Finite element analyses of low-velocity impact damage of foam sandwiched composites with different ply angles face sheets

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A B S T R A C T
In the current studies, low-velocity impact properties and impact damage response of foam sandwiched composite with different ply angle face sheets were investigated experimentally and numerically. Low-velocity impact tests were performed using an instrumented Drop-Weight Machine (Instron 9250HV). The FE (finite element) software, ABAQUS/Explicit was employed to simulate low-velocity impact properties of foam sandwiched composite. A crushable foam model was used in order to explore core behaviors, while the Hashin criteria were used to predict the failure of the face sheets. The contact load histories, peak load, and energy absorption were obtained to compare the numerical and experimental results at several impact energy levels. The failure morphologies, damage size and damage shape were evaluated and compared with different types of sandwich structures. The comparisons illustrated the existence of a good agreement between the experimental and FEM results.

1. Introduction
Currently, the fields of composite structural materials have proved to be a dynamic part of a number of applications around the globe. Their usage in automobiles, locomotives, windmills and consumer industries is quite evident. Different face sheets, core materials and the core-facings interfaces are the actual source of their quite intriguing and inimitable properties [1–4].

The impact design problem is approached in two ways. The first one is experimental and requires several measurements of the impact behavior of the studied material under different loading conditions and sample geometry. The second one is mainly related to the simulation of the impact phenomena using finite element methods and requires very powerful hardware and software resources [5]. For experimental analyses of the influence of these variables, numerous tests were required [6]. In order to achieve more accurate results and to minimize the number of experimental tests and hence reduce design costs and time of such tests, it is essential to use numerical simulation models. These models should be accessed through experimental testing. Two of the few analytical models that have been used are mass spring model [7,8] and an energy balance model [9,10] they have been used to predict the peak load, the load history and to study the impact response of composite sandwich structures due to the complex interaction between the composite face sheet and core during deformation and failure. For more detailed analyses, most researchers used finite element simulations. Mines and Alias [11] used the Hashin criterion and the Lee extended Hashin’s arguments to consider the modes of laminate failure (fiber breakage, matrix cracking, and delamination). They used a foam model based on critical state theory with adjustments to take into account volumetric effects and a non-associative flow rule. Icardi and Ferrero [12] used the latest 3D version of the Hashin’s criterion with in situ strengths to predict the failure of fibers and the matrix, Choi Chang’s criterion and a Heuristic criterion for delamination. Von Mises yield criterion has been used for considering the foam core to be a homogeneous isotropic material. Sadighi and Pourlayev [13] used a model of a crushable foam material which was validated by uniaxial compression test. The results described the response of sandwiched composites, impactor displacements in terms of core and face thicknesses, core material, impactor energies for static and impact results. The experimental results were in good agreement with the analytical and FE analyses. Foo et al. [14] developed a three-dimensional finite element model to analyze low-velocity impact response and damage in honeycomb sandwich composites (the FE results compared well with experimental results). Ivañez et al. [15] showed the accuracy of the finite element model, determined by comparing experimental results with numerical predictions at several impact energies in terms of contact force histories, peak force, maximum displacements of upper and lower face sheets, and absorbed energy. Agreement with the experimental results was satisfactory. The flexural behavior and failure mechanisms of composite sandwich beams in flatwise and edgewise positions had been studied experimentally, analytically and numerically by Manalo et al. [16]. The experimental investigation showed that
under flexural loading, the composite sandwich in the flatwise position failed with sudden brittle type failure. In the edgewise position, the presence of fiber composite skins increased the ultimate strength of the composites. The theoretical prediction of failure was found to be in good agreement with the experimental results.

Low-velocity impact properties and residual tensile strength of carbon fiber composite lattice core sandwich structures were investigated by Wang et al. [17]. It has been shown that according to FE analysis results, degradation of residual tensile strength in sandwich structures could be divided into three stages: lower impact energy degradation stage; plateau stage; higher impact energy degradation stage.

The objective of this work is to experimentally and numerically investigate the impact damage and failure mode of foam sandwich composite with different ply angle face sheets. In order to evaluate the internal and external damage resulting under low velocity impact, the sandwiched composite samples were tested on an instrumental Instron Dynatup 9250HV-Drop Weight Impact Testing Machine. From FEM modeling, the impact damage mechanisms were revealed to show the damage initiation, progression and the failure of the composite panel. The combination of different stacks sequences of carbon fiber prepreg and foam structures, the impact behaviors of such kind of materials are not well investigated. Finally, comparison of experimental results with numerical results at several impact energies in terms of contact load histories, peak load, and absorbed energy of sandwich structures was done.

2. Experimental and materials

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

The skin used in this article consists of carbon-fiber/epoxy prepreg of TR 50512L with high specific strength and stiffness. The fiber areal weight was 227 g/m² and the nominal resin content was 38 wt%. The material was supplied by Mitsubishi Rayon Co., Ltd.; the skin properties are shown in Table 2. The upper and lower skins consist of eight plies each with different stacking sequence.

Fabricating the foam sandwich composite with different ply angles, consists four different structures $[0°]_8, [90°]_2, [±45°]_2, [0°, +45°, 90°, −45°]$. The vacuum was applied in order to ensure a good bonding between the overall layers of the composite and for uniform distribution of the resin in the sample. The overall dimensions of the sandwich panel were $150 \times 100$ mm with 15 mm thickness. The face sheets were bonded to the core with epoxy resin adhesive.

Impact tests were conducted by using an instrumented drop weight testing system (Instron-Dynatup 9250HV Drop Weight Impact Testing Machine). This was designed 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 mm was adopted for all types of testing. Specimen with dimensions of 150/100 mm supported by fixture at the bottom of the drop tower facilitates and a circular clamped condition with a clear span of 120 mm. 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 used. In this investigation, we used a new standard, ASTM D7766/D7766M-11 which provides instructions for modifying laminate quasi-static indentation and drop-weight impact test methods to determine damage resistance properties of sandwiched constructions, for testing the sandwiched composite panels.

3. Finite element model

The explicit finite element computer software, ABAQUS/Explicit, was employed for impact simulation. The sandwich plate was modeled as a rectangular plate clamped at its top and bottom circumferential edges to simulate the clamped condition in the test machine, as shown in Fig. 1. Interfaces between face sheets and foam core were undamaged under impact process. The face sheets were meshed with linear reduced integration shell elements (S4R). The laminate was represented by a shell element in the through-thickness direction. The foam core was meshed with linear reduced integration solid elements (C3D8R). Due to the poor aspect ratio of these elements, a reasonably fine mesh was required to ensure convergence. A graded mesh is thus being created; where the region in the vicinity of the impactor was finely meshed. Finally, the semi-spherical steel indenter with diameter 12.7 mm was modeled as a rigid body. It was meshed with 4-noded linear tetrahedron continuum elements with the Young’s modulus of 200 GPa and the Poisson’s ratio of 0.3.

The core was modeled as an elastic–plastic material. The elastic part of the response of the core was defined as ‘ELASTIC ISOTROPIC’ option with the parameters: Young’s modulus and Poisson’s ratio. The plastic part of the response of the core material was modeled in a kinematic hardening plastic model.

Under the impact load, the specimen deformed and the contact pressure increased, and the bilinear kinematic hardening material model was used for the core material. The foam core was assumed to be perfectly bonded to the core material. The contact interaction between the panel and the indenter was modeled by the general contact provided by the ABAQUS package. The contact model was defined as ‘SPECIAL SKIN SHELL options in the ABAQUS/Explicit’, which were assumed to be perfectly bonded to the core material. The contact force between the panel and the indenter was calculated by a normal force on the contact surface and a friction force on the contact surface in a sliding direction perpendicular to the contact surface.

Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal stiffness, ( E_{11} ) (GPa)</td>
<td>109</td>
</tr>
<tr>
<td>Transverse stiffness, ( E_{22} ) (GPa)</td>
<td>8.82</td>
</tr>
<tr>
<td>Out-of-plane stiffness, ( E_{12} ) (GPa)</td>
<td>8.82</td>
</tr>
<tr>
<td>Poisson’s ratio, ( v_{12} )</td>
<td>0.342</td>
</tr>
<tr>
<td>Poisson’s ratio, ( v_{13} )</td>
<td>0.342</td>
</tr>
<tr>
<td>Poisson’s ratio, ( v_{23} )</td>
<td>0.52</td>
</tr>
<tr>
<td>Shear modulus, ( G_{12} ) (GPa)</td>
<td>4.32</td>
</tr>
<tr>
<td>Shear modulus, ( G_{13} ) (GPa)</td>
<td>4.32</td>
</tr>
<tr>
<td>Shear modulus, ( G_{23} ) (GPa)</td>
<td>2.2</td>
</tr>
<tr>
<td>Longitudinal tensile strength, ( X ) (MPa)</td>
<td>1132</td>
</tr>
<tr>
<td>Longitudinal compressive strength, ( X ) (MPa)</td>
<td>1132</td>
</tr>
<tr>
<td>Transverse tensile strength, ( Y ) (MPa)</td>
<td>50</td>
</tr>
<tr>
<td>Transverse compressive strength, ( Y ) (MPa)</td>
<td>50</td>
</tr>
<tr>
<td>Longitudinal shear strength, ( S_{12} ) (MPa)</td>
<td>75</td>
</tr>
<tr>
<td>Transverse shear strength, ( S_{23} ) (MPa)</td>
<td>1532</td>
</tr>
</tbody>
</table>

Density, \( \rho \) (kg/m³) 75
using the ‘CRUSHABLE FOAM’ and the ‘CRUSHABLE FOAM HARDENING’ options in the ABAQUS software. The hardening behavior was defined in terms of uniaxial compression yield; stress versus strain. In order to get the experimental uniaxial compression curve, a uniaxial compression test was carried out for the stress–strain curve shown in Fig. 2. These were used as input data in the card ‘CRUSHABLE FOAM HARDENING’. The elastic region of the stress strain curve was determined by the value of the Young’s modulus. The elastic region was followed by a yield plateau where the stress remained constant while the strain was increased. This was due to the fact that foam materials usually consist of cells which begin to collapse when the stress reaches the yield stress. As the load continues, all the cell walls inside the foam crushed together. Then the stress increase at the last stage of the compression stress strain curve. A non-linear finite element model is developed for simulating the impact behavior of foam beam and panel specimens. The ABAQUS/Explicit commercial program is used [18].

The face sheet was modeled as elastic material, with parameters of carbon/epoxy which are presented in the Table 2. The shell section was used to define the face sheets layer structure, material type and orientation of each layer. The face sheets failure criteria proposed by Hashin [19] criteria to detect the failure modes in the matrix and fiber under both tension and compression failures and involve four failure modes. The failure modes included in Hashin’s criteria are as follows:

\[
\begin{align*}
\sigma_{11} & \geq 0: \\
\frac{\sigma_{11}^2}{Y_c^2} + \sigma_{12}^2 + \sigma_{13}^2 & = \begin{cases} 
\geq 1 & \text{failure} \\
< 1 & \text{no failure}
\end{cases} \\
\sigma_{11} & < 0: \\
\frac{\sigma_{11}^2}{X_c^2} & = \begin{cases} 
\geq 1 & \text{failure} \\
< 1 & \text{no failure}
\end{cases} \\
\sigma_{22} + \sigma_{33} & > 0: \\
\frac{\sigma_{22} + \sigma_{33}}{Y_c^2} + \sigma_{23}^2 - \sigma_{22}\sigma_{33} + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} & = \begin{cases} 
\geq 1 & \text{failure} \\
< 1 & \text{no failure}
\end{cases} \\
\sigma_{22} + \sigma_{33} & < 0: \\
\left(\frac{Y_c}{2S_{23}}\right)^2 - 1 & \geq \begin{cases} 
\left(\sigma_{22} + \sigma_{33}\right)^2 - (\sigma_{22} + \sigma_{33})^2/4S_{23}^2 + \sigma_{23}^2 - \sigma_{22}\sigma_{33}/S_{23}^2 & = \geq 1 & \text{failure} \\
< 1 & \text{no failure}
\end{cases} \\
\sigma_{33} & > 0: \\
\frac{\sigma_{33}}{Z_c^2} & = \begin{cases} 
\geq 1 & \text{failure} \\
< 1 & \text{no failure}
\end{cases} \\
\sigma_{33} & < 0: \\
\frac{\sigma_{33}}{Z_c^2} & = \begin{cases} 
\geq 1 & \text{failure} \\
< 1 & \text{no failure}
\end{cases}
\end{align*}
\]

where \(\sigma_{ij}\) terms are components of the stress tensor \(i\) and \(j\) are local coordinate axes parallel and transverse to the fibers in each ply, respectively. The \(z\)-axis coincides with the through-thickness direction.

4. Results and discussion

4.1. Validity of FEM

The accuracy of the finite element model was determined by comparing experimental results with numerical results at several impact energies in terms of contact load histories, peak load, and absorbed energy. Figs. 3–6 shows the load–displacement plots of experimental and numerical for foam sandwich composites with cross-ply, angles-ply, quasi-isotropic, and unidirectional face sheets at 15, 30, and 60 J, respectively. The comparisons show that there exists a good agreement between the experimental and FEM within all sandwich structures. The load–displacement curves were found to exhibit same tendency, and similar behavior was
observed for experimental and numerical results (i.e. exhibiting a linear increase with a small deformation). This behavior was attributed to the condition when the indenter contact with the specimen, initiating delamination and dent in the top face sheet. However, in experimental and numerical curves; multiple oscillations after the peak load have been observed for all samples at all energy levels, which may result from vibrations of the supports, initiation of damage in the material, and the natural frequencies of the system. For low energy level (15 J), the numerical result agrees with experimental results very well, the prolonged unloading region indicates that the load was successfully carried by the top face sheets. It observed that the damage was limited just to the top face sheets without further propagation to the foam, and the bottom face sheet. On the contrary, for unidirectional, the top face sheet completely failed and propagation of the failure occurred up to the foam. As seen from the pictures of the sample at 15 J in Figs. 7–10. 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 was damaged; whereas the indenter contact with the bottom face sheets without significant damage. But in the case of unidirectional, the three faces were damaged, and it is quite different in the load–displacement curve. There is a two peak load value as compared to the other structures. As seen from the pictures of the sample at 30 J in Figs. 7–10. In the case of high impact energy levels (60 J), the load–displacement curves for all sandwich structures show the same behavior. However, after the sudden drop in peak load, a prolonged plateau region was observed which indicated the penetration of the indenter through the core. A secondary peak value was also observed, showing the load carried by the bottom face sheet and depicted that the specimen were completely penetrated before the final failure occurs. This behavior was quite evident from the samples impacted at 60 J as shown in Figs. 7–10. In related work being done by Icardi and Ferrero [12], there were unable to get the slope change for low and medium impact energy. However, in our studies, this slope change is quite evident. Also at high impact energy, current studies depicted two peak loads showing upper and lower face sheets failure which is in contrast to work done previously. It can be seen from the curves that in the case of high impact energy levels, the maximum displacements of the experimental results are significantly bigger than the numerical results. This finding leads to the conclusion that there was no good agreement between the experimental and numerical results for the second peak load. This was due to the fact that in the experimental result in all sandwich structures at high impact energy levels, a debonding between the foam and bottom face sheets and also delamination between the layers occurred which cannot be observed in FEM. This behavior was quite evident from the samples impacted at 60 J, in the cross-sectional view in Figs. 7–10.

Experimental and numerical curves illustrate that the displacement was increased with the 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
The experimental and numerical peak load obtained from load–displacement curves were compared at any impact energy levels. The numerical results were quite close to the experimental ones. The peak load in numerical results was slightly higher than experimental data, and the differences were in the reasonable range. This varies due to initial defects in sandwich composite which cannot be calculated in FEM. For example, 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. The peak load did not vary much within cross-ply, angles-ply, and quasi-isotropic face sheet sandwich structures. The experimental and numerical peak load obtained from load–displacement curves have been investigated previously [15]. In that investigation, the numerical results have been slightly underestimated as compared to experimental results (10.9%). But current studies have shown further improvement of the comparison between numerical and experimental results (~5%).

Fig. 11 shows the experimental and numerical peak load versus the impact energy of foam sandwich composites with unidirectional and cross-ply face sheets. It shows that at all impact energy levels in experimental and numerical results, the peak load does not vary much within all sandwich structures. Samples with unidirectional face sheet show the lowest peak load. This is due to the fact that the fiber orientation in the transverse direction is poor which reduce the stiffness and strength. Whereas the samples with cross-ply shows highest peak load within all structures because of the angle of interlacement between fiber crossover points is so high.

The energy absorbed by elastic deformation of the foam sandwich composite was calculated from the area under the load–displacement curve. The absorbed energy as a function of impact energy is shown in Fig. 12. The absorbed energy increased with the increment of the impact energy levels which indicated a contribution of the foam core in the energy absorption process. From Fig. 12, three regions can be distinguished: for lower impact energies 15 J, the absorbed energy was very low and is in quite agreement with the results being reported previously [15]; for medium energy levels, all energy was absorbed by the samples (this means that for both low and medium impact energy levels the sample does not completely failed); and for higher impact energy (60 J), the absorbed energy was higher because the sandwich composites failed. Higher energy absorption levels were caused by the failure...
of three faces; upper face sheet, foam, and bottom face sheet. There was good agreement between experimental and numerical curves and have followed the same trend and the results were very similar demonstrating that the numerical model is capable of accurately predicting the dynamic loading response of sandwich structures.

Fig. 12 shows the experimental and numerical absorbed energy versus impact energy of foam sandwich composites with unidirectional and angle-ply face sheets. It shows that in the case of low and medium impact energy levels, the absorbed energy was almost same for all sandwich structures. In the case of high impact energy level, the samples with unidirectional face sheet show the minimum energy absorption. However, the foam sandwich composite with angle-ply face sheet shows the maximum energy absorption value for all conditions which have been considered. This was attributed to the fact that laminates containing (±45°) plies were more flexible. Similar results were being reported by Dorey [20]; it was found that laminates containing (±45°) surface ply offered superior impact resistance and increased flexibility (i.e. The ability to absorb energy elastically) of the composite.

In the foam sandwich composite with a unidirectional face sheet, the curves have demonstrated that for medium and high energy levels, the 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 led to the information that it cannot absorb energy more than (30 J). In the case of other structure the curves show that for the low impact energy levels less than (30 J) all energy was absorbed by the sandwich structures. However for the high impact energy more than (30 J) all energy cannot be absorbed by the sandwich structures. This was due to the significant damage (delamination and debonding) occurs in the case of high impact energy levels.

4.2. Analysis of sandwich composites failure

4.2.1. Failure morphologies

The failure morphologies of experimental and numerical of foam sandwich composites with different play angles face sheet at different impact energy levels are compared in Figs. 7–10. It can be seen that the agreement of the failure morphology between experimental and numerical is fairly reasonable. 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 med-

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Fig. 8. Comparison of impact damage between experimental and FEM simulation of foam sandwich composite with angle-ply face sheet.
ium 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 failed due to the indenter penetration the three faces. Previous experimental studies by Xia and Wu [21,22] proposed that the damage extent of foam core sandwich composites with various facings may be characterized by the average damage angle, penetration depth, and maximal cracking width. However, our studies could be considered as further improvement of work done by Xia and Wu [21,22], as further detailed elucidation of the results along with numerical model has also been presented in current studies.

Figs. 7–10 described the experimental and numerical top surfaces, and cross-sectional views for the foam sandwich composites with different ply angles. 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 observe 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. For the three other structures, at low impact energy level less than 30 J, small damage area was observed in the top face laminate consists primarily of delamination and matrix cracking. For the high impact energy more than 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. Within all impact energy levels report that delamination occur between adjacent plies which have different fiber orientation. However the bottom laminates of the angle-ply, cross-ply and quasi-isotropic have a small damage area in the form of delamination and in the last layer the fiber pull out in the same direction of the fiber orientation. Furthermore, in this case, the debonding between the face sheets and the core occurs in the impactor location area. This often plays a critical role in the form with the reduced bending stiffness, strength and the energy absorption capabilities as seen in Figs. 7–10 (C). However, numerically for the same structures, debonding between the foam and face sheets and also delamination between the adjacent plies cannot be observed or quite negligible. This was due to the fact that the top and bottom surfaces were defined as SPECIAL SKIN SHELL options in the ABAQUS/Explicit. It was a kind of membrane element, which was assumed to be perfectly bonded to the core material.

**Fig. 9.** Comparison of impact damage between experimental and FEM simulation of foam sandwich composite with quasi-isotropic face sheet.
4.2.2. Damage size and damage shape

The pictures in Figs. 7–10 illustrate the experimental and numerical outcome of the top surface for foam sandwich composites with different ply angles. From these figures, it can be concluded that the numerically obtained damage size agrees well with the experimental ones. The damage size increased with an increase in the impact energy levels within all sandwich structures.

Fig. 10. Comparison of impact damage between experimental and FEM simulation of foam sandwich composite with unidirectional face sheet.

Fig. 11. Comparison between experimental and numerical peak-force values at several impact energies.

Fig. 12. Experimental and numerical absorbed energy versus impact energy.
Unidirectional face sheet showed largest damage size in the top face laminate which could be attributed to the fiber orientation in the direction of the major axis, and the stress wave propagation along the fiber direction. 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.

Also, compared with the experimental results, the numerically obtained damage shape was more symmetrical. It is very interesting to find that the damage shapes demonstrated in Fig. 13 can be generalized as elongated, circular, oblong, and diamond shapes; for unidirectional, quasi-isotropic, cross-ply, and angle-ply, respectively. The elongated delamination shape was oriented parallel to the fiber direction; and circular delamination shape was generally associated with a combination of the fiber orientation and this structure reduces as lateral delamination increases. The oblong and diamond delamination shape for cross-ply and angles-ply respectively, have two orientations of the fiber but by different angles, \([0^\circ]/[90^\circ]/[0^\circ]\) and \([+45^\circ]/[-45^\circ]\); this allowed the face sheet to split in the fiber direction which leads to the subsequent delamination shape.

4.2.3. Damage mechanisms

To discuss the damage mechanisms of the foam sandwich composite with different ply angles, Fig. 14 showed the cross-section of damage mechanisms obtained from ABAQUS with various times at high impact energy levels (60 J). We can summarize the general impact damage mechanisms of foam sandwich composites. As the indenter firstly comes in contact with the top face sheets, the top face sheet damages at \((t = 0.0016 \text{ s})\). After the top face sheet has been damaged, the indenter penetrated the foam. When the stress was greater than its maximum stress, the element will be deleted at \(t = 0.012 \text{ s}\). Then the foam faces were completely penetrated and the indenter finds its contact with the bottom face sheet. The indenter completely penetrates the composite at \((t = 0.018 \text{ s})\) followed by the final failure.

The pictures in Figs. 7–10 illustrate the experimental and numerical results of the cross-section for foam sandwich composites with different ply angles. It shows that the penetration depth becomes deeper 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 lead to sample penetration. At medium impact energy, the unidirectional sample was completely penetrated up to three faces i.e. 15 mm. But for others the bottom face sheet was not penetrated. In all specimens at different impact energy levels, the failure mechanisms predicted from the simulations are similar to the failure mechanisms observed in the experimental investigation. From the comparisons between the FEM results and the experimental results, the FEM simulation could be extended to predict the failure propagation and impact strength of the sandwiched composite panel.

4.2.4. Stress wave propagation calculated from FEM

The stress wave propagates from the top face sheet to the foam, then from the foam to the bottom face sheet. The stress wave depends on the elastic modulus and the density of the material while the variation of the time from face to face depends on the thickness of the face.

Three nodes (top face, foam, and bottom face) were selected in the finite element model and the stress wave histories of the three nodes under the impact velocity of 60 J are shown in Fig. 15. It is shown that the maximum stress appears on top and bottom face sheet while the minimum stress appears at foam. The reason is that the foam has low elastic modulus and low density as shown in the properties of foam and skin materials in Table 1. From the curve, the first peak stress value in the top face sheet was observed at the time 0.001 s (this time is so close to the time when the foam reaches the first peak stress values i.e. 0.0015 s) suggested that stress wave need 0.0005 s to propagate to the foam (quite short time). This could be attributed to the thickness of the face sheet which was too small. However, the first peak stress values in the bottom face sheet observed at the time 0.0045 s, this time so far from the time when the foam reaches the first peak stress values, and indicate that the stress wave need 0.003 s to propagate to the bottom face sheet (quite long time). This is due to the fact that the foam has high thickness, and low density, which led the stress wave propagation not so fast.

![Fig. 13. Comparison between numerical and experimental damage shapes at high impact energy level.](image-url)
Fig. 14. Damage mechanisms of foam sandwich composite at high impact energy levels with virus time.
sheets will influence the impact behaviors, including the impact in experimental. The damage size and damage shape was more symmetrical than those plies cannot be observed or quite negligible. And the numerical levels. However, in numerical, the debonding between the foam sandwiched laminated composites will have high impact damage tolerances and energy absorptions.

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