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Impact Damage Resistance of Several Laminated Material Systems

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The impact damage resistance of several laminated materials systems (AS4/3501-6, IM7G/X8553-50, and A370-5H/3501-6 graphite/epoxy, and wet layup glass/epoxy) was studied by conducting impact tests, measuring the force–time response, and determining the damage caused by different impactor velocities. Various laminate configurations were utilized to better understand the role of stacking sequence and fiber orientation. The results indicate that force is a key parameter in the assessment of impact damage resistance, particularly the force needed to cause incipient damage. Incipient damage is generally in the form of matrix cracks in laminates made from unidirectional tape. This is followed by delamination at the interface with the cracked ply. This damage mode does not change when the material system is changed, although the force at which the damage occurs is affected. Furthermore, ply angle does not change the damage modes that occur, although it does affect the extent of the damage. However, the form of the material, that is, fabric vs unidirectional ply, does affect the damage that occurs. By its woven nature, fabric naturally inhibits the formation of long matrix cracks. This also restricts the amount of delamination that occurs. This in turn results in fiber breaks occurring as the energy dissipated by delamination in other configurations must be dissipated by another mechanism, fiber breakage, in this case. A discussion of the results in terms of the assessment of damage resistance is provided. Needs to provide better understanding are identified.

Introduction

An important issue in the design of composite structures is the impact response of these material systems and the configurations in which they are utilized. Therefore, issues surrounding impact have received considerable attention in the structural design process, in the materials development world, as well as in the research community.[1,2] These issues can generally be divided into two separate areas: damage resistance and damage tolerance.[3] The first area, damage resistance, deals with the damage state brought about by an impact event. The second area, damage tolerance, concerns the changes in the structural performance due to a damage state. To properly assess the damage tolerance of a structure, it is first necessary to accurately define the damage state that does, or can, exist.

There is, therefore, a need to understand the ways in which laminated composite structures are damaged from impact. Variables such as material system, ply stacking sequence, laminate thickness, and ply angles affect the impact response and resulting damage.[2] However, much of the work to date has been hampered by a lack of standard test methods and established test techniques. The most commonly used test procedure, the so-called "compression after impact" test,[4] actually measures the combined effects of damage resistance and damage tolerance.[5] A number of authors[4–13] have concentrated on damage resistance aspects. Nevertheless, a general understanding of the damage resistance of composites and their structures, as well as of the mechanisms that contribute to damage resistance, does not exist.

The current work therefore focuses on providing data to help in this understanding. The overall objective is to determine and compare the impact damage resistance of various material systems. This overall objective is pursued by considering three specifics: identifying the incipient damage types and levels, observing the damage progression, and observing the relationship between force–time response and the resulting damage. In addition, the force and damage data acquired can be utilized to verify and adjust, as necessary, the many analyses that exist for predicting the response and resultant damage due to impact. This aspect is not addressed in the current paper.

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Overall Approach

Four material systems were investigated: Hercules AS4/3501-6 graphite/epoxy prepreg tape, Hercules A370-5H/3501-6S graphite/epoxy fabric prepreg, Hercules IM7G/X8553-50 graphite/epoxy prepreg tape, and a woven fabric fiberglass/epoxy wet layup. The first material system, AS4/3501-6, is unidirectional and has a first generation "brittle" (low strain-to-failure) matrix system. It was chosen to provide a baseline for comparison. The IM7G/X8553-50 unidirectional prepreg system has IM7 fibers (slightly higher strain-to-failure than AS4 fibers) embedded in an experimental "toughened" (high strain-to-failure) matrix and provides comparison of a toughened matrix system with a standard brittle system. The A370-5H/3501-6S system has the same fibers and matrix as the AS4/3501-6 tape except that the fibers are arranged in a five-harness satin weave. This allows a direct comparison of tape and fabric layups. The glass/epoxy system is composed of Interglas 92125 dry woven fiberglass prepared in a wet layup with Rutapox L20/SL resin. This system is used in the aircraft industry and is used here to provide a direct comparison with the graphite/epoxy fabric system. The basic ply properties of these various material systems are provided in Table 1.

Several different layup configurations were utilized to provide various comparisons. These configurations are summarized in Table 2. Note that the use of parentheses here indicates a fabric layup in contrast to brackets, which indicate a tape layup. The direct comparison between the AS4/3501-6 and IM7G/X8553-50 material system was provided via a family of 12-ply laminates in $[\pm\theta_2/0_2]_s$ configurations. This also allowed investigation of the effect of layup angle θ. The plies were repeated twice, thereby doubling the "effective ply thickness" to limit the number of ply interfaces where delamination could occur and to make matrix cracks more apparent. The two AS4/3501-6 quasi-isotropic layups were utilized to provide a direct comparison to the $(45_2/0_2)_s$ fabric layup. Although the ply thicknesses are somewhat different, the fiber orientations are the same and the ply stacking sequence, except for the woven nature of the fabric, is also the same. Finally, the glass/epoxy and graphite/epoxy fabric layups can be directly compared.

In addition to identifying the incipient damage type, the general damage characteristics of these laminates were also of interest. To

Table 1 Ply properties of the material systems

Material system	E_L, GPa	E_T, GPa	ν_{LT}	G_{LT}, GPa	t_{ply}, mm
AS4/3501-6	142	9.8	0.30	6.0	0.134
IM7G/X8553-50	152	8.3	0.30	5.9	0.144
A370-5H/3501-6S	73	73	0.06	4.4	0.350
Glass/epoxy	19	19	0.06	1.0	0.260

Table 2 Test matrix

	Material system			
Laminate[a]	AS4/ 3501-6	IM7G/ X8553-50	A370-5H/ 3501-6S	Glass/ epoxy
$[\pm15_2/0_2]_s$	10[b]	13	—	—
$[\pm45_2/0_2]_s$	10	10	—	—
$[\pm60_2/0_2]_s$	11	10	—	—
$[90_4/0_2]_s$	11	10	—	—
$[\pm45_2/0_2/90_2]_s$	10	—	—	—
$[(\pm45)_2/(0/90)_2]_s$	9	—	—	—
$(45_2/0_2)_s$	—	—	9	8
$(90_2/0_2)_s$	—	—	—	6
$(0_2/45_2)_s$	—	—	—	6
$(45/0)_{2s}$	—	—	—	5
$(0/45)_{2s}$	—	—	—	6

[a]Parentheses indicate a fabric layup; brackets indicate a tape layup.
[b]Number indicates number of specimens tested.

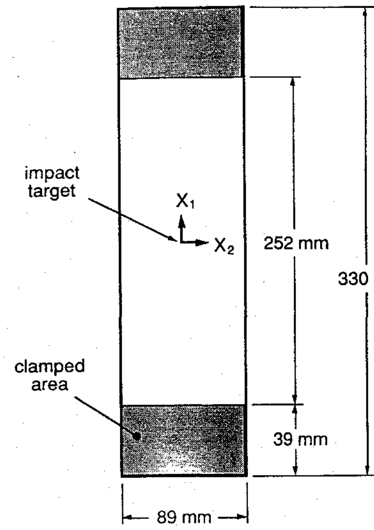

Fig. 1 Specimen geometry.

observe the progressive stages of damage, impact tests were performed at various velocities while holding constant the impactor mass (1.53 kg), tup shape (hemispherical) and diameter (12.7 mm), specimen geometry (later described), and boundary conditions (two sides clamped, two sides free).

The impact velocities utilized ranged from those causing incipient damage to those causing penetration of the specimen, where possible, resulting in velocities from 0.5 to 5.5 m/s. These velocities were determined for each layup based on results from preliminary tests. Several trial impacts were performed on specimens of each layup and material to determine an approximate velocity range in which damage occurred. Using this information, an initial impact velocity was determined for each laminate where damage could easily be detected by x rays (using dye penetrant and a drilled hole as later described) or visually for the glass/epoxy specimens. Subsequent impacts were performed at slower velocities, in 0.5 m/s increments, until no damage was detected. In addition, laminates were generally impacted at a common velocity of 5.0 m/s to provide a comparison between all layups and material systems. Additional specimens were used to further isolate the incipient damage velocity for each layup in 0.1-m/s increments.

During each impact test, force–time measurements were taken. After each test, the damage state in the specimen was determined using a variety of nondestructive and destructive techniques as subsequently described.

Experimental Specifics

An overview of the experimental methods are given herein. Full details can be found in Ref. 14.

Specimen Preparation

The specimen geometry is shown in Fig. 1. The specimens are 89 mm wide and 330 mm long and are clamped at the ends, resulting in a 252 mm test span. The specimen width was chosen so that damage from the impact of the 12.7-mm diameter hemisphere could progress without the interference of edge effects of the coupon.

The specimens were obtained from 304 × 356 mm plates. In the case of the three prepreg systems, the laminates were layed up by hand and cured in an autoclave under temperature, pressure, and vacuum as recommended by the manufacturer. These three material systems have a cure temperature of 177°C. The 3501-6 systems were postcured for 8 h at 177°C. The glass/epoxy system required a wet layup procedure followed by an autoclave cure for 8 h at 60°C under only vacuum. This was followed by a 15-h postcure at 80°C.

All specimens were cut from the cured plates using a water-cooled diamond-grit cutting wheel. Thickness measurements were taken on each specimen. The average measured per ply thicknesses were within 3% of the nominal ply thickness reported in Table 1 in all cases.

Impact Testing

Impact tests were conducted with an impact testing machine previously developed[15] and illustrated in Fig. 2. A striker unit is used to hit a 0.66-m-long steel rod mounted in linear bearings. The rod has a force transducer and hemispherical tup mounted at the front end. The rod travels horizontally in the bearings towards the test specimen. A timing flag and light gate system are used to obtain the velocity of the rod just before impact. An antirebound lever is used to prevent multiple impacts to the test specimen.

The test specimens were clamped at both ends with the sides free in all tests. The specimen holding jig is illustrated in Fig. 3. Each specimen is held firmly between the aluminum blocks by eight bolts torqued to 10 N · m. Sandpaper of 80 grit roughness is glued to the blocks to help prevent slippage of the specimen during the impact test. All impacts occurred at the specimen center.

All tests were conducted with the 1.53-kg mass. Force data were taken by a Macintosh IIx computer at a frequency of 50 kHz. Preliminary tests showed this was sufficient to capture the necessary information. The raw force data were modified to account for the fact that the force at the transducer location is different from the force at the tip of the tup where the specimen is contacted due to the dynamic nature of the event. Newton's law is applied to a free body diagram of the impactor rod system to account for the difference. Given the masses of the tup, force transducer, and rod, it is found that the force at the end of the tup is approximately 4% larger than the force measured by the force transducer.

Damage Evaluation

Three methods were used for damage evaluation: visual inspection, x rays, and deply. After impact, all specimens were visually inspected and the graphite/epoxy specimens were also x-rayed with the aid of dye penetrant that is opaque to x rays. Dye penetrant was injected into the damage area via a syringe placed in a 0.74-mm-diam hole that was drilled at the center of the impacted specimen. A piece of flash tape was placed on the back surface to contain the dye penetrant. The dye did not penetrate well into the damaged glass/epoxy specimens. Thus, these specimens were not x-rayed but were visually inspected using backlighting. This is possible due to the translucent characteristic of the glass/epoxy.

Subsequent to the nondestructive evaluation, specimens were deplied via a process in which the epoxy portion of the composite is burned off in an oven leaving behind the fibers and traces of an enhancing agent.[16] In this case, gold chloride, in a solution of

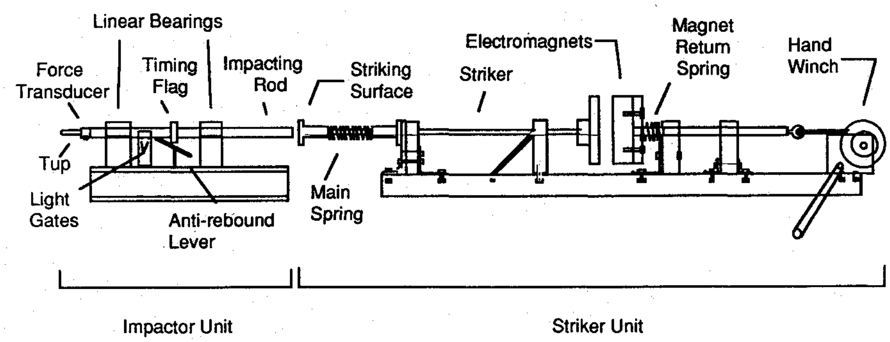

Fig. 2 Impact testing machine.

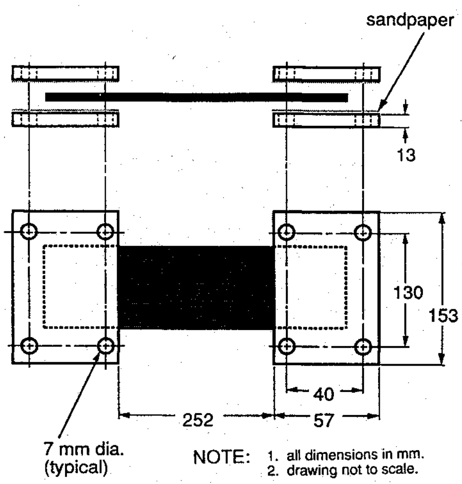

Fig. 3 Specimen holding jig.

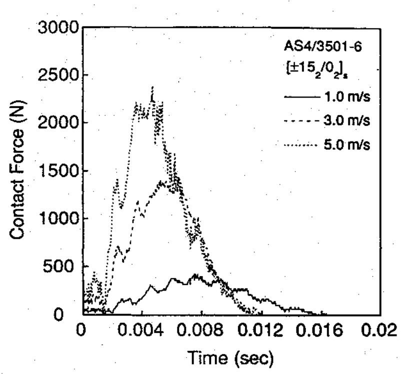

Fig. 4 Force–time signatures of AS4/3501-6 $[\pm15_2/0_2]_s$ laminate impacted at 1.0 m/s (undamaged), 3.0 m/s, and 5.0 m/s (penetrated).

isopropyl alcohol, was first injected into the specimen. This leaves a residue after the burnoff process that clearly outlines the edges of the delamination at each interface. Once again, the solution did not properly flow in the glass/epoxy specimens, and no information concerning delamination was obtained for the glass/epoxy specimens. Sketches of the damage as observed were made for each ply. Only interfaces where the fiber angle changed were separable by this technique, as expected.

Results and Discussion

Force–Time Signatures

A typical force–time response is shown in Fig. 4. It can be seen that as the impactor velocity increases, the basic shape of the force–time signature does not change. However, the maximum contact force increases, whereas the duration of the impact decreases. A number of authors[12,13,17,18] have indicated that the maximum contact force is an important parameter in considering impact damage resistance. Thus, it is important to look at this value.

The peak contact force vs impactor velocity is plotted for the AS4/3501-6 laminates in Fig. 5 and for their IM7G/X8553-50 counterparts in Fig. 6. It can be seen that this peak force increases nearly linearly with impactor velocity. This does not hold true for the highest velocities in the case of the AS4/3501-6 laminate, but this is due to specimen penetration as later discussed. Furthermore, comparison between the two material systems shows that the peak contact force is not affected by the material system in these cases. This is reinforced in Fig. 7 where the force–time signature is nearly exactly the same for the $[\pm45_2/0_2]_s$ laminates made from the two material

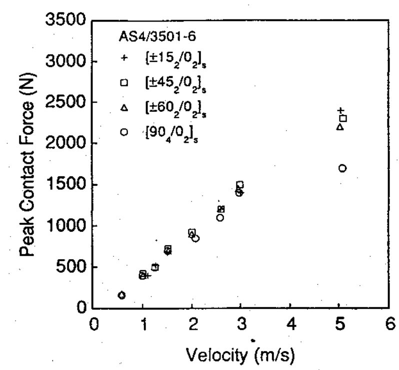

Fig. 5 Peak force vs impact velocity for 12-ply AS4/3501-6 laminates.

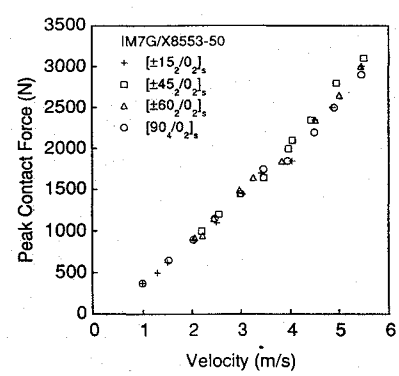

Fig. 6 Peak force vs impact velocity for 12-ply IM7G /X8553-50 laminates.

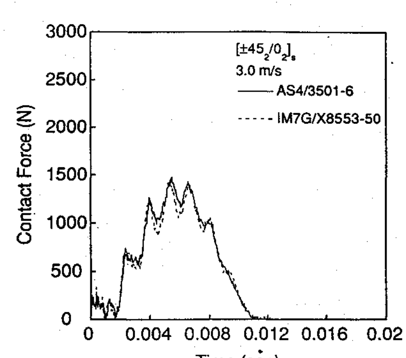

Fig. 7 Force–time signatures of AS4/3501-6 and IM7G/X8553-50 $[\pm45_2/0_2]_s$ laminates impacted at 3.0 m/s.

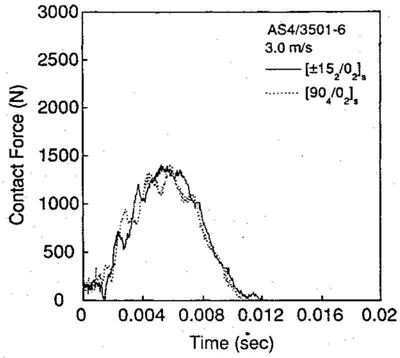

Fig. 8 Force–time signatures of AS4/3501-6 $[\pm15_2/0_2]_s$ and $[90_4/0_2]_s$ laminates impacted at 3.0 m/s.

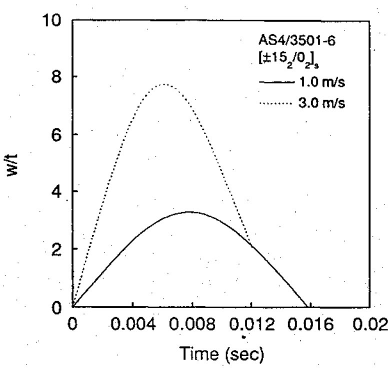

Fig. 9 Derived center deflection curves (normalized by thickness) for AS4/3501-6 $[\pm15_2/0_2]_s$ laminates impacted at 1.0 and 3.0 m/s.

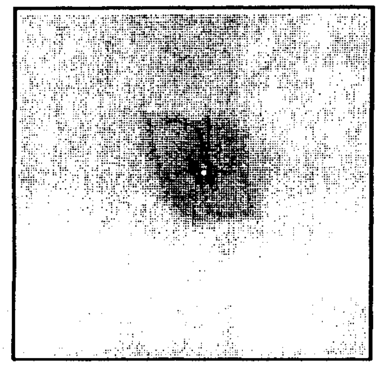

Fig. 10 X-ray photograph of AS4/3501-6 $[\pm45_2/0_s]_s$ laminate impacted at 3.0 m/s.

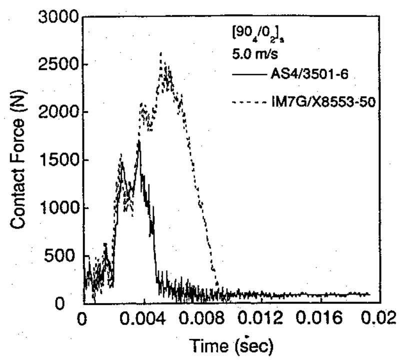

Fig. 11 Force–time signatures of AS4/3501-6 and IM7G/X8553-50 $[90_4/0_2]_s$ laminates impacted at 5.0 m/s.

systems. These results are not surprising since the major difference between these two systems is in their strain-to-failure, not their stiffness properties, which govern the force–time response.

However, the data in Figs. 5 and 6 also show the rather surprising result that the lamination angle does not affect the peak contact force. Similar plots for the impact duration would also show relative insensitivity to the lamination angle. This is more closely examined for the two extremes of this laminate sequence, $[\pm15_2/0_2]_s$ and $[90_4/0_2]_s$, in Fig. 8. This does show some difference in the force–time signature, but despite the fact that the bending stiffness parameter along the span (D_{11}) varies by a factor of 8 between these two laminates, the maximum contact force is virtually unchanged. Even in the case of the fabric laminates, where there is a factor of 7 reduction in all of the stiffnesses between the glass/epoxy and graphite/epoxy laminates, the peak contact force for the same impact conditions differs by no more than 25%.

It is suggested that the importance of nonlinear membrane effects in these tests is an important contributor to the results noted.[19] Double integration of the force–time histories results in a time history of the center deflection.[20] A typical result is shown in Fig. 9 with the center deflection normalized by the specimen thickness. For all of the cases encountered, the center deflection is one to several times the laminate thickness, indicating the importance of nonlinear effects in the response.

Some authors[12] have utilized the force–time history to determine the incipience of damage via a dropoff in the force. Other authors[13] have indicated that it is not possible to determine the occurrence of first damage. The current results clearly show that it is not possible to determine damage incipience from the impact force–time history. For example, the force–time responses for three different impact velocities of the AS4/3501-6 $[\pm15_2/0_2]_s$ laminate shown in Fig. 4 are nearly identical. However, for the lowest velocity of 1.0 m/s, no damage occurs, whereas the higher velocity of 3.0 m/s results in matrix cracking and delamination (see Fig. 12). Penetration occurs at the highest velocity of 5.0 m/s. This inability to detect damage incipience from the force–time history is better illustrated in Fig. 7 where the force–time histories for the $[\pm45_2/0_2]_s$ laminates of the AS4/3501-6 and IM7G/X8553-50 material systems are shown. The former material shows substantial damage, again in the form of matrix cracks and delamination as seen in Fig. 10, whereas the latter shows no damage. Nevertheless, the force–time histories are virtually identical, indicating that damage incipience cannot be determined for the AS4/3501-6 case from this plot. However, penetration of a specimen is clearly indicated in the response by a sharp drop in load as shown in Fig. 11 for the $[90_4/0_2]_s$ laminate configuration of the same two materials. The AS4/3501-6 laminate is penetrated, whereas the IM7G/X8553-50 laminate is not.

Damage Characteristics

Matrix cracking was the incipient damage mode in the 12-ply tape laminates of both the AS4/3501-6 and IM7G/X8553-50 material systems. This was followed by delamination, as shown in Fig. 12 for the AS4/3501-6 $[\pm15_2/0_2]_s$ laminate and in Fig. 13 for the IM7G/X8553-50 version of the same laminate. Deplying shows that the initial damage occurred on the backside of the laminate and that the delamination occurred at the interface with the cracked ply and was bounded by the fiber angles of the two adjacent plies. This can be seen in the deply transcription for the AS4/3501-6 laminate in Fig. 14. This "bounding" of the delamination has been observed by previous authors.[21] The location of the initial damage and the greatest amount of damage towards the backside of the laminate can be attributed to the dominance of the tensile stress field there due to bending and membrane effects. Cantwell and Morton[10] have shown that the thickness plays an important role in the location of the damage. They found that thicker laminates damage on the impacted surface due to the dominance of contact stresses, whereas thinner laminates damage away from the impact surface due to bending and stretching effects. All of the laminates investigated herein fit into the latter category.

As the lamination angle changed, the basic damage mechanisms did not change, although the overall footprint of the damage changed significantly. This can be seen by comparing the damage in the AS4/3501-6 $[90_4/0_2]_s$ laminate shown in Fig. 15 with that for the $[\pm15_2/0_2]_s$ laminate shown in Fig. 12. Once again, a matrix crack in the θ ply is the initial damage followed by delamination at this ply interface. In the case of the $[90_4/0_2]_s$ laminate, the delamination that develops is much wider since the bounding 0-deg ply has a much greater angle difference from the 90-deg ply than in the case of the

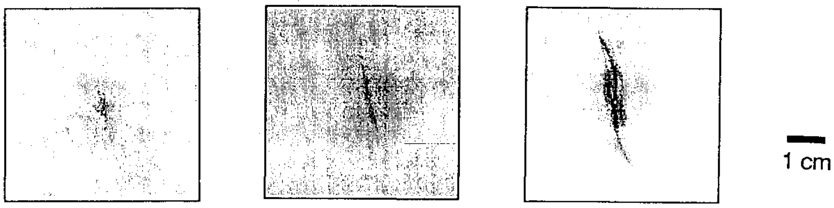

Fig. 12 X-ray photographs of AS4/3501-6 [$\pm 15_2/0_2$]$_s$ specimens for impact velocities of 1.1 m/s (incipient level) (left), 1.3 m/s (center), and 3.0 m/s (right).

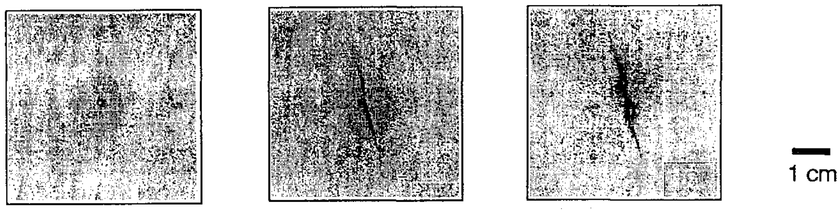

Fig. 13 X-ray photographs of IM7G/X8553-50 [$\pm 15_2/0_2$]$_s$ specimens for impact velocities of 1.5 m/s (incipient level) (left), 4.0 m/s (center), and 5.0 m/s (right).

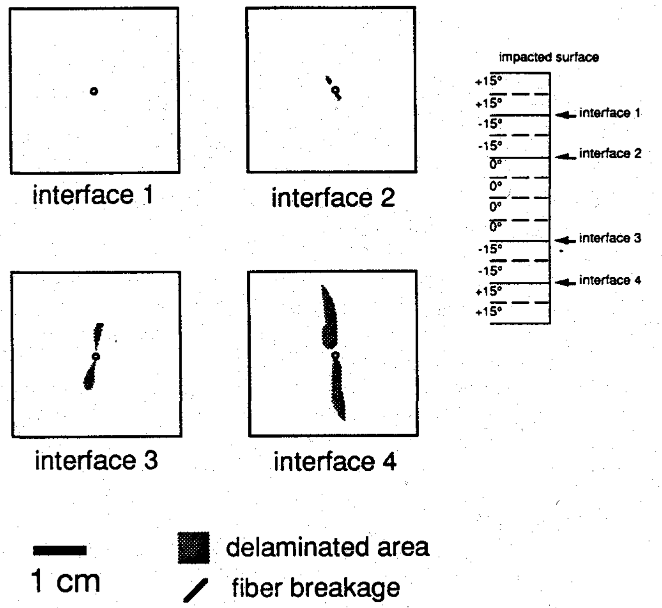

Fig. 14 Deply transcription of AS4/3501-6 [$\pm 15_2/0_2$]$_s$ specimen impacted at 3.0 m/s.

[$\pm 15_2/0_2$]$_s$ laminate. This is clearly seen in the deply transcription of Fig. 16.

It is clear that the change in matrix material, from a brittle to a tough system, did not generally affect the damage modes that occur. However, the material did have a significant effect on the incipient damage velocity and resultant force, as well as on the amount of damage that occurs at a similar velocity. A direct comparison of the damage in the two material systems for the same impact condition can be made for the case of the [$\pm 45_2/0_2$]$_s$ laminate in Fig. 17 where there is substantial damage in the AS4/3501-6 version but virtually none for the IM7G/X8553-50 case. A comparison across all laminates can be made by considering the velocity and resulting force at which incipient damage occurs as reported in Table 3. This is directly possible since the force history was independent of the material system. Thus, differences in damage must be attributable to the material properties and not the structural response. In all cases, the IM7G/X8553-50 damages less or requires a higher velocity and force to damage. This can be directly attributed to the higher matrix tensile strain-to-failure of the IM7G/X8553-50 system (1.0 vs 0.5% for AS4/3501-6) since matrix cracking and delamination are matrix modes of failure.

There was one case where the change in material system did affect the type of damage that occurred. In the case of the AS4/3501-6 laminates, fiber damage never occurred before laminate penetration (defined as fiber damage in all of the plies), which was achieved for all laminates. It was not possible to penetrate any of the IM7G/X8553-50 laminates at the velocities utilized, but fiber damage was observed in some cases at the higher velocities/contact forces. This was particularly true when there was less delamination in the laminate, such as for the [$\pm 15_2/0_2$]$_s$ configuration. This observation is discussed later.

The quasi-isotropic tape laminates were more easily damaged than the quasi-isotropic fabric counterpart as indicated by the incipient damage levels in Table 3. This is attributed to the ability of the fabric to inhibit the formation of long matrix cracks due to its woven nature. The tape laminates continued to show matrix cracking followed by delamination as the damage modes, whereas the damage in the fabric laminate was not easily defined. This makes it hard to directly compare fabric and tape laminates due to the different damage modes that occur[12] and actually makes it difficult to define incipience in fabric laminates since a predominant matrix crack does not form.

The quasi-isotropic tape laminate with effective plies of double thickness, [$\pm 45_2/0_2/90_2$]$_s$, damaged at lower velocities/forces than that with plies of single thickness, [$(\pm 45)_2/(0/90)_2$]$_s$. This is a similar effect as reported by Flaggs and Kural[22] in that plies of larger effective thickness can crack at lower values of applied stress. In addition, the deply transcription of Fig. 18 shows that the former laminate, which has fewer interfaces between plies of different fiber orientation, has larger delaminations at these interfaces than the latter laminate, which has approximately twice the number of interfaces. It is postulated that the formation of delamination is a way in which a laminate absorbs energy during impact. Therefore, the total delaminated area, summed over all of the interfaces, should be about the same given that the two laminates are approximately the same in other respects. The deply transcription of Fig. 18 indicates that this appears to be the case.

This "energy-absorbing" hypothesis can be extended to consider a tradeoff between delamination damage and fiber damage. Previous authors[5,23] have indicated that since the formation of delamination absorbs energy, it is probable that laminates that delaminate less are more likely to find other ways to dissipate energy, such as in the breaking of fibers. This was indicated in the current work both by the IM7G/X8553-50 laminates and the fabric laminates. In these cases, particularly the fabric laminates, delamination was restricted, and fiber damage occurred even without penetration of the laminate.

Finally, the damage behavior of all of the glass/epoxy laminates was very similar regardless of layup. Because of the difficulties encountered using x-ray and deply techniques with this material, it is difficult to determine the incipient damage mode. The damage generally appeared to be localized matrix cracking with some delamination followed by some fiber breakage. The illustration of the

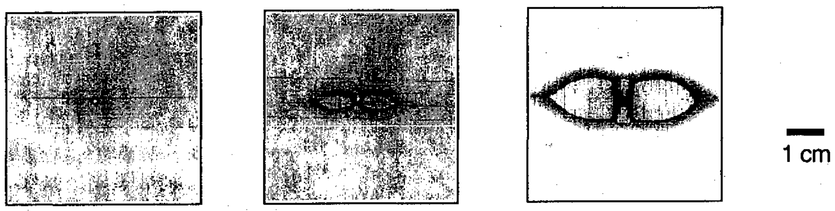

Fig. 15 X-ray photographs of AS4/3501-6 $[90_4/0_2]_s$ specimens for impact velocities of 0.9 m/s (incipient level) (left), 2.0 m/s (center), and 3.0 m/s (right).

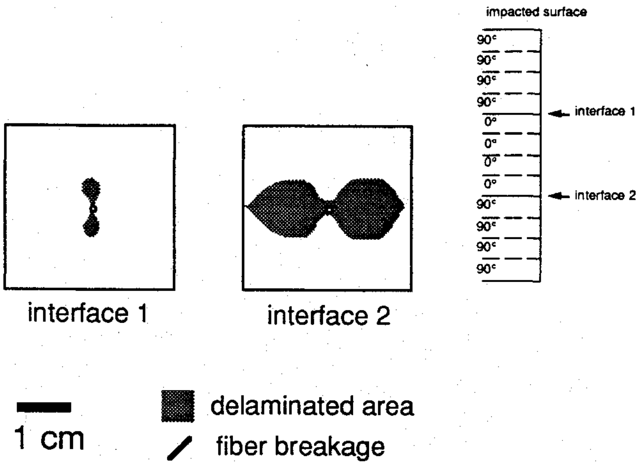

Fig. 16 Deply transcription of AS4/3501-6 $[90_4/0_2]_s$ specimen impacted at 3.0 m/s.

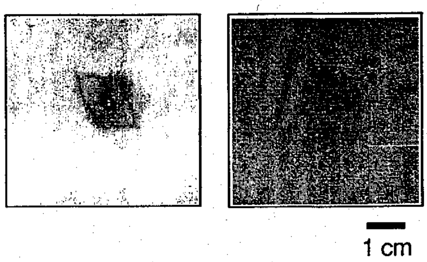

Fig. 17 X-ray photographs of AS4/3501-6 (left) and IM7G/X8553-50 (right) $[\pm 45_2/0_2]_s$ laminates impacted at 3.0 m/s.

Table 3 Damage velocity[a] (and force)[b] to cause incipient damage

	Material system			
Laminate[c]	AS4/ 3501-6	IM7G/ X8553-50	A370-5H/ 3501-6S	Glass/ epoxy
$[\pm 15_2/0_2]_s$	1.1(400)	1.3(500)	—	—
$[\pm 45_2/0_2]_s$	1.2(450)	2.2(1000)	—	—
$[\pm 60_2/0_2]_s$	0.9(275)	2.2(950)	—	—
$[90_4/0_2]_s$	0.9(300)	1.5(650)	—	—
$[\pm 45_2/0_2/90_2]_s$	2.1(1000)	—	—	—
$[(\pm 45)_2/(0/90)_2]_s$	3.0(1550)	—	—	—
$(45_2/0_2)_s$	—	—	4.1(2400)	1.5(600)
$(90_2/0_2)_s$	—	—	—	1.5(600)
$(0_2/45_2)_s$	—	—	—	1.5(550)
$(45/0)_{2s}$	—	—	—	1.5(550)
$(0/45)_{2s}$	—	—	—	1.5(550)

[a]Velocity in m/s.
[b]Units of force value contained in parentheses are N.
[c]Parentheses indicate a fabric layup; brackets indicate a tape layup.

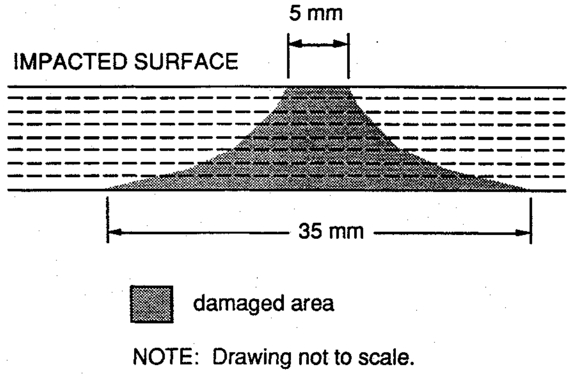

Fig. 19 Illustration of cross section of glass/epoxy $(45/0)_{2s}$ specimen impacted at 5.0 m/s.

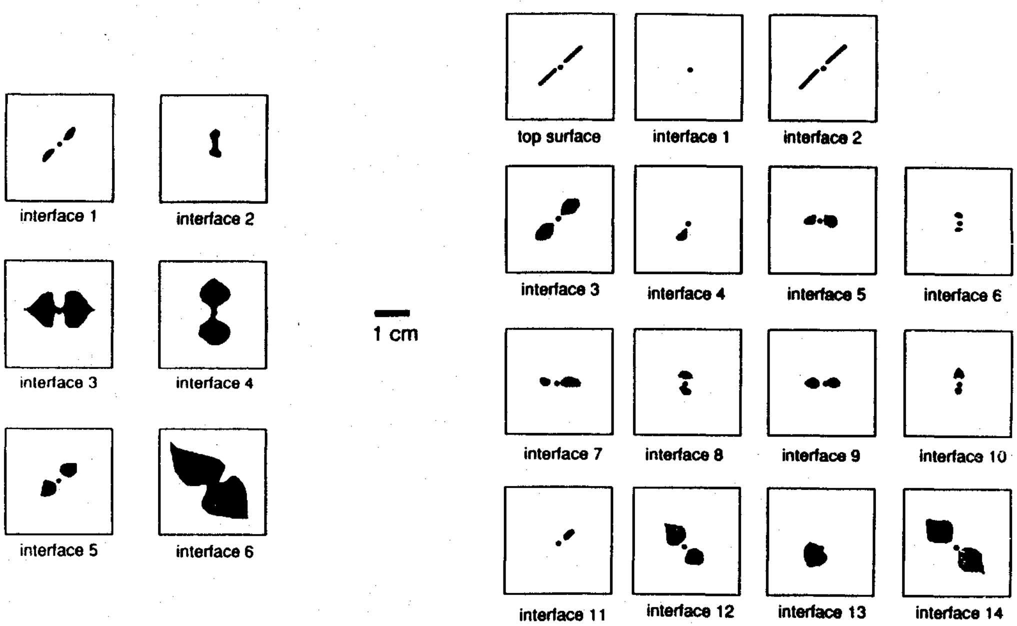

Fig. 18 Deply transcriptions of AS4/3501-6 $[\pm 45_2/0_2/90_2]_s$ (left) and $[(\pm 45)_2/(0/90)_2]_s$ (right) laminates impacted at 5.0 m/s.

cross section of an impacted glass/epoxy specimen in Fig. 19 shows an increasing area of damage through the thickness away from the point of impact. The results do clearly show that the glass/epoxy fabric system damaged at significantly lower velocities, and resultant forces, than the graphite/epoxy fabric system.

Implications

A clear result of the current work is the affirmation that contact force is a key parameter in assessing impact damage resistance. The force necessary to cause incipient damage is a figure of merit by which various laminate configurations and material systems can be evaluated as shown in Fig. 20. Although the current work shows that the point of damage incipience cannot be determined from the force–time history, other techniques can be utilized to determine the force level.

It, however, becomes more difficult to make comparisons beyond damage incipience. The force needed to cause penetration could be used as another figure of merit as shown in Fig. 21. However, it is difficult to make comparisons between these two extremes since the damage type can differ from case to case. Previous work has shown that the two-dimensional footprint of the damage (integrated through the thickness) is not a sufficiently representative parameter and three-dimensional mapping is needed.[5,24]

Any test developed for damage resistance will need to consider the structural configuration. Damage resistance is both a structural and material response. For example, the laminates in the current work showed that membrane effects were important in the response, and this resulted in damage on the backside of the laminates. Previous work[10] has indicated that other geometrical configurations can result in damage to the impact side of the laminate. In the current work, the fact that the same structural configuration was maintained throughout the tests made it possible to compare the various configurations and material systems. Nevertheless, the use of force as an important damage resistance parameter would likely be limited to a comparative assessment.

This is reinforced by the observation that final ranking really depends on the damage tolerance needs.[12] This ranking will therefore depend on the loading and structural configurations. For example,

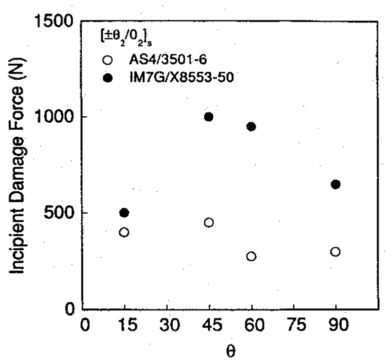

Fig. 20 Incipient damage force vs layup angle for 12-ply laminates of AS4/3501-6 and IM7G/X8553-50.

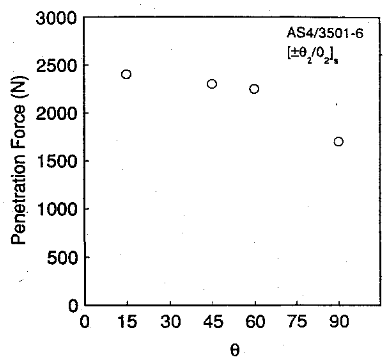

Fig. 21 Penetration force vs layup angle for 12-ply laminates of AS4/3501-6.

the current work indicates that due to energy-absorbing considerations there may be a tradeoff between damage in the form of delamination and in the form of fiber breaks. Although a large area of delamination is not desirable in a structural application subjected to predominantly compressive loads, such delaminations have little effect on tensile strength[25] and would probably be more desirable than fiber breakage for tensile applications.

A final implication concerns the need to include the progressive development of damage in models to predict the impact response and final damage state due to an impact event. The current results clearly show that the presence of damage does not influence the global structural response in terms of the force–time signature. No change in this behavior is seen until penetration of the specimen occurs. Therefore, it is unnecessary to include the effects of damage in determining the global response. However, it is likely that the damage will affect the local response, in terms of the contact behavior and the local stress field, and would need to be considered for this assessment.

Summary

The impact damage resistance of several laminated material systems has been studied. Force–time histories from impacts of a 1.53-kg mass were measured and the resultant damage assessed by nondestructive and destructive techniques. The force–time histories did not change substantially for laminates of different bending stiffnesses, indicating the importance of geometric nonlinearities in this particular configuration. This emphasizes the point that damage resistance is a combined structural/material response. For a particular configuration, a comparative assessment of various materials and laminate configurations can then be made.

The results show that force is an important parameter in characterizing damage resistance. The contact force necessary to cause incipient damage is recommended as a damage resistance parameter and is used to compare the different material systems and laminates tested. The tougher IM7G/X8553-50 material system is more impact damage resistant than the brittle AS4/3501-6 material for all laminates considered. However, it is difficult to compare these configurations to those made from fabric since the damage modes that occur differ. The tape laminates have damage incipience in the form of a predominant matrix crack. This is followed by a delamination at the neighboring ply interface. Fabric, by its woven nature, inhibits the formation of a dominant matrix crack, and thus incipience is in the form of a region of damage of fine cracks. Little delamination occurs, but eventually fiber breaks do occur at higher impact velocities unlike most of the tape cases. This is attributed to the need to dissipate energy via other fracture modes than delamination.

Although force can be used as a characterizing parameter for impact damage resistance, attention must be paid to the final use of the part in this assessment since different types of damage will have different ramifications in terms of damage tolerance and structural performance. There is, therefore, still a need to better understand the general three-dimensional damage state that occurs in composite structures subjected to impact. Standard metrics need to be developed to allow quantitative comparisons of damage states in different laminates. This will allow a true assessment of impact damage resistance. Until that goal is achieved, the force necessary to cause incipient damage can be utilized as a comparative parameter.

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