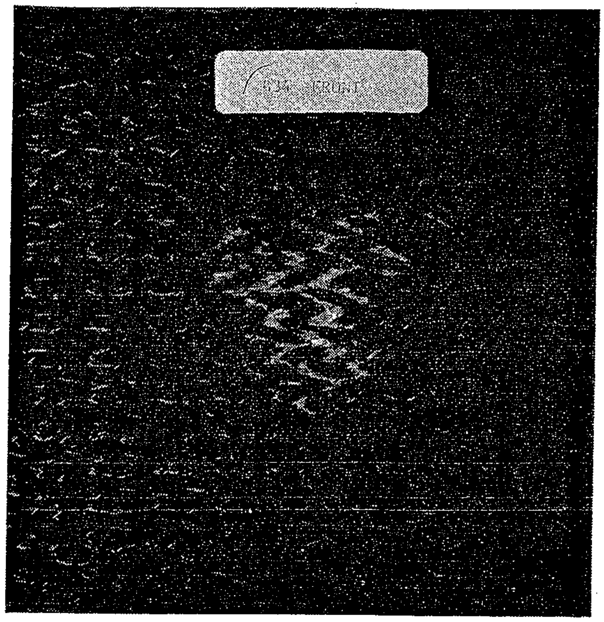

Figure 5a. *Post-impact photo (front) of specimen B34.*

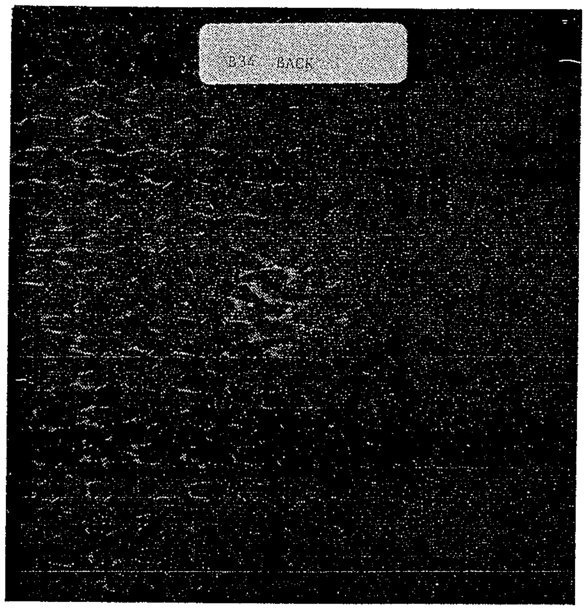

Figure 5b. *Post-impact photo (back) of specimen B34.*

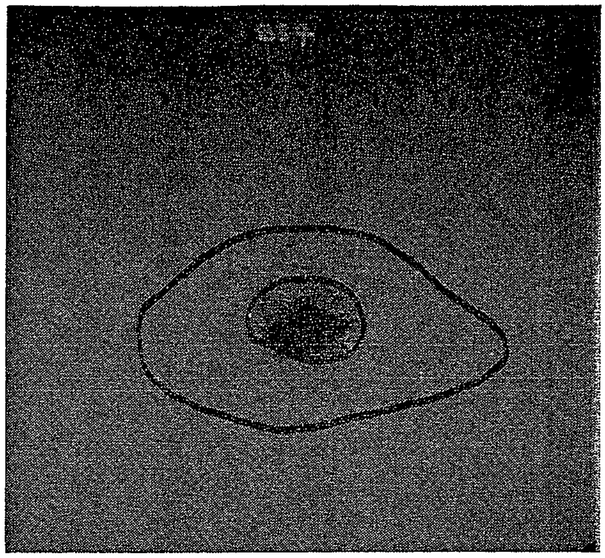

Figure 5c. *Post-impact X-ray of specimen B34 (the inner enclosed area represents the first damage zone; the area between the two enclosed lines is the second damage zone).*

machine, impacted specimens and post-static flexure test plates were trimmed with diamond saw to 76.2 mm in the transverse direction to ensure failure under compression load in the braiding (longitudinal) direction. An intact plate was tested and used as the control. The compressive strength of this specimen (B47) was 156.2 MPa.

Table 1 shows the results of specimens tested with the impact pendulum and the gas gun. The last column in this table presents the residual compressive strength (X_{CR}). Figure 7 shows the fraction of compressive strength reduction against the impact energy. For comparison, strength reduction fraction of specimens tested in plate flexure test are shown on the ordinate.

TESTS OF LAMINATED COMPOSITE

In comparing the impact properties of laminated and braided composites the selection of laminate needs a rational basis. It seems very difficult, if not impossible, to construct a laminated composite which has simultaneously the same in-plane stiffness and flexural properties as that of the braided composite used in this study. Figure 8 shows the comparison of in-plane and bending stiffness of the braided composite and a quasi-isotropic laminate, which is one of the most widely used laminating configuration. Properties for braided composite shown in the figure were measured experimentally, while curves for laminate were calculated from classical lamination theory. In addition to mechanical properties, weight, which is proportional to the plate thickness if the same constituent materials and fiber volume fraction are used for both composite systems, should also be taken into consideration. Based on these factors a 32-ply quasi-isotropic laminate made of Hercules AS4/3501-6 prepreg was used. The graphite fiber used (AS4), as Celion 12k graphite fiber used in the 3-D braid, is also a PAN base high modulus, high strength fiber with 10k filaments in a single fiber tow. Thickness of cured laminate was about 3.8 mm. Tests done on laminated panels were static plate flexure test and pendulum impact with the 12.7 mm hemispherical nose impactor.

Figure 9 shows the comparison in static plate flexure test. Impact load history in a pendulum test of a laminated composite is shown in Figure 10 along with that of a braided panel. Impact test results for five tested laminated panels are given in Table 2. Energy loss fractions of impacted laminates are shown in Figure 4 along with that of braided specimens.

In energy loss fraction versus impact energy plot there exists a sudden jump between 23.8 J and 28.9 J impact energy level. This phenomena may depend on the laminate configuration. Impacted panels from impact energies lower than this jump showed barely visible surface impact damages. At higher impactor energy the laminates showed very severe fiber breakage on the back surface and had a serious indentation on the impacted surface. The damages observed in the two laminated panels impacted at relative higher energy level suggested that the impactor was about to penetrate the laminated panels.

Table 1. Results of braided composite tested in pendulum and gas gun impact.

I.D.	V_I (m/s)	V_R (m/s)	E_I (J)	E_L (J)	(Frac.)	F (KN)	A_1 (cm²)	A_T (cm²)	X_{CR} (MPa)
B37[a]	1.45	0.98	14.5	7.9	(.54)	8.3	0.0	3.9	131.5
B32[a]	1.80	1.07	22.5	14.6	(.64)	10.1	0.8	15.5	124.4
B34[a]	2.26	1.14	35.4	26.4	(.75)	9.8	3.2	22.6	118.1
B33[a]	2.70	1.25	50.5	39.7	(.79)	9.2	6.5	23.2	124.8
B38[a]	3.01	1.40	62.6	49.0	(.78)	12.6	4.4	34.8	96.6
B42[b]	1.42	0.92	14.0	8.2	(.59)	7.8	0.0	1.5	138.5
B46[b]	1.85	0.90	23.7	18.1	(.76)	8.7	1.2	4.9	144.1
B44[b]	2.22	0.94	34.2	28.0	(.82)	8.2	3.2	10.3	131.2
B43[b]	2.68	1.12	49.9	41.2	(.83)	8.6	3.7	20.6	113.4
B36[c]	43.2	22.2	13.5	10.0	(.74)		0.0	11.0	146.8
B35[c]	65.0	26.8	30.6	25.4	(.83)		0.6	33.5	116.5
B31[c]	86.3	34.3	54.0	45.5	(.84)		3.1	63.2	70.5

[a]Pendulum impacted with 25.4 mm dia. impactor.
[b]Pendulum impacted with 12.7 mm dia. impactor.
[c]Impact tested with gas gun.
Note: V_I, impactor incident velocity; V_R, impactor rebound velocity; E_I, incident impact energy ($1/2MV_I^2$); E_L, energy loss [$1/2M(V_I^2 - V_R^2)$]; F, maximum impact force; A_1, area of damage of zone 1 estimated from X-ray; A_T, total damage are; X_{CR}, residual compressive strength.

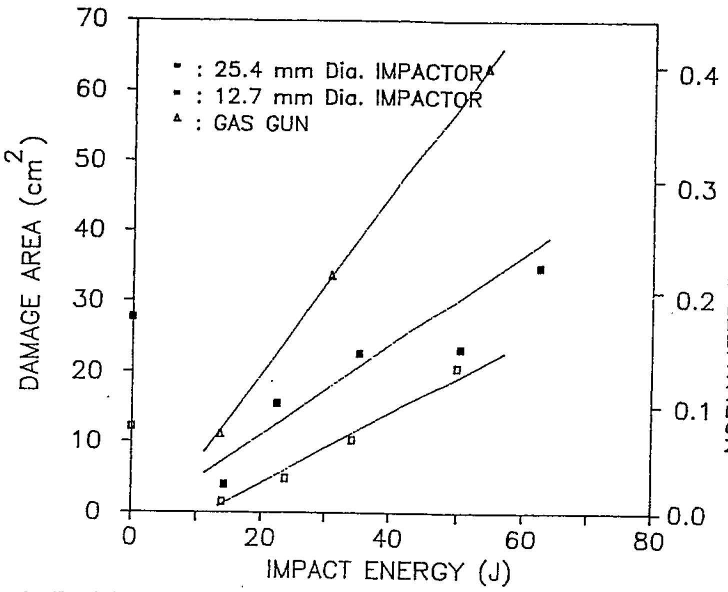

Figure 6. *Total damage area in impacted braided specimens as related to impactor kinetic energy.*

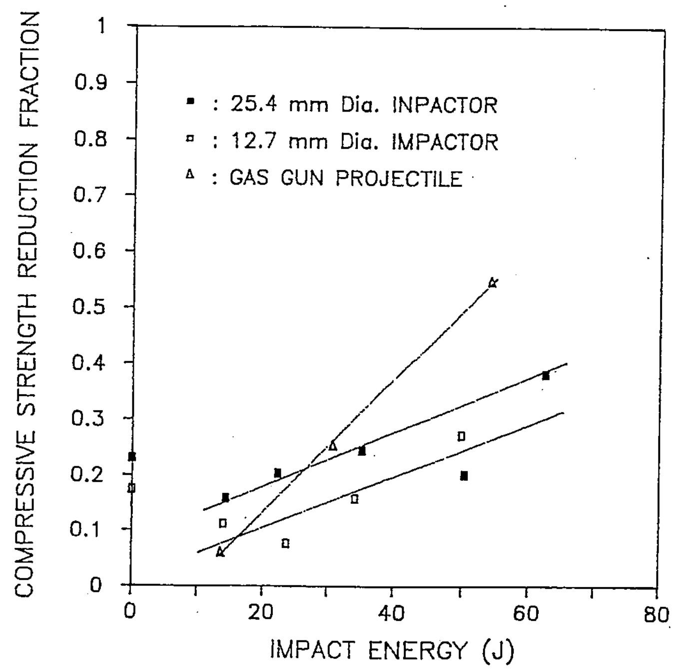

Figure 7. *Compressive strength reduction for post-impacted braided panels as related to impact energy.*

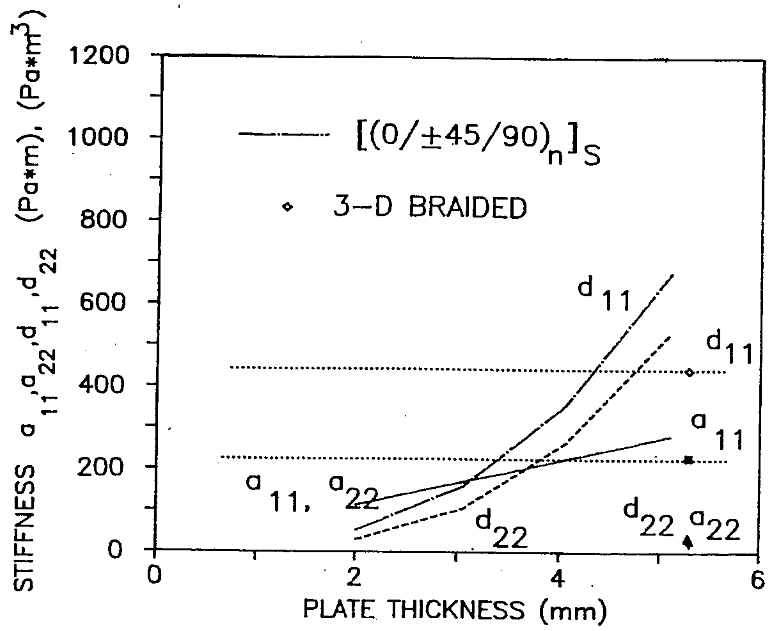

Figure 8. *In-plane stiffness (a_{11} and a_{22}) and bending stiffness (d_{11} and d_{22}) of braided composite (symbol) and a quasi-isotropic laminate (line) as a function of plate thickness.*

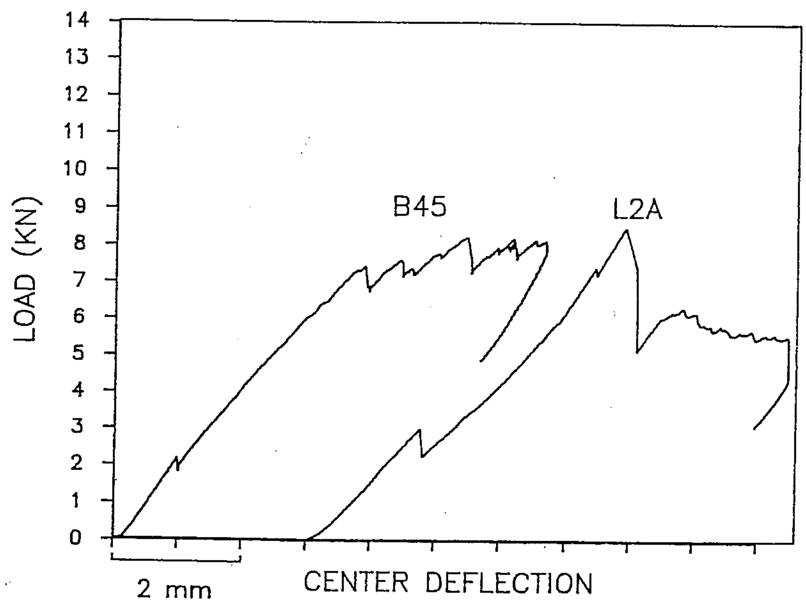

Figure 9. *Static load–deflection curves for a braided composite and a laminated panel.*

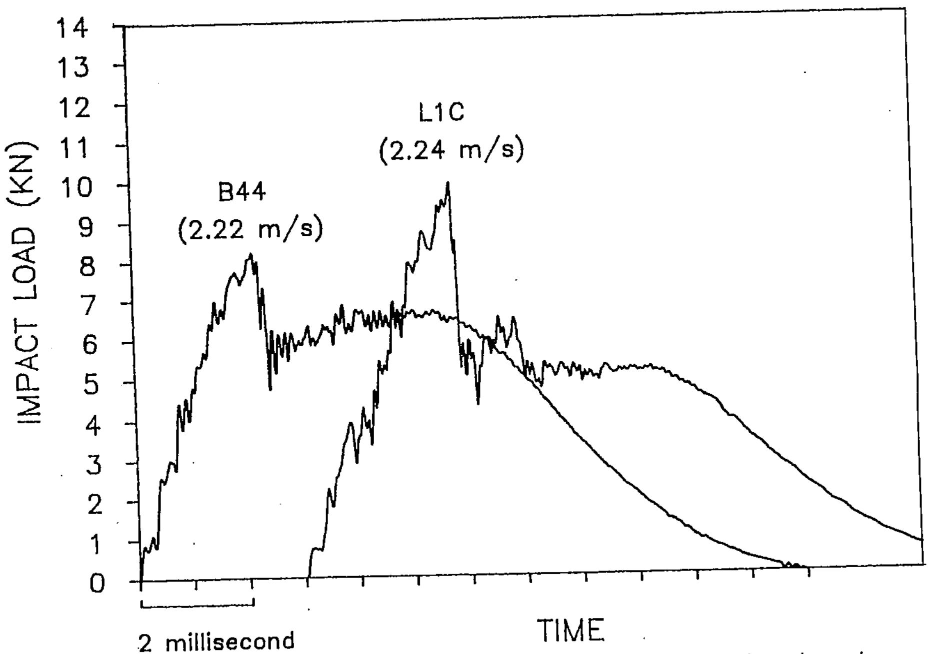

Figure 10. Impact force history of a braided specimen and a laminated panel.

Table 2. Pendulum impact test results of laminated plate.

I.D.	V_I (m/s)	V_R (m/s)	E_I (J)	E_L (J) (Frac.)	F (KN)
L1A	1.46	1.03	14.8	7.5 (.51)	7.5
L2B	1.63	1.08	18.5	10.4 (.56)	8.8
L1B	1.86	1.12	23.8	15.2 (.64)	10.6
L1D	2.04	0.85	28.9	23.9 (.83)	10.1
L1C	2.24	0.83	34.7	29.9 (.86)	9.9

Note: V_I, impactor incident velocity; V_R, impactor rebound velocity; E_I, incident impact energy ($1/2MV_I^2$); E_L, energy loss [$1/2M(V_I^2 - V_R^2)$]; F, maximum impact force.

DISCUSSION

Should a static test be able to yield a similar response as that of large mass, low velocity impact, it would be very economical to conduct screening tests for impact resistance of a large variety of composite systems. Plate deflections of the pendulum impact tests were calculated from integration of the impactor accelerations, which are derived from impact force-time results. This calculated deflection includes plate indentation, which is two orders less than the plate deflection in static tests and is assumed negligible on this occasion. Figure 11 shows the force-deflection curves of two impact tests (B34 and B33) and a static plate flex-

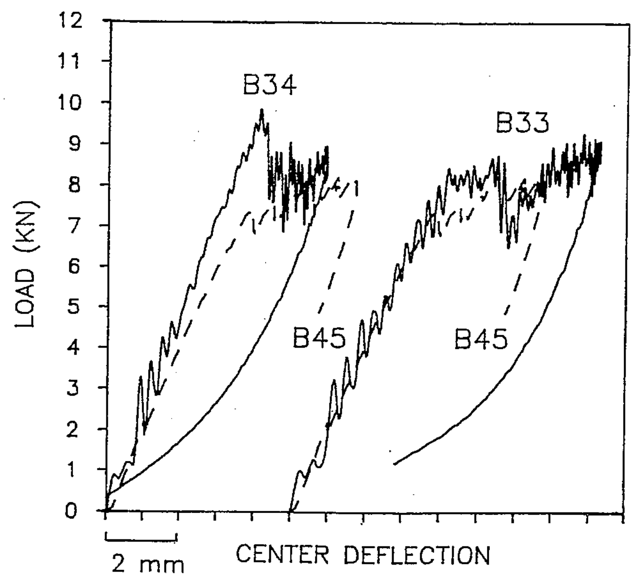

Figure 11. *Force-deflection of two impacted braided panel (B34 and B33) and a static tested plate (B45).*

ure test (B45). If vibrations from the impact test are ignored, the force-deflection curves of B33 and B45 agree with each other very well. For most of the specimens tested the match seems not as good as that of B33. Comparison was made in the damage area and residual compressive strength for all pendulum impact tested specimens against those of static tests. It was found to draw a conclusive remark on this issue seems difficult from tests performed in this study.

Impact tests with the instrumented pendulum show that the energy loss fraction is higher for a small diameter impactor with the same impactor mass. However, plates experienced lower maximum impact force for the small impactor. Static tests for two sizes of indenter also showed that plates tested with smaller diameter indenter had slightly lower maximum failure load. The trend shows that the energy loss fraction from a small diameter impactor levels off at a lower impact energy level than that from a large diameter impactor. For the same impactor kinetic energy, the fraction of energy loss was larger in the case of gas gun impact, where a smaller mass at much higher velocities was used.

In gas gun impact dynamic effects are more pronounced. From [11] the impact contact duration of projectile impact on glass/epoxy specimens was found about 1.0 millisecond, which is approximately an order less than the pendulum impact tests performed in this study. Multiple contacts were reported in gas gun impact [11]. It is believed that low amplitude flexural waves propagating at high frequencies caused separation of fiber tows spread in a larger area. In pendulum impact the damage is more severe and localized and is dependent on the size of impactor nose diameter. Impact from a small nose impactor may produce higher out-of-plane deformation and/or deeper indentation in a smaller area, and thus absorbs more impactor kinetic energy than does an impactor of large nose diameter. In the aspect of degrading load-carrying capability, especially for compression, impactors fired from a gas gun are more detrimental than large mass pendulum impactors at comparatively low velocities. However, impact from a gas gun is less prone to cause fiber tow breakage, which is a severe damage mode if composite residual tensile strength is of concern.

Braided composites, though they are not a laminated construction, contain many small slant interfaces where fiber tows are laid face-to-face or approximately side-by-side. Due to different fiber orientation in the neighboring fiber tows inter-fiber-tow stresses may develop when the composite is subjected to mechanical or thermal loads. High stress field may exist in fiber tow-resin pocket interface also. In an impact, inter-fiber-tow stresses may cause extensive separation of fiber tows in a braided composite when a brittle epoxy is used as matrix. In [13], where multi-dimensional woven graphite/PEEK composites were tested with drop-weight impact, no cracking damage in resin pockets or separation of fiber tows were specifically mentioned. Instead, the thermoplastic resin pockets were considered effective in stopping the cracks which initiate within the fiber tows.

Another factor which may have influence on the extent of the separation of fiber tows where fiber tows are laid approximately side-by-side is the relatively low transverse strength of the braided composite tested in this study. Whether lay-in weft could reduce such damages is of interest to pursue.

Separation of fiber tows seems a minor damage mode as compared to fiber tow breakage. Post-impact compression tests, however, showed that this damage mode, which appeared prevalent in gas gun impacted specimens as shown in plots of damage areas (Table 1 and Figure 6), may severely impair the load carrying capacity of braided structure. It is believed that separation of fiber tows in braided composites is analogous to delamination damage in laminated composites in the aspect of weakening the load-sharing and/or load-transferring mechanisms. Without adequate bonding, the fiber tows of a braided structure is nothing but, to some extent, a flexible fiber-skeleton which may be weak in sustaining compressive loads.

The inherent characteristics of braided composite, which has fiber tow intertwined, may be able to effectively confine damage in a relatively small area. Nonetheless, this damage confining mechanism, which retards damage propagation through breaking up the area of interface in contrast to a large interface area in a laminate, would induce very high stress gradients in a localized area because the intertwined fiber tows are less effective in dissipating applied stresses. High stresses in fiber crimp areas where two fiber tows intertwined may account for the fiber tow breakage in most of the specimens tested in this program. In [5], Gause and Alper found that braided graphite/epoxy composites does not increase damage threshold, which is determined from the impact force at the incipient damage, as compared to composite laminates. Similar results, in terms of maximum impact force, were obtained in this study for braided and laminated specimens impacted with the 12.7 mm impactor as shown in Tables 1 and 2.

Detailed study of load-deflection curves of static plate flexure tests and that of pendulum impact tests revealed that regardless of static or impact tests and independent of impactor size the first pronounced load drop occurred at approximately 4 mm center deflection. Loading forces corresponding to this load drop were generally higher for large nose size impactor or indentor than for the small one. It is believed that this load drop is associated with fiber tow breakage and is determined from the fiber failure strain.

Due to intertwining, filaments in a single fiber tow may be tightly compacted together around crimp area. Whether tight compaction causes difficulty for resin to wet-out the crimp area in impregnation and induces dry fibers needs further investigation.

In compressive strength reduction fraction versus impact energy plots (Figure 7), plates impacted with the gas gun show the steepest slope in strength reduction. For pendulum impact the large impactor caused less severe strength reduction. This trend seems to correlate well with that of energy loss.

From static plate load-deflection curves and pendulum impact force history, braided composites tested show better damage tolerance than the quasi-isotropic laminate. In Figure 9 it was found that after the more pronounced load-drop (i.e., at approximately 4 mm center deflection for braided specimen B45 and 5 mm center deflection for laminated specimen L2A) specimen B45 showed even higher load carrying capacity. The eventual load decrease at around 8.5 mm deflection was due to termination of the test. However, for specimen L2A no load increase is noticed in the load-deflection curve after approximately 5 mm deflection.

Similar observations can be found in the impact load versus time curves. The severe load decreases in the curves are considered associated with more serious damages that may be a delamination and a fiber breakage in a laminate and a fiber tow breakage in a braid. Beyond that point the braided specimen was able to sustain a relative high impact load for a period of time. In contrast, a laminate dissipates a relatively higher impactor impart energy in the course of damage and was not able to carry as much impact load afterwards.

Since the laminate selected in this study has no grouped layers (no two or more adjacent layers have the same fiber orientation) delamination damage may not be as severe as those that have. The mass of the impactor also plays a role in the relative contribution of each damage mode at different impact energy levels. The abrupt jump observed in the energy loss fraction versus impact energy plot may give an explanation on this aspect. Should small mass be used, the jump may be less pronounced. Other factors such as impactor nose shape, boundary conditions, and impactor velocity are important parameters that influence the impact response of a composite material system in an impact test. It is apparent that to conduct tests which examine all these parameters and that associate with laminate configurations will be too exhaustive, as noted in [1]. An analytical model taking all major parameters into consideration seems urgently needed for predicting the characteristics of a composite material system under impact loads.

CONCLUSIONS

An experimental study on the impact response and damage tolerance of a three-dimensional braided graphite/epoxy composite was carried out with an instrumented impact pendulum and a projectile gas gun. Impact force-time curves obtained from pendulum impact tests are important in revealing information about the development of the impact event and about the damage in the impacted specimen. Maximum impact force and energy loss fraction in a pendulum impacted composite are dependent on the nose size of the impactor. In force-deflection curves the first pronounced load-drop occurred at approximately the same center deflection for all the specimens tested in static plate flexural test and for those specimens tested in pendulum impact test that have an obvious first load-drop in force-deflection curves.

Braided composite showed better damage tolerance than a quasi-isotropic laminate which has about the same bending stiffness in the primary direction in either static test or impact test. The intertwining nature of fiber tows in the braid accounts for the capability of containing propagation of damage. Nevertheless, this characteristic is responsible for the tendency of early tow breakage in an impact and low static in-plane strength.

Damages involved in impacted braided specimens were matrix cracking, separation of fiber tows, and fiber tow breakage. The extent of each individual damage mode may depend on the matrix system, the fiber tow size, and the braiding pattern employed for the braid. With approximately the same kinetic energy, small mass projectile fired at high velocity from a gas gun caused more widespread damages to the composite panels than large mass, low velocity pendulum impactor. However, the prevalent damage mode may be different in the impacted specimens from the two respective impact facilities. Matrix cracking and separation of fiber tows predominated in the gas gun impacted specimens, while fiber tow breakage commonly existed in pendulum impacted braided panels. Separation of fiber tows is a relatively severe damage mode if residual compressive strength is of concern. Further microscopic examination is necessary to investigate possible damage within fiber tows and inside the braid.

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