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A Comparative Study on the Impact Resistance of Composite Laminates and Sandwich Panels

ROCCO FERRI AND BHAVANI V. SANKAR*
Department of Aerospace Engineering
Mechanics and Engineering Science
University of Florida
Gainesville, FL 32611

ABSTRACT: An experimental study was conducted to compare the damage resistance and energy-absorbing capabilities of graphite/bismaleimide composite laminates and foam-core sandwich panels. Two types of tests were conducted: static indentation and drop weight impact. The load-displacement response and energy absorbed were recorded for quasi-static and impact tests. The amount of core compression in sandwich panels was also measured. Damage in the laminates and sandwich panels was assessed by using ultrasonic C-scan, X-radiography, and photo-micrography. The load-displacement responses and damage area obtained from quasi-static and impact testing matched very well for the laminates. The quasi-static and impact responses for the sandwich panels have the same overall trend but differ due to the viscoelastic properties of the foam core. Test results show that the sandwich panels can absorb more energy than the laminates and undergo less deflection to absorb the same maximum energy as the laminates. Impact energy above a statically determined threshold level has been shown to cause extensive foam core damage.

INTRODUCTION

THERE EXISTS A need for lightweight materials with high flexural stiffness for use in aircraft and aerospace structures and also in vehicles for ground and marine transportation. To meet this need, sandwich panel construction is most often used. Sandwich construction generally consists of three types of materials bonded together. The outermost laminations are called *face sheets*, and the inner lamination is called the *core*. The face sheets act very much like the flanges of an I-beam by taking the bending loads. The core material acts like the web of the I-beam by resisting shear loads and increases the stiffness of the structure by spreading the face sheets apart. The core also gives continuous support to the face sheets because the adhesive layer rigidly joins the component parts together

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*Author to whom correspondence should be addressed.

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into a single structure. A major concern when utilizing sandwich construction is the effect of low-velocity impact. Although metallic face sheets have been used in the past, current emphasis is on the use of fiber-reinforced composite laminates. A considerable amount of research has been done on the impact resistance of laminated composites rather than sandwich composites. Experimental and analytical studies have confirmed that static indentation tests provide useful information about the failure mechanisms and failure loads for large mass impactors at low velocities [1–4]. The major damage modes in composite laminates that occur from an impact are matrix cracking, fiber fracture, and extensive delaminations. In the case of impact on a sandwich structure, not only are the face sheets damaged, but there is an additional capability for energy absorption by the core. Therefore, damage to the face sheets, the core, and the face sheet/core interaction needs to be studied. The effects of core stiffness and loading configuration on the impact resistance were investigated by Rhodes [5] and Oplinger and Slepetz [6]. Other authors [7,8] have studied the damage modes in the face sheets and the core and the interaction between them. In most previous studies, honeycomb core material was used rather than foam. The modes of failure for these two core types are quite different. Computational and experimental methods were used by Nemes and Simmonds [9] to investigate the impact response of foam-core sandwich panels.

APPROACH

Sandwich construction is being considered for use in many structural components. In this paper, we will determine whether it is advantageous to use a sandwich construction rather than a laminated composite. The impact damage resistance will be compared for both material types. A sandwich panel can be considered to be a symmetric laminated composite plate that has been split into two sub-laminates, which are then bonded to a foam core. Both material types have essentially the same in-plane stiffness. Static indentation tests were performed on composite laminates and sandwich panels in order to gain a better understanding of damage initiation and progression in plates of different sizes. If the impact mass is much greater than that of the plate, and also if the impact velocity is low, then a static test gives essentially the same results as a low-velocity impact test and can help explain the complex damage mechanisms that occur during impact [10]. Low-velocity impact tests were also performed in order to compare the response and damage with corresponding behavior under static loading.

For this study an instrumented drop weight impact test facility was designed and built by the first author. The laminate and sandwich panel face sheet material used is Hexcel F6V613-F650 graphite/bismaleimide prepreg fabric. The core material used is Divinylcell H60 (60 kg/m^3) crosslinked PVC foam. Two specimen types were originally used for this study: 8-ply laminate and sandwich panels, each 250 mm × 250 mm. The effects of plate dimension and thickness were later introduced. Eight- and four-ply laminates of dimension 125 mm × 125 mm were also tested. Damage in laminates and sandwich panels was assessed using ultrasonic C-scan, X-radiography, and photo-micrography.

Damaged specimens were X-rayed with the aid of a zinc iodide enhancement fluid. Detailed descriptions of specimen fabrication, experimental procedures, and damage evaluation are given in Reference [11].

METHODS

Specimen Fabrication

Graphite/bismaleimide laminates and sandwich panel face sheets were fabricated from 305-mm-square prepreg fabric. The fabric consists of T300 carbon-fiber tows woven into a five-harness-satin (5HS) weave impregnated with F650 matrix material. Each laminate was laid-up by hand, placed into a vacuum bag, and cured in an autoclave. The rough edges of the laminates were trimmed using a water-cooled diamond grit cutting wheel. The 8-ply and 4-ply laminates have a cured thickness of 2.65 mm and 1.43 mm respectively. Sandwich panel fabrication consists of three main steps: face sheet construction, sandwich panel assembly, and final specimen preparation. The thickness of the foam core was 16 mm. The face sheets are bonded to the core using the two-part adhesive Henkel UK-8103A-B.

Quasi-Static Tests

Quasi-static indentation tests were performed on a Tinius-Olsen 12,000-lb capacity loading machine. Laminates and sandwich panels were simply supported on all edges, as shown in Figure 1. Specimens were centrally loaded with a 25.4-mm-diameter stainless steel indenter. Two specimen support frames were used: 240 mm and 115 mm square. The tests were conducted at a displacement rate of 0.02 mm/s (0.05 in/min) until specimen failure. A linear variable differential transformer (LVDT) was used to measure the actual indenter displacement, eliminating the possibilities of compliance in the loading machine. Another LVDT was used to measure the bottom center displacement of the specimen. The difference between the indenter and bottom displacement yields the indentation or core compression. The load and two LVDT data were acquired at a rate of 2 Hz by a Nicolet 4094 digital oscilloscope. The data was then transferred to a computer for processing.

Impact Tests

The drop weight impact facility, also shown in Figure 1, is a modified version of the one described by Winkel and Adams [12]. The cross-head has a mass of 7.62 kg and can be raised to a maximum drop height of 1.37 m (4.5 ft). The maximum obtainable impact velocity is about 5 m/s. Friction was minimized using chrome-plated steel guide rods and self-lubricating precision linear bearing. The impact force was measured using a piezoelectric force transducer (PCB Piezotronics, Inc., model 208A15) with a 44 kN load capacity. The impact and rebound times were measured by passing a 12.7-mm (0.5-inch) wide flag through an infrared photo-detector block. The specimen types and the indenter were the same

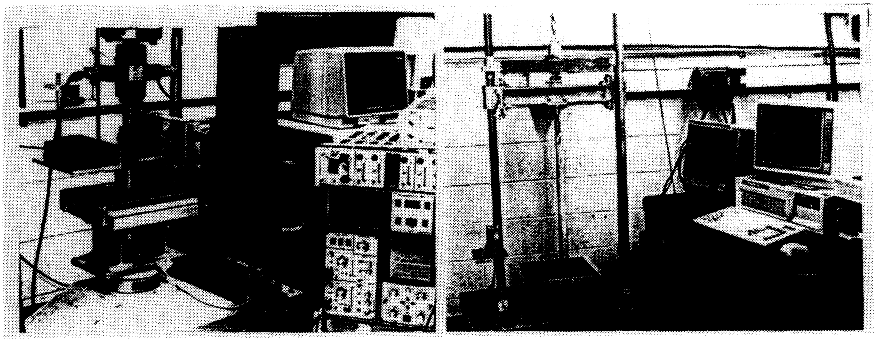

Figure 1. Static indentation setup (left); drop weight impact facility (right).

as used in static tests. Only the larger (240-mm-square) support frame was used for impact tests. The impact force and time signals were acquired at a rate of 50 kHz by a LeCroy 6810 Waveform Recorder and the instrument control software Waveform Catalyst. A computer program was written in ASYST to read both signals and then calculate impact and rebound velocities, force-time, force-displacement, and energy-time relations. The reduced data were written to a spreadsheet and then plotted.

RESULTS AND DISCUSSION

Laminate Results

A typical quasi-static load-displacement curve for an 8-ply laminate is shown in Figure 2. It may be noted that when the deflection exceeds the thickness of the laminate (about 3 mm), the nonlinearity in the load-deflection curve due to large deflection becomes pronounced. An early drop in load is apparent at approximately 1500 N for all 8-ply laminates tested. This could be due to matrix cracking or the formation of a small delamination in the contact region. As the load is increased, the plate deflection becomes much larger than the amount of indentation. Intermittent crackling noises, typical of matrix cracking, occur as the load is increased. When the load reaches a critical value, there is a large drop in load accompanied by a loud noise that indicates fiber failure. The interlaminar shear stresses in conjunction with flexural stresses are responsible for the initiation of delaminations and ultimate fiber failure [13]. The effect of plate size and thickness on the failure load is shown in Figure 3. The small load drop and the maximum load for the 8-ply 125-mm-square laminates are similar to 8-ply 250-mm-square laminates. The failure load of the 4-ply 125-mm-square laminates is approximately half that of 8-ply 250-mm-square laminates.

The initial portion of the quasi-static load-displacement response for the 8-ply 125-mm-square laminates is nearly linear. The reduced plate geometry and support conditions effectively make the laminate stiffer. The larger the unsupported

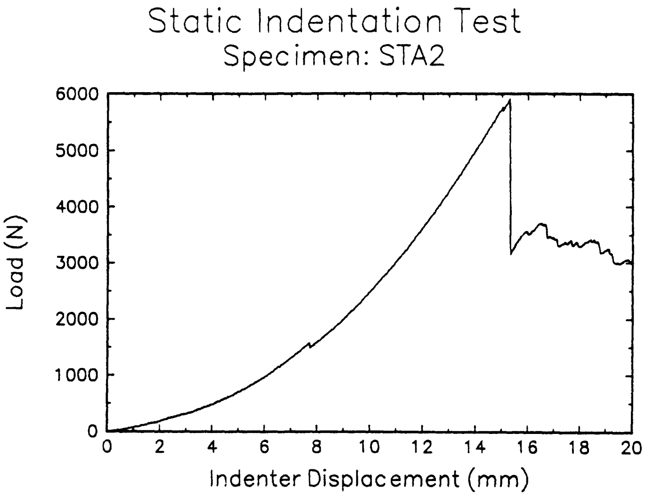

Figure 2. Static load-displacement response for an 8-ply 250-mm-square laminate.

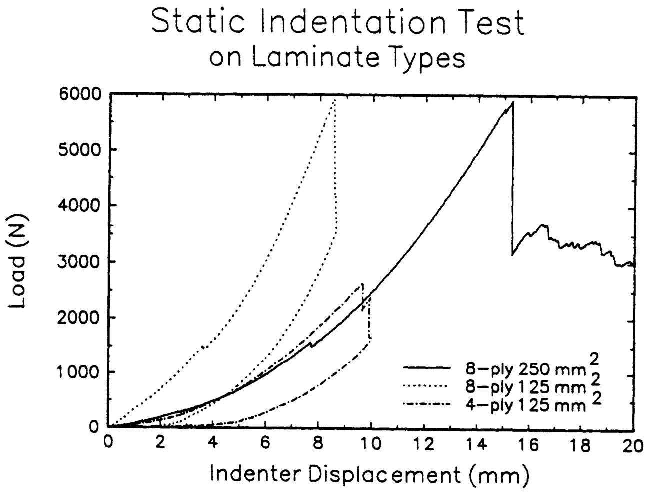

Figure 3. Static load-displacement comparison for all laminate types.

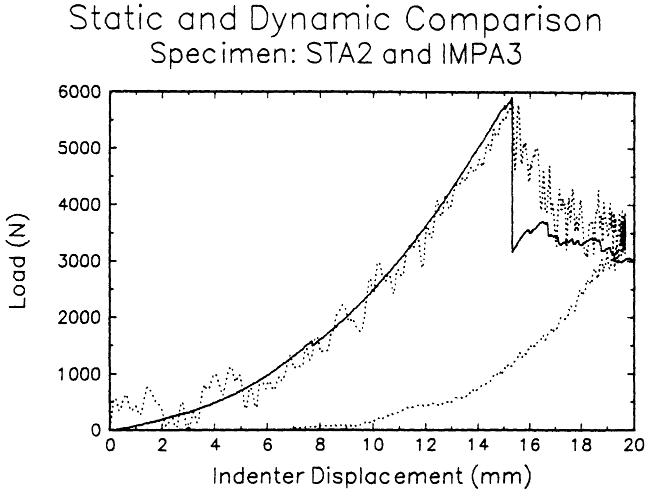

Figure 4. *Static and dynamic comparison for 8-ply 250-mm-square laminates.*

span becomes, the larger the flexural stresses. The average failure load and energy absorbed for each laminate type statically tested is as follows: 8-ply 250 mm square: 5640 N, 28.5 J; 8-ply 125 mm square: 5259 N, 18.9 J; and 4-ply 125 mm square: 2524 N, 8.3 J. A dynamic load-displacement response for an 8-ply specimen 250 mm square is compared with a corresponding static response in Figure 4. Impact rest results or 8-ply 250-mm-square laminates are presented in Table 1. The dynamic response of the impacted specimen matches the static response very well. With the exception of plate vibration, both responses are nonlinear, and failure occurs at approximately the same load and displacement.

Laminate Damage Evaluation

Since the load-displacement response is virtually the same as the dynamic response, the damage will also be the same if maximum force is used as a parameter. Ultrasonic C-scan results [11] show that the static and impact specimens have very similar damage areas. Visible damage on composite laminates included surface matrix cracks, separation of fiber tows, and fiber breakage. An X-radiograph of a cross-shaped damage pattern is shown in Figure 5. Within the darker area of

Table 1. Impact test results for type A laminates.

Specimen I.D.	Impact Velocity (m/s)	Impact Force (N)	Energy Absorbed (J)
IMPA2	2.83	5970	9.12
IMPA3	3.50	5902	35.3
IMPA4	4.10	6744	38.5 (failure)

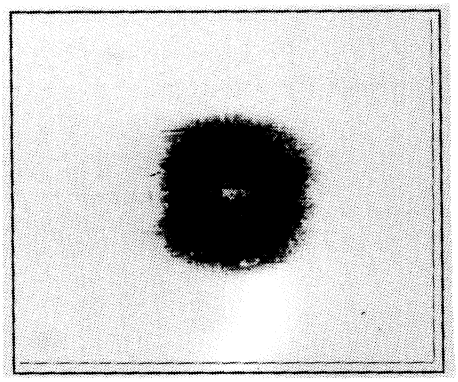

Figure 5. Specimen: IMPA3. X-ray of typical cross-shaped damage pattern.

the X-radiograph, there commonly exist matrix cracks and fiber-tow breakage. Within the lighter areas, the damage is mainly separation of fiber tows. The damage pattern on all laminates tested initiates with the rupture of warp or fill fibers on the back surface of the laminate. The fiber damage continues to propagate along the boundaries of adjacent tows rupturing fibers in the warp or fill directions. This process may explain the subsequent increase in load after the initial large load drop. However, after a small increase in load, the damage continues to grow in an unstable manner and the load starts dropping continuously until penetration occurs.

Sandwich Panel Results

A typical quasi-static load-displacement curve for a sandwich panel is shown in Figure 6. The entire load-displacement curve can be broken down into three regions. In the first region, air expressed by core compression causes the initial load-displacement response to be nonlinear. The load then increases linearly up to top face-sheet failure. The load at which face sheet failure occurs is on average 25% higher than 4-ply 125-mm^2 laminates tested. The increase in the failure load is due to the support that the core provides to the face sheets. The core compression is also shown in the same figure. The core is compressed an average of 3.6 mm before face sheet failure occurs. The average static load and energy absorbed for top face-sheet failure is 3385 N and 11.3 J respectively. The modes of failure within the second region are primarily increased face-sheet fiber damage and core compression. Rupturing fiber tows in the warp and fill directions and the inability of the core to support the applied load causes the load to steadily decrease while increasing the core compression. In the third region, the indenter begins loading the bottom face sheet and causes the load to increase linearly. The stiffness is initially very similar to the stiffness observed in region 1, but a small drop in load causes the stiffness to change. This small drop in load is due to core failure. The average load drop is 124 N and was observed in all panels statically

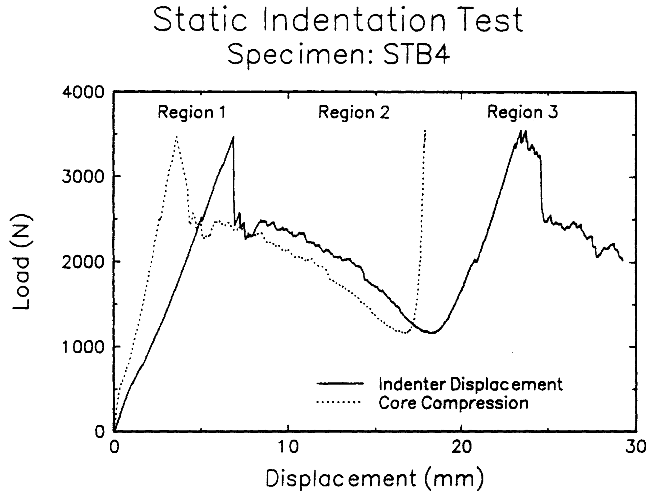

Figure 6. Static load-displacement and core compression for a sandwich panel.

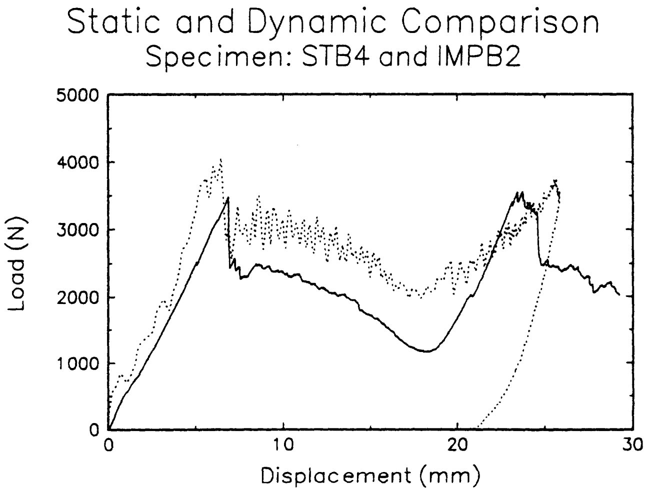

Figure 7. Static and dynamic comparison for sandwich panels.

tested. The average load and energy required to cause this drop in load are 2114 N and 38.7 J respectively. The load continues to increase until the bottom face-sheet fails. The bottom face-sheet in statically indented panels has an average failure load of 3693 N, which is approximately 8% higher than the top face-sheet failure load. The total average energy absorbed by the sandwich panel from a quasi-static test is approximately 48 J. A dynamic load-displacement response of a sandwich panel is compared to a corresponding quasi-static response in Figure 7. Results of sandwich panel impact testing are presented in Table 2. Although the overall trend is the same, the loading rate appears to have an effect on the behavior of the sandwich panel. The viscoelastic properties of the core increase the apparent stiffness in region 1 and the overall load-carrying capability of the panel under impact loading. The difference in stiffness in region 3 is primarily due to core failure in specimen IMPB2.

Sandwich Panel Damage Evaluation

Foam core failure was expected to cause a loss in stiffness in quasi-static and dynamic tests. Ultrasonic C-scan, operating in a pulse/echo mode, was able to detect damage only at the face-sheet/core interface. Operating in a through-transmission mode might have detected areas of severe core damage through the thickness of the panel. To assess the amount of core damage, several sandwich panels were sectioned and visually inspected. Photographs of sectioned panels are shown in Figure 8. The effect of flexure from a static or dynamic test adds a compressive stress above the midplane and a tensile stress below the midplane of the sandwich panel. Compressive stresses above the midplane compress the core and do not allow the propagation of delaminations in the top face sheet. The failure mechanisms involved with top face-sheet failure are similar to other laminates tested where fiber damage occurs along the boundaries of adjacent fiber tows. Visual inspection and C-scan techniques did not detect damage in the bottom face-sheets on impacted sandwich panels. Top face-sheet deplying was extensive within the damage region. Below the midplane, the core is subjected to shear-induced tensile stresses on 45-degree planes (principal stresses). A stiff bottom face-sheet increases the magnitude of these stresses. The tensile stresses are responsible for initiating the cracks at 45-degree angles. Continued loading on the bottom face-sheet creates peeling stresses that cause the cracks to propagate parallel to the adhesive bond layer. The peeling stresses are also responsible for increasing the bottom face-sheet failure in statically indented panels. Failure

Table 2. Impact test results for type B sandwich panels.

Specimen I.D.	Impact Velocity (m/s)	Impact Force (N)	Energy Absorbed (J)
IMPB1	3.83	4152	53.5
IMPB2	4.12	4062	60.7
IMPB3	2.83	3355	28.7
IMPB4	3.53	3647	46.2

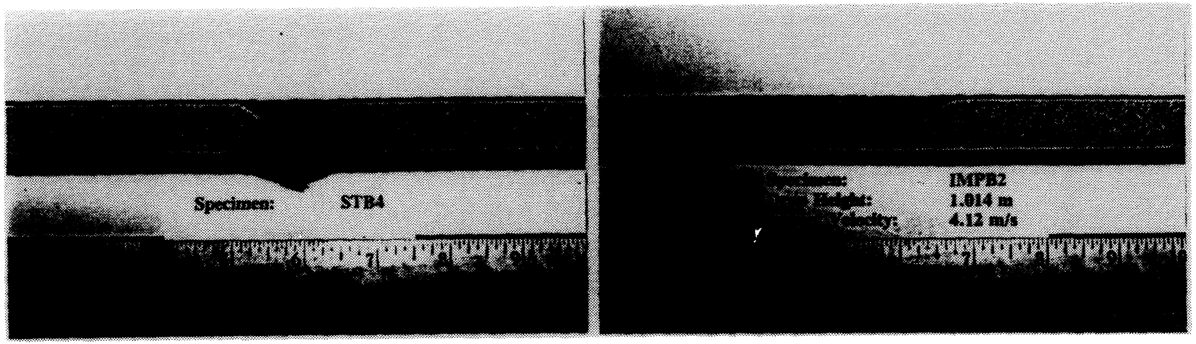

Figure 8. *Typical foam shear cracks and face sheet failure from a static test (left); extensive core failure from an impact test (right).*

of the adhesive bond layer was not observed in sectioned panels. Based on static test results and visual damage inspections, an average of 38.7 J was required to initiate shear cracks in the core. If this value is used as a threshold value, it can be compared to the impact test results in Table 2. Impact specimen IMPB3 absorbed 28.7 J of energy and is expected to have the least amount of core damage.

SUMMARY

The damage resistance and failure mechanisms of graphite/bismaleimide composite laminates and foam-core sandwich panels were investigated. Two types of tests were performed: quasi-static indentation and drop weight impact. The load-indentation, energy absorbed and damage patterns were compared for each material type. Results from quasi-static indentation tests on laminates show that the failure load is independent of the aerial dimensions of the laminate but is dependent upon the thickness of the laminate. The quasi-static response of 8-ply 250-mm-square laminates is nonlinear, and the center deflection is very large. Such large deflections may be unsuitable for many applications. Since the load-displacement response for 8-ply 250-mm-square laminates is virtually the same as the dynamic response, C-scan results [11] show that the damage areas are also the same. Based on this result, an analytical model can be used to predict the impact response of these laminates.

Results from sandwich panel testing show that the overall response is dependent upon the behavior of the face-sheets and the core. The core is compressed immediately after loading but provides support to the top face-sheet. The modes of failure in the top face-sheet are similar to other laminates tested. The quasi-static and impact responses for the sandwich panels have the same overall trend but differ due to the viscoelastic properties of the core. The increased loading rate appears to have an effect on the behavior of the sandwich panel. The extent of core failure was observed to be greater in impacted panels. Propagation of shear cracks was observed only in impacted panels. A core failure threshold value was determined from quasi-static tests. Impact energy levels above the threshold caused shear cracks to propagate parallel to the adhesive bond layer. There was no evidence of damage in the bottom face-sheets on impacted panels. Energy absorbed by crack propagation prevented damage to the bottom face sheet. Test results show that the sandwich panels can absorb more energy than the laminates and undergo less deflection. Up to the initiation of core failure, the sandwich panel can absorb approximately 25% more energy than the 8-ply laminate. Other factors such as core thickness and density may increase the energy absorbed.

Only through proper design and fabrication can sandwich panels be used effectively rather than composite laminates in load-bearing structures. One important design consideration yet to be investigated is the impact damage tolerance. Extensive core failure should drastically reduce the damage tolerance. Further work, both experimental and analytical, will be done to understand the factors that affect the energy-absorbing capabilities of a sandwich panel. A model that predicts the impact response can also be used to determine the stresses throughout the panel so that a failure criterion can be applied to predict the onset of core failure.

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