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What is This?
Static and low-velocity impact on mechanical behaviors of foam sandwiched composites with different ply angles face sheets

Ramadan Mohmmed, Fa Zhang, Baozhong Sun and Bohong Gu

Abstract

The current studies give a brief account of analysis of static and low-velocity impact on foam sandwiched composites comprising composite faces from carbon/epoxy and cores from Rohacell (polymethacrylimide). The face sheets consist of four different stacking sequences as unidirectional, cross-ply, angle-ply and quasi-isotropic, which were fabricated by using hand lay-up process. Later, the composite panels were subjected to quasi-static and low-velocity impact loading using MTS and an instrumented Drop-Weight Machine (Instron 9250HV), respectively. The load-displacement curves have been obtained to characterize the failure mechanisms in the face sheets and the core. Impact parameters were evaluated and compared for different types of sandwich structures. Failure modes were studied by sectioning the samples at the impact location and observing under optical microscope. The results evaluated from static test have shown that the unidirectional have the highest peak load. However, the dynamic test data indicated that the foam sandwich with unidirectional face sheet have lowest peak load, lowest displacement at peak load and minimum energy absorption. It has also been observed that largest damage size, highest penetration depth and shear cracking have been experienced by unidirectional as compared to cross-ply, angle-ply and quasi-isotropic face sheets.

Keywords
Foam sandwiched composites, impact tests, penetration depth, cracking width, delamination

Introduction

Currently, composite structural materials have been widely used in various automobiles, locomotives, windmills and consumer industries due to their preferable properties such as stiffness to bending, low weight, thermal insulation, acoustic damping, ease of machining and molding. The properties of foam core sandwich composites depend on different face sheets, core materials and the core-facings interfaces. These structures comprise two major components i.e. skin (such as glass, or carbon fiber reinforced laminates) and the core (such as wood, honeycomb, corrugated structures; open and closed cell foams). The most commonly used sandwich structures are honeycombed and closed-cell. However, honeycomb sandwich constructions have certain disadvantages i.e. low surface area of the core for bonding, its sensitivity to hot and humid environments and high manufacturing and maintenance cost. On the contrary, closed-cell core materials are preferred due to their light weight, high stiffness, increased support surface for bonding with the face sheets, low thermal conductivity and an adjustable density. Another advantage is their overall formation by the resin film infusion (RFI), resin transfer mold (RTM) and vacuum assistant resin infusion (VARI) processes. By varying the core material such as its thickness and material of the face sheet of the sandwich structures, it is quite possible to achieve various properties and desired performance. When a composite was subjected to a low-velocity impact of sufficient energy, different damages have been observed.

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These damages were found to cause reduction in structural stiffness and strength, leading to growth of the subsequent damage and hence final fracture.9,10 The dynamic behaviors of sandwich structures, especially low-velocity impact behavior, have been source of diverse investigation since long time. Kim and Jun11 have observed the effects of face lay-up sequence (graphite/epoxy) and core density (Nomex honeycomb) of a sandwich plate on the impact delamination area of the laminated face sheets. It has been shown that higher density core and laminates of relatively small angular orientation between adjacent plies tend to be more damage-resistant than those of relatively larger angular orientation and small density core. Sun and Wu,12,13 Anderson et al.14 and Rizov et al.15 suggested experimental results for low-velocity indentation of sandwich panels and sandwich beams in related studies. Several failures modes (matrix cracking of the face sheets, skin/core debonding and core crushing) have been identified. The monitoring factors of these failures were found to be density of the core and facings structures. However, Cantwell et al.16 had shown that impact properties of polymeric foam sandwich structures and their dynamic response were dependent on the elastic properties of the core material. Lendze et al.17 suggested that in sandwich structures, it is the top skin that was found to suffer some damage (delamination) due to impact. Later, damage analyses performed on hybrid composite panels by Hosur et al.18 showed that nanoclay-infused foams had a smaller damage area than their neat counterparts. However, the average damage angle, penetration depth and maximal cracking width were found to be the main factors effecting the damage extent of foam core sandwich composites with various facings by Xia and Wu.19,20 As the susceptibility of sandwich structures to localized (impact) damage was one of the main reasons of its non-applicability in large primary aircraft structures of airliners. Investigation of the damage tolerance of representative composite sandwich panels has shown that the foam core material had a considerable influence on the amount of damage detected by ultrasonic TTU C-scan.21 Compression after impact (CAI) tests, however, showed that this core damage had no significant influence on the residual compressive strength of the specimens.

The main objectives of the current studies are to experimentally investigate the impact damage and failure modes of composite sandwich structure with different face sheets. Foam sandwich composite with different ply angles would be evaluated on an instrumental Instron Dynatup 9250HV drop-weight impact testing machine (to evaluate the internal and external damage resulting under an optical microscope). The effects of stacking sequences on the damage resistance of composite sandwich have been elaborated and a quantitative comparison of the relative values of the impact parameters and damage resistance parameters has been also presented. An attempt has been made to explore the impact behaviors for the combination of different stack sequences of carbon fiber prepreg and foam structures as these types of materials are still not well-investigated.

### Experimental and materials fabrication process

#### Core material

The core of the sandwich specimens used in this article consists of ROHACELL® 71 IG-F (Industrial Grade), which is closed-cell rigid foam plastic based on polymethacrylimide (PMI) chemistry. Commercially, it is available in a fine cell size grade (ROHACELL® IG-F). It has good mechanical properties with good thermal stability and has shown chemical resistance at low temperatures with low heat conductivity. The foams properties are presented in Table 1. The foams are provided by the company Evonik Röhm GmbH.

#### Skin material

The skin used in this article consists of carbon-fiber/epoxy prepreg of TR 50S12L with high specific strength and stiffness. The fiber areal density was 1.6 g/cm³ and the resin density was found to be 1.36 g/cm³ (the skin properties are shown in Table 1). The material is being supplied by Mitsubishi Rayon Co., Ltd. The upper and lower skins consist of eight plies each with a different stacking sequence.

### Table 1. Description of the properties of foam and skin materials being used.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Density kg/m³</th>
<th>Compressive strength MPa</th>
<th>Tensile strength MPa</th>
<th>Shear strength MPa</th>
<th>Elastic modulus GPa</th>
<th>Shear modulus GPa</th>
<th>Elongation at break %</th>
<th>Volume fraction ( V_f )%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rohacell® 71 IG</td>
<td>75</td>
<td>1.5</td>
<td>2.8</td>
<td>1.3</td>
<td>0.092</td>
<td>0.029</td>
<td>3.0</td>
<td>–</td>
</tr>
<tr>
<td>carbon/epoxy</td>
<td>1600</td>
<td>1200</td>
<td>1500</td>
<td>70</td>
<td>135</td>
<td>0.5</td>
<td>2.0</td>
<td>67</td>
</tr>
</tbody>
</table>
Fabrication process

The foam sandwich composites were prepared with different ply angles, consists four different \([0^\circ]/C_{14}^0, [0^\circ]/C_{14}^9, 0^\circ]/C_{14}^0, [0^\circ]/C_{6}^{45}/C_{14}^{15} \] \(s\). The carbon/epoxy prepreg was cut in different angle orientation. The skin is laminated over the core material by hand lay-up method followed by drying of the sample in the oven under vacuum at temperature 90°C for 40 min. The temperature was increased up to 135°C for 60 min and then allowed to cool down at room temperature. The mould pressure was 0.1 MPa for the composite sandwich manufacture. In order to ensure good bonding between the overall layers of the composite and for uniform distribution of the resin, the sample was being subjected to vacuum. Release paper was used on the top and bottom surface to improve the surface and matrix shrinking was not observed on both surfaces of the samples. The overall dimensions of the sandwich panel are 150\( \times \)100 mm with 15 mm thickness and the skin weight found to be 33.1 g. The face sheets were bonded to the core with an epoxy resin adhesive.

The fabrication process is one of the most important steps in the application of composite materials, because every step in the manufacturing process affects the final mechanical properties of the composite structure. In manufacture process many defects like the uniform distribution of the resin in the sample and the bonding between the overall layers of the composite are observed. Also void defects observed in the face sheets laminates was around 3.76%, which was measured by theoretical calculation as follows:

Composites real volume

\[ V_c = V_f + V_m + V_v \]  
(1)

Composites theoretical volume

\[ V_{c\text{theo}} = \frac{M_c}{\rho_c} \]  
(2)

\( \rho_c = \rho_f v_f + \rho_m v_m \)  
(4)

The volume of the void

\[ V_v = V_{c\text{Re}} - V_{c\text{theo}} \]  
(5)

Whereas, \( a, b, c \) are the laminate length, width and thickness; \( M_c \) the laminate mass; \( \rho_c, \rho_f, \rho_m \) the density of laminate, fiber and matrix; \( v_f, v_m \) the volume fraction of fiber and matrix.

Quasi-static test

For the quasi-static three-point bending tests, MTS 810 Material Test System-647 Hydraulic wedge Grip machine was used as shown in Figure 1. The applied velocity is 2 mm/min, and the indenter diameter 12.7 mm. The specimen dimensions are listed in Table 2. Load–displacement plots were obtained for each test specimen, and three specimens of each type of sandwich composite are tested.

Impact test

Impact tests were conducted by using an instrumented drop weight testing system, Instron-Dynatup 9250HV drop-weight impact testing machine. This was designed and constructed to perform low-velocity impacts on specimens. It enables to perform tests for different impact energies. The hemispherical indenter with a diameter of 12.7 was adopted for all tests. Specimen with dimensions of 150/100 mm support fixture at the bottom of the drop tower facilitates a circular clamped condition with a clear span of 120 mm as shown in Figure 2. Different impact energies are achieved by adjusting the drop height. Impact energy levels of 15, 30 and 60 J corresponding to drop-heights of 133, 267 and 535 mm, respectively, were being used. At least three samples were subjected to testing at each impact energy level. In addition, the load-displacement histories for all the samples were recorded.

Results and discussions

Static tests

The quasi-static tests were being performed in order to obtain the load-displacement curves for all the
specimens. These curves were used to determine the behavior of the failure modes of sandwich structures with different stacking sequence face sheets. The curves obtained in the quasi-static tests are shown in Figure 3; all of these curves were similar in nature for the four different skin type structures: unidirectional, angle-ply, cross-ply and quasi-isotropic. The curves can be divided into three regions. The first region, linear in appearance, can explain the elastic deformation of the sandwich composites. In this region, two peak loads observed are $F_1$ and $F_2$. $F_1$ does not explain the damage but generally represents when the displacement of the indenter was affected in the upper skin or this could be due to the wrinkling of the compressive skins or the presence of some imperfections on the skins. The load in the second region drops about 20–50% of the peak load in the load–displacement curve observed for all sandwich structures; this sudden drop suggested the foam cracking. After the crack is initiated in tensile side, it propagates to the compressive side within the core in all types of specimens before the final failure occurs. After the load drop, the specimen continued to sustain the load but never exceeded the previous peak load as only the fiber composite skins were carrying the load, which is reflected in the third region in the load-displacement curves. In this region, plateau region was observed until reaching the final failure. The final failure occurs when the upper skins crush due to compressive failure or in some case the skin and the foam debonding occur due to core shear failure. Comparing the peak loads of the foam sandwich structures in quasi-static, it is evident that the unidirectional has a higher peak load compared with quasi isotropic, angle-ply and cross-ply. This variation in peak load can be attributed to the fiber orientation.

**Failure modes**

The failure mode of the sandwich structure materials tested under bending conditions can be summarized as tensile failure, compressive failure followed by the cracking of the core material. The sudden failure of the specimen during quasi-static as mentioned earlier
occurs due to the load transferred to the core and is more than its strength at the time of skin failure. Since core materials generally have lower mechanical properties than skins (due to their lower density of later), those affected the damage initiation characteristics and the local indentation behavior of the sandwich panels. This led to the core failure before the face sheet.

The experimental investigation showed that under static loading, the composite sandwich failed with sudden brittle type failure due to shear failure of the core and compressive failure of the skins followed by debonding between the skin and the core. Comparing the failure modes of foam sandwich with unidirectional, angle-ply, cross-ply and quasi-isotropic face sheets, it can be observed that all sandwich structures have similar behavior of failure. Figures 4 and 5 show the pictures on the failure modes of unidirectional structure and cross-ply structure. Almost similar behaviors like cross-ply have been observed by other structures. Figure 4 shows the multiple crack generation in the foam sandwich with a unidirectional face sheet. The multiple cracks were generated along the tensile side of the specimen. All cracks propagate toward the compressive side of the specimen. However, the final failure occurs when the upper skin crashed and the skin-foam undergoes debonding.

Figure 5 shows the single crack generation in the foam sandwich composites with cross-ply face sheet. The crack initiated close to the central neutral axis on the tensile side and has been propagated to the compressive side. During this process of crack propagation, debonding between the foam and bottom skin is also observed before skin failure. However, the final failure occurs when the upper skin crashed and the bottom skin-foam suffers debonding.

The damage in the face sheets subjected to static loading can be classified into matrix cracking and delamination, with fiber breakage. Indentation of the face sheet can often occur at the indenter location as a result of the fiber breakage. The exact order and relative size of these failure modes depend upon the face sheet configuration. The pictures in Figures 4 and 5 show the face sheets damage of unidirectional and cross-ply. The figures report that the damage occurs along the fiber orientation. The foam sandwich composite with unidirectional face sheet observed largest damage size in the top face laminate, which could be attributed to the fiber orientation in the direction of the major axis. However, quasi-isotropic face sheet showed smaller damage size compared to other structures. This could be attributed to the small relative angular orientation between adjacent plies.

The skin-core interface often plays a critical role in the form of reduced bending stiffness and strength. The face-core interface is typically induced by the cracks initiated from the tensile side and propagated towards the compressive side within the core in all sandwich
structure specimens that led to the lower face sheet and the core debonding due to high bending load.

Crack propagation paths in foam sandwich composite specimens were shown experimentally and Figures 4 and 5 show the crack propagation for all specimens located below the face/core interface. It was reported that the crack generally propagates in the core because this was the weakest link in the sandwich construction. Furthermore, during the manufacturing process of the foam sandwich composite, the resin penetrates the partly open cells on the foam surface and forms an interface layer of the cell size; this layer is generally stronger than the core making crack. As a consequence, the debonding between the face sheet and the foam occurs with the final failure as seen in Figures 4 and 5. Thus, it should be pointed out that manufacturing process of the foam sandwich composite plays an important role in the face/core interface.

Dynamic tests

The load-displacement plots at different energy levels have been obtained by using the drop weight testing method in order to analyze the impact damage and failure model of the foam sandwich composite with different stacking sequence face sheets. At each impact energy level, sample was sectioned at the impact location and observed under an optical microscope to understand the failure modes. The failure modes involved in impact damage under varied impact energies of foam sandwich composites with different ply angles face sheets. Later on, these modes were being described and characterized by the, upper skin failure, core shear failure, lower skin failure, penetration depth and the debonding between the face and core materials. Figures 6–8 illustrate the load-displacement plots for foam sandwich composites with cross-ply, angles-ply and quasi-isotropic face sheets at 15, 30 and 60 J, respectively. The pictures of top, bottom surface and cross-sectional view for the foam sandwich composites with cross-ply, angles-ply, quasi-isotropic face sheets are presented in Figures 9, 10 and 11, respectively. The peak load does not vary much within all sandwich structures (cross-ply, angles-ply and quasi-isotropic face sheets) and at all impact energy levels (around 2.8 to 3.2 kN). The displacement was found to be increased with an increase in the impact energy levels. The variation of displacement from low- to high-impact energy was attributed to the penetration depth of the indenter through the three facing of the sandwich structure (top face sheet, foam, and bottom face sheet). The load-displacement curves were showing same tendency, exhibiting a linear increase, with a small deformation. This behavior was attributed to the condition when the indenter comes in contact with the specimen, initiating delamination in the top face sheet. There is a sudden drop in the load as the load reaches the peak load value, which clearly indicates the damage of the top face sheets. For low energy level, the prolonged unloading region depicts that the load was being carried by the top face sheets and small damage was found to occur at the top of the foam below the impact location as seen from
the pictures of the sample at 15 J in Figures 9–11. It has been seen that the damage was limited, i.e. just at the top face sheet without further propagation to the foam and the bottom face sheet. After a sudden drop occurs at the peak load, the load-displacement curves at medium impact energy level (30 J) exhibited a prolonged plateau region. In this case, the foam undergoes certain damage, whereas the indenter comes in contact with the bottom face sheet without damage, as seen from the Figures (9–11) of the sample at 30 J; the top face sheet completely failed leading to foam penetration and cracking. In the case of high-impact energy level, sudden peak load drop has led to a prolonged plateau region which indicated the interaction of the indenter through the foam core. The indenter penetrates the foam and makes contact with the bottom face sheets. A secondary peak value was also observed and it was suggested that it could be due to the load carried by the

Figure 7. Load-displacement curves for low-velocity impact tests of foam sandwich composites with angles-ply face sheets at 15, 30 and 60 J.

Figure 8. Load-displacement curves for low-velocity impact tests of foam sandwich composites with quasi-isotropic face sheets at 15, 30 and 60 J.
bottom face sheets. After both peak values have been appearing, many oscillations occur which is caused by the dent and delamination of the top face sheet and bottom face sheet. The specimens are completely penetrated followed by the final failure. This is quite evident from the picture of samples impacted at 60 J as shown in Figures 9–11, the top face sheets and foam were being penetrated and the bottom face sheets remain without penetration but still some damage occurs.

Figure 12 illustrated the load-displacement plots for the foam sandwich composites with unidirectional face sheets at 15, 30 and 60 J. The layouts of top, bottom surface and cross-sectional view of the foam sandwich composites with unidirectional face sheets are presented in Figure 13. The peak load did not vary much within the situation of all impact energy levels. The load-displacement curves were showing a linear increase with a small deformation. Once the load reaches the peak load value, a sudden drop in the load has been observed. This indicated the perforation on the top face sheet. For low energy level (15 J), the prolonged unloading region indicated that the load carried by the foam leads to the top face sheet failure. Some damage occurs on the foam below the impact location as seen from the pictures of the sample at 15 J (Figure 13). The top face sheets completely failed and propagation of the failure to the foam by core cracking and penetration depth. The bottom face sheets remain generally undamaged because the indenter did not penetrate the bottom face sheet. As compared to the foam sandwich composite with cross-ply, angles-ply and quasi-isotropic face sheets at low energy level (15 J), the top face sheet were not completely failed and the indenter did not penetrate the foam without causing damage in the foam. This could be evaluated that the fiber orientation in the transverse direction was poor for unidirectional,
thus, it was easy to penetrate. The load-displacement curves at medium impact energy (30 J) and high impact energy (60 J) show the same behavior. However, after the sudden drop in peak load, many oscillations immediately followed leading to a prolonged plateau region, which indicated the penetration of the indenter through the core. A secondary peak value was also being observed, showing the load carried by the bottom face sheet, and depicted that the specimen were completely being penetrated before the final failure occurs. This behavior is quite evident from the samples impacted at 30 and 60 J as shown in Figure 13. For both impact energy levels, the indenter penetrates the top face sheet and the foam; however, in the case of medium impact energy (30 J), the indenter contacted with the bottom face sheet and small damage was observed on the bottom surface of the specimen. But for the high-impact energy, all the three faces (top, bottom face sheets and foam) were penetrated as seen from the pictures of the sample at 30 J and 60 J (Figure 13). In comparison to cross-ply, angles-ply and quasi-isotropic face sheets, for medium impact energy (30 J), it is quite different in the load-displacement curve. There are no two peak load values because the bottom face sheets did not carry the load. However, for the unidirectional face sheets, there are two peak load values. For the sample at 30 J, the bottom face sheets remain undamaged. But for the unidirectional face sheet, there was damage in the bottom face sheet. The high-impact energy levels (60 J) show almost similar behavior in the load-displacement curve for the four structures skin types: cross-ply, angle-ply, quasi-isotropic and unidirectional.

Totally 36 samples were being tested under low-velocity impact conditions at 15, 30 and 60 J. Three samples of four different sets of sandwich

**Figure 10.** Pictures of the top, bottom surfaces and cross-sectional view of samples with angles-ply face sheets at 15, 30 and 60 J.
constructions i.e. unidirectional, cross-ply, angle-ply and quasi-isotropic face sheets were prepared. The impact parameters were shown in Table 3. In general, the peak load did not vary much within same sandwich structures at different impact energies levels. The repeatability of the testing for each structure has been shown in Table 3. For the same impact energy, the samples with cross-ply, angle-ply and quasi-isotropic face sheet shows high peak load. However, for the samples with unidirectional face sheet, the peak load was so lower as compared to other results (40%). This is due to the fact that the fiber orientation in the transverse direction is poor, which reduces the stiffness and strength of the sandwich structures. Whereas, the samples with cross-ply, angle-ply and quasi-isotropic face sheet have more uniformly dispersed ply sequence in the face sheets. However, the cross-ply shows highest peak load within all structures because the angle of interlacement between fiber crossover points was so high.

The average of displacement at the peak load for the samples with unidirectional face sheets increased with the increase in the impact energy levels. Whereas for the samples with cross-ply and quasi-isotropic face sheet, the average of displacement at the peak load decreases with the increase in impact energy level. For the sample with angle-play face sheet, the average of displacement at peak load was decreased with increase in impact energy levels and then increased at 60 J. And also this structure showed the highest displacement at peak load.

Figure 11. Pictures of the top, bottom surfaces and cross-sectional view of samples with quasi-isotropic face sheets at 15, 30 and 60 J.
which was playing an important role for absorbed energy.

The energy absorbed by elastic deformation of the foam sandwich composite was calculated from the area under the load-displacement curve. The energy absorption increased with an increase in the impact energy levels for all sandwich structures. At low and medium energy levels, all energy was absorbed by the samples, which mean that the sample does not fail completely. In the case of high-impact energy levels, the absorbed energy was higher because the sandwich composites failed. Higher energy absorption levels were caused by the significant damage (delamination and debonding) that occurs in three faces of sandwich structures. In the case of low- and medium-impact energy levels, the absorbed energy did not vary much within all sandwich structures. However, in the case of high-impact energy level, the samples with unidirectional face sheet show the minimum energy absorption. Whereas, the foam sandwich composite with angle-ply face sheet shows the maximum energy absorption value for all conditions that have been considered. This was attributed to the fact that laminates containing (+45°) surface ply offered superior impact resistance and increased flexibility. This led to their ability to absorb energy elastically i.e. so high for the composite structures. The Table 3 have illustrated that for medium and high energy levels of foam sandwich composite with unidirectional face sheet, the average of absorbed energy has the same value. This means that the sandwich composite with a unidirectional face sheet completely failed in the case of medium-impact energy levels; this clearly indicates that it cannot absorb energy more than (30 J).

**Failure modes**

Comparing the failure modes of unidirectional, angle-ply, cross-ply and quasi-isotropic, it can be observed that all sandwich structures have similar behavior of failure. At low-impact energy levels, the top face sheets failure and for the medium impact energy levels, the top face sheets completely failed, leading to the penetration of the indenter within the foam and contact with the bottom face sheets. Whereas in the case of high-impact energy levels, the three faces of the foam sandwich composites were failing due to the indenter penetration within the three faces. The damage size increased with an increase in the impact energy levels within all sandwich structures.

Figure 13 shows the view of top, bottom surface and cross-sectional area of the foam sandwich composites with unidirectional face sheets. The top face laminate suffered significant damage in the form of matrix crack and fiber fracture breakage, no delamination was observed at the interface between the plies, this is due to the fact that all the adjacent plies (eight plies) have the same fiber orientation, this behavior has been found within all impact energy levels. It showed largest damage size in the top face and bottom face laminate, which could be attributed to the fiber orientation in the
direction of the major axis, this cause largest splitting in the fiber direction.

Figures 9, 10 and 11 show the top, bottom surface and cross-sectional view for the foam sandwich composites with angle-ply, cross-ply and quasi-isotropic face sheets, respectively. For the low-impact energy level (15 J), small damage observed in the top face laminate consists primarily of delamination and matrix cracking. For the medium-impact energy level (30 J), the top face laminate is completely failed, which create significant damage in the top face sheet and consists of delamination with matrix crack and fiber breakage. In the high-impact energy level (60 J), the top laminate has the same damage like the medium-impact level (30 J); however, the bottom laminates of the angle-ply, cross-ply and quasi-isotropic have small damage in the form of delamination and in the last layer, the fiber pull out in the same direction of the fiber orientation. For angle-ply, cross-ply and quasi-isotropic within all impact energy levels report that delamination occur between adjacent plies, which have different fiber orientation.

The pictures of top, bottom surface in Figures 9–11 at (60 J) illustrate that the damage size in the top face sheets of quasi-isotropic face sheet was smaller as compared to other structures. This could be attributed to the small relative angular orientation between adjacent plies (45°). However, the damage size in the bottom face sheet of the angles-ply face sheet was smaller compared to other structures, which was due to laminates containing (±45°) surface plies more flexible as compared to laminates with (0°) surface layers.

The manufacturing defects in the laminates were playing an important role in the failure mode of the
Table 3. Impact parameters for foam sandwich composite with different ply angles face sheets.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Test no</th>
<th>Impact energy (J)</th>
<th>Peak load (kN)</th>
<th>Displacement at peak load (mm)</th>
<th>Absorbed energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
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<td>15</td>
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<td>1.85</td>
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(continued)
sandwich structures. The defects like the uniform distribution of the resin in the samples, the bonding between the overall layers (Poor adhesion) of the composite and the void defects can be observed from the cross-section images in Figures 9–11 and 13. These defects can cause delamination and debonding under impact and load conditions, and also affect the mechanical behavior of sandwich composite such as the stiffness and strength.

The delamination shapes are illustrated in Figure 14 can be generalized as elongated, circular, diamond and oblong shapes. Elongated shape was for unidirectional structure, the elongated delamination shape was oriented parallel to the fiber direction as seen in Figure 14(a) and circular delamination shape for the quasi-isotropic face sheet (Figure 14 (b)). This delamination shape is generally associated with a combination of the fiber orientation, and this structure tends to reduce as lateral delamination grows. The oblong and diamond delamination shape for cross-ply and angles-ply, respectively, Figure 14(c) and (d), have two orientations of the fiber but by different angles. [0°/90°] and [±45°]. This allowed the face sheet to split in the fiber direction which leads to this delamination shape.

Table 4 indicates the damage parameters for foam sandwich samples with unidirectional, cross-ply, angle-ply and quasi-isotropic face sheets at 15, 30 and 60 J energy levels. Figures 9–11 and 13 illustrate the pictures of the impact surface, back surface and cross-sectional view for the foam core sandwich composites of these samples. Table 4 and Figures 9–11 and 13 show that the penetration depth becomes deeper and...
the maximal cracking width found to be bigger with increasing impact energy level. The results elucidate that angle-ply have the lowest penetration depth up to 3 mm as compared to other samples being used. On the contrary, the unidirectional sample has the maximum penetration depth up to 9 mm for low-impact energy level, which leads to sample penetration. At high impact energy, the unidirectional was completely penetrated up to three faces, i.e. 15 mm. But for others the bottom face sheet was not penetrated. For the range of maximal cracking width, only unidirectional sample has shown cracking at low-impact energy level. The cracking width was found to be increased by increasing impact energy for all samples. In middle- and high-impact energy level, unidirectional has shown lowest whereas cross-ply exhibited maximum cracking width. The lowest cracking width value at increasing energy levels exhibited by unidirectional samples was attributed to the orientation of fiber in one direction, which leads to shear cracking. However, in other samples, this behavior could lead to the tensile cracking.

Conclusions
Static and low-velocity impact tests were carried out for sandwich composites with different stacking sequence face sheets (unidirectional, cross-ply, angle-ply and quasi-isotropic). Three samples of each set were tested under quasi-static and impact loading. The major conclusions are the following:

- Static test found that cracks initiate from the tensile side and propagate to the compressive side within the core in all sandwich structure specimens. The final failure occurs when the upper skin crashed and the skin-foam faced debonding.
- Transient load-displacement curves give qualitative indications of the state of damage in the sample. At all the energy levels, foam sandwich composite with unidirectional face sheets (due to poor fiber orientation in the transverse direction) could not sustain the impact loading beyond 1.82 kN. On the other hand, the samples with cross-ply, angle-ply and quasi-isotropic face sheet shows high peak load with minimum deviation from each other.
- In the case of the high-impact energy level (60 J), the foam sandwich composite with angle-ply face sheet shows the maximum energy absorption value (48.3 J). Whereas, the foam sandwich composite with unidirectional face sheet shows the minimum energy absorption value (30.6 J).
- For the same impact energy level, the unidirectional sample has the maximum penetration depth. On the other hand, the angle-ply has the lowest penetration depth as compared to other samples being used. Unidirectional samples have core shear cracking in comparison to other samples (cross-ply, angle-ply and quasi-isotropic) that have tensile cracking. This behavior could be attributed to more uniformly dispersed ply sequence which is responsible for maximum cracking width.
- In comparison to the static behavior with dynamic behavior, it is quite apparent that the unidirectional has highest peak load than other structures in the static test. On the contrary, the unidirectional has lowest peak load in the dynamic test.

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Conflict of interest
None declared.

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References


