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RESEARCH PAPER

Investigation of the effect of impactor shape on the behaviour of composite sandwich plates with aluminium foam core at low-speed impact: An experimental study

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Abstract

In this paper, the effect of impactor shape and type of porcelain layer on the surface of composite sandwich panels under the impact of drop weight has been investigated. The core of the sandwich plate is A356 aluminium foam reinforced with SiC particles produced by fusion method using $CaCO_3$ foaming agent. The surface of the plates is made of epoxy glass with a quasi-isotropic, orthogonal porcelain layer and also a pure aluminium layer is used. For the impact test, the drop weight impact device was used and to investigate the effect of the impactor shape spherical, parabolic and cone impactor manufactured. Some of the effective parameters in evaluating the behaviour of materials at impact load including maximum impact force, maximum displacement and the amount of specific energy absorbed by the plate for different situations are compared with each other. The results indicate that the greater the radius of curvature of the impactor, the greater the maximum impact force. Also, plates with quasi-isotropic composite surface have the highest adsorbed energy and plate with aluminium surface has the lowest amount of adsorbed energy. The orthogonal surface performs better in terms of maximum impact force and maximum centre displacement. Therefore, depending on the use of sandwich panels, the use of composite surfaces (quasi-isotropic or orthogonal) instead of aluminium in the design of energy-absorbing structures was recommended.

Keywords: Low Velocity Impact; Composite Sandwich Sheet; Aluminum Foam; Impactor Shape; Layout, Energy-absorbing

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1. Introduction

In recent decades, the application of composite sandwich panels with aluminium foam core has expanded in the aerospace, automotive, renewable energy, and civil engineering industries [1-5] due to its unique mechanical properties [6-10]. The behaviour of these materials against impact loads is one of the biggest concerns in this regard [11-14]. Impact loads can be caused by falling objects and cause significant internal damage and reduce the residual strength of composite sheets [15-19]. On the other hand, to reduce the weight of the structure, the creation of cavities filled with air or neutral gases inside the base material and the production of a porous material called "foam" has been considered by many researchers [20-22]. Many metals and alloys, such as aluminium, steel, copper, nickel, zinc, magnesium, and titanium, can be foamed using a variety of manufacturing processes [23]. Among these, the use of aluminium metal as a foam base material, due to its lightweight and low melting point and also due to its high specific stiffness [24-33], good corrosion resistance, high strength to weight ratio, excellent energy absorption capacity, recyclability , and also the ability to produce relatively homogeneous and isotropic cellular structures has attracted much attention in recent years [34], [35]. The presence of cellular infrastructure in metal foams, especially aluminium foams, allows them to absorb a large amount of kinetic energy from the impact before it causes structural damage, and therefore in cases where resistance impact or penetration is required [36], [37], [46-50], [38-45], these materials act as energy absorbers [51-54]. Having the mentioned features has caused aluminium foams to be used in the mentioned applications [55]. Aluminium foam is also used as a core material in sandwich structures with different surfaces under different loads such as impact [56]. Caminero et al. [57] investigated the effect of thickness and layer of porcelain on the amount of post-impact compressive strength of composite sheets. The results showed a decrease in the level of degradation in exchange for an increase in energy absorption. Also, thicker plates had higher post-impact compressive strength due to their increased flexural stiffness. They found that plates with a non-orthogonal porcelain layer performed better in impact loading. Wang et al. [58] studied the behaviour of sandwich composite plates with aluminium foam core under the quasi-static influence and observed the behaviour of the samples in three stages of elasticity, yield, and failure. With the increase of the epoxy resin layer, the energy absorption capacity increased. Crupi et al. [59] predicted the behaviour of sandwich composite plates with aluminium foam cores under impact load. They compared their experimental results using an analytical model. In their results, they pointed out the separation of the aluminium surface from the core as the main cause of sample destruction. Also, the amount of energy absorption by the samples depended on the mechanical properties of the core foam of sandwich plates. Long et al. [60] characterized the degradation process of sandwich composite plates with foam cores under low impact velocity using the finite element model. They have studied the effects of impact energy, foam density, and porcelain layer. They found that the type of sample destruction was affected by the amount of impact penetration. As before the penetration of the separation of the surface plates according to the laws of composite materials has occurred and after the penetration of the degradation area is observed as a ring. Liu et al. [61] studied the behaviour of sandwich composite plates with aluminium foam core and metal composite surface. With increasing the thickness of the foam, the amount of energy absorption also increased. Also, with increasing the thickness of the composite surface layer, a significant increase in energy absorption was observed. They also observed good agreement between the experimental results and the finite element model using the software. Liu et al. [62] also investigated the behaviour of composite plates to high-velocity aluminium foam cores. They evaluated the accuracy of their experimental results using the finite element model and studied the effect of the impactor shape as well as the impact angle. Their results indicate an increase in the amount of energy absorbed due to the increase in the thickness of the top layer. In this case, separation of the top layer has been observed on the upper surface of the sample and especially around the impact site. They also reported that the top layer of the upper surface of the plate did not separate from the foam core as the thickness of the aluminium foam core increased. Kara et al. [63] investigated the flexural behaviour of sandwich structures with aluminium foam cores of different thicknesses. They found that sandwich composite sheets are a good choice for energy-absorbing design and their efficiency is proportional to increasing the thickness of the foam and changing the type of fibres used in the surface of the samples. Wang et al. [64] studied the behaviour of sandwich plates under medium-speed impact load using an experimental method. They observed that the material used in the core plays an important role in deformation, the amount of energy absorbed, the degradation mechanism, and the rate of impact of the impact on the plate. They introduced polypropylene honeycomb core as the optimal choice for post-impact deformation rate. Han and Chu [65] investigated the behaviour of sandwich composite plates with aluminium foam core and metal surface. Their results showed that with the impact energy of 50 joules, only the upper surface of the plate was destroyed, with the energy of 70 joules in addition to the destruction of the upper surface, the impact penetration was observed and finally, with the energy of 100 joules, the impact penetration destroyed the lower surface. Also, a good agreement between experimental and numerical results was reported. Rajaneesh et al. [66] studied and analysed composite sandwich sheets with foam core and soft metal surface. They compared the results of impact force, absorbed energy and shape of destruction in two ways, which showed a good agreement. Based on studies conducted in the past and considering the type of application of sandwich plates with an aluminium foam core in various industries, in the present study, the possibility of replacing glass-epoxy composite plates instead of the usual metal-aluminium surface and evaluating the effect of impact geometric shape on composite layers are covered. Since the geometric shape of the impactor (impactor curvature radius) varies depending on the application of the plates in the industry, to fully understand the behaviour of composites against impact loads, it is necessary to study their response to common geometric shapes. As mentioned in previous studies, the type of sandwich plate surface and the impactor shape play an essential role in the behaviour of the plate in this type of loading. Therefore, the effect of the surface type of the composite sandwich plate should be considered more. Accordingly, the main innovations and goals of this research that have not been addressed so far are

1. Investigating the possibility of replacing glass-epoxy composite plates instead of the usual aluminium metal surface.
2. Evaluating the effect of impact geometric shape (radius of curvature).
3. Investigating the effect Type of porcelain layer of composite surfaces.

For this purpose, three types of impact (cones, parabolic and spherical), as well as three types of porcelain layers of aluminium, orthogonal composite and quasi-isotropic composite are used. All the stages of making composites are summarized in the following flowchart (Fig. 1).

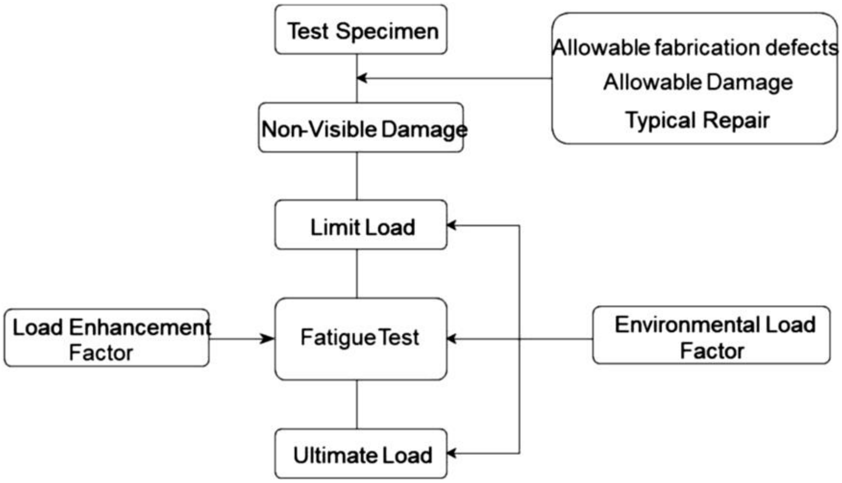

Fig. 1 All stages of manufacturing and testing composites

2. Materials, production method and production of samples

In this research, cast aluminium alloy A356 with the chemical composition listed in Table 1 was selected as the base metal. SiC particles with a purity of 98wt% and an average particle size of 11 µm were prepared as a reinforcing phase that also has a stabilizing role or viscous agent in the foam production process. SiC particles were heated for one hour at 951 ° C and then for 2 hours at 651 ° C to remove contaminants and adsorbed gases and thus improve the wettability of SiC particles by molten aluminium. Calcium carbonate powder with a purity of 99.5wt% and an average size of 5 µm was used as a foaming agent. This powder was heated at 211 °C for 2 hours in order to remove moisture and surface pollution and increase the wettability properties and consequently better distribution of these particles in the aluminium melt. To produce a foam product, first, a composite ingot from an aluminium matrix with certain amounts of SiC particles was produced and cast using the vortex casting method at a temperature between 651-711 °C. This ingot was stirred in the next stage and after re-melting at 651 ° C with a speed of 1411 rpm. At this stage, 1wt% of magnesium was added to the melt and then the mixture was stirred by adding calcium carbonate powder for one minute. After a few minutes and after the production of carbon dioxide gas, the foam produced is removed from the furnace and cooled in ambient air. 3wt% of calcium carbonate powder and 11% by volume of SiC particles are used in this stage to produce products. Figure (2) shows the aluminium foam made by the above method.

Table 1: Chemical composition of cast aluminium alloy A356 [67]

Combination	Si	Mg	Fe	Cu	Ti	Zn	Mn
wt.% [a]	6.81	0.35	0.19	0.09	0.07	0.02	0.01

[a] weight percent of chemical composition of cast aluminium alloy A356

Fig. 2 Aluminum foam sample produced

To make the composite surface of the samples, glass fibres in the form of the one-way fabric have been used. Each layer has a thickness of 0.2 mm and a mass of 200 g / m^2. This type of fibre is currently considered for various applications in the industry. ML503 epoxy resin and HA11 hardener, which are commonly used in various industries, have also been used. The mechanical properties of the composite sheets together with the resin used are given in Table 2. In this research, the manual porcelain layer method is used to make the composite layer of the surface of the plates and the surface thickness of all samples, without considering the adhesive layer of the connector, is considered to be 2 mm (similar to the thickness of the aluminium surface). The connection of the surfaces to the aluminium foam core for their chemical compatibility was done with the same two-component epoxy resin that was used in the production of composite surfaces, with a very small thickness.

Table 2: Mechanical properties of using for fabricating composite surface [68]

Mechanical properties	Value (MPa)
Longitudinal tensile modulus	19940
Transverse tensile modulus	5830
Shear modulus	2110
Longitudinal tensile strength	700.11
Longitudinal compressive strength	570.37
Transverse tensile strength	69.85
Transverse compressive strength	122.12
shear strength	68.89

The dimensions of the samples based on the fixture of the device used are 120 × 120 mm with a thickness of 20 mm (Table 3). Figure (3) shows an example of a sandwich composite plate with aluminium face sheets.

Table 3: Geometric and weight characteristics of the specimens

Face sheet type	Foam core thickness (mm)	Face sheet thickness (mm)	Sample weight (g)
Aluminium	20	2	388
Quasi-isotropic	20	2	301
Orthogonal	20	2	287

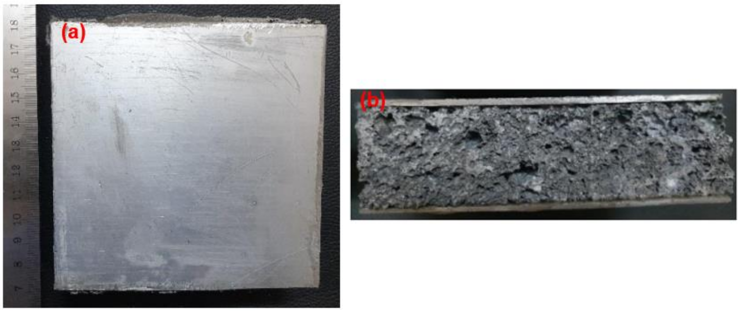

Fig. 3 Sample Sandwich Composite Plate with Aluminum Case (a) Front View (b) Side View

3. Impact test machine

One of the most important and effective factors in studying the impact phenomenon is the initial energy of the projectile. In this study, the low-velocity impact was performed by a drop weight machine; which may occur due to the sudden fall of the work tool during maintenance on the composite structure. For this purpose, the drop weight device available in the failure mechanics laboratory of the Faculty of Mechanical Engineering, K.N. Tusi University of Technology has been used. In this device, the projectile is located on a rail with very little friction that can fall freely. In this research, the low amount of friction in the rails and equipment of the device has been omitted according to the manufacturer's recommendation. The total mass of the striker and the accessories attached to it (force sensor, bearings, etc.) is 7 kg, which can fall on the target from a maximum height of 1 m. The capacity of the power sensor is 10 kN and with a data collection frequency of 25 kHz. The mass and height of the projectile can be changed and therefore different kinetic energies can be applied. In this experiment, for all samples, the impact mass and accessories with a weight of 10 kg, changes to 17 kg and falls from a height of 70 cm on the target sample. Thus, the initial impact potential energy for all samples will be 116.7 joules. Figure (4-a) shows the general view of the device used. According to the shape of the square samples made, it is placed on a special support and then emptied by a square clamp and fastened by four screws. Thus, all four edges of the sample are 10 mm wide and 100 x 100 mm free. The striker falls exactly on the midpoint of the free space of the sample. Figure (4-b) all tests are performed according to ASTM D7136 standard. In order to prevent the impact of the impact on the sample again, a pneumatic jack is used which acts quickly after the first impact and stops the striker to prevent secondary collisions Fig. (4-c).

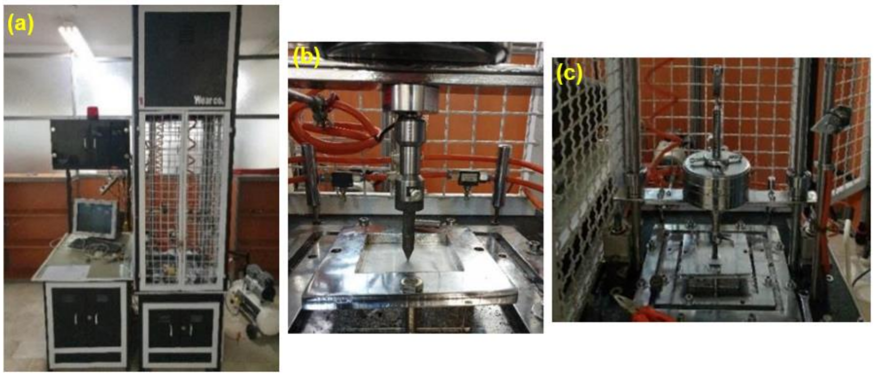

Fig. 4 Drop weight device (a) General scheme (b) Moment of impact on the specimen (c) pneumatic jack equipment for secondary impact prevention

4. The effect of the impactor shape and the porcelain layer of the surfaces

In this research, the effect of the impactor shape and the type of face sheets of the sandwich plate is investigated. Since the most common type of percussion is hemispherical, this type of percussion has been used in most studies. As previously explained, the impact geometric shape varies according to the application of sandwich plates in different industries and therefore can be very effective in impact load evaluation parameters. Therefore, in this research, three types of conical, parabolic and spherical impact shapes have been used. Therefore, in this research, three types of conical, parabolic and spherical impact shapes have been used. All three impactors with a diameter of 13 mm and a penetration height of 60 mm are made of hardened CK45 steel. Figure (5) shows these three types of impactors along with the weight of each. Since the weights of parabolic and spherical impactor are exactly the same and do not differ significantly from the conical type (about 3%), so the effect of the impactor weight difference on the results can be neglected. Therefore, in the present study, only the impact geometric shape has been evaluated as a parameter affecting the behaviour of the plate and its weight effect has been omitted without causing significant error in the results. This hypothesis has been considered in similar works.

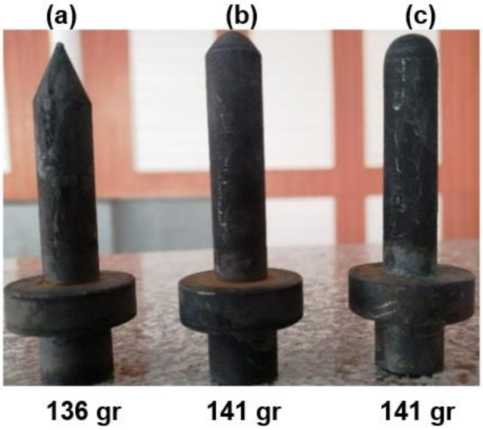

Fig. 5 Three types of impactor shapes (a) cone (b) parabolic (c) spherical with their weight

In addition, in the present study, the effect of face sheets has also been investigated. In evaluating other previous studies, most of the sandwich face sheets with metal or simple composite surfaces have been studied and less effect of the type of porcelain layer of composite surface has been studied. In addition to fabricating samples with aluminum surfaces, this study also fabricated orthogonal and quasi-isotropic composite surfaces and the results were compared. Figure (6) shows face sheet with a composite surface.

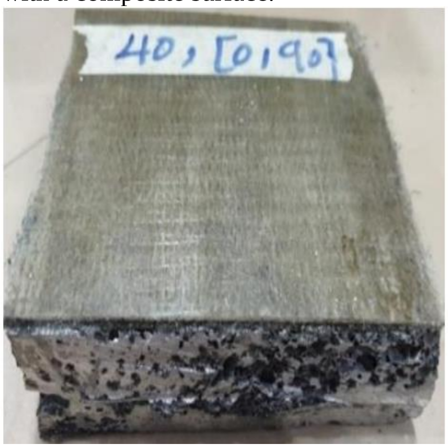

Fig. 6 sandwich composite plate with cross-ply surface

5. Results and discussion

As mentioned before, all tests are performed according to ASTMD 7136 standard at room temperature (this test method determines the damage resistance of multidirectional polymer matrix composite laminated plates subjected to a drop-weight impact event. The composite material forms are limited to continuous-fibre reinforced polymer matrix composites, with the range of acceptable test laminates and thicknesses). To prevent laboratory error, each experiment was performed on three similar samples and by comparing statistical parameters (mean value and standard deviation) the accuracy and reliability of laboratory results were ensured. Before starting the test by the device, its calibration process was performed according to the manufacturer's instructions, which include the steps of calibrating the sensor, temperature calibration, and initial settings of the device. Figure (7) shows a comparison of force-time diagrams for three different shock absorbers on a sandwich composite plate with an aluminium surface taken by the force sensor of a data device. These diagrams show the maximum increase in impact force versus the increase in the radius of the impact of the impactor. The lowest impact force is related to the conical striker, which is due to the impact of the striker inside the sample. Most of it belongs to the striking spherical type. Due to its geometry, the spherical striker does not have the ability to penetrate the sample, so it applies a strong force to the sample at the first moment. Since the initial impact energy is the same in all three types of impact, this phenomenon is due to the reduction of the impact surface by reducing its curvature. Similar results as seen in this section have been reported in previous studies. Since the experimental results did not show a significant dependence on the type of top layer of the sandwich plate, so in this section, only the results with the aluminium surface are presented.

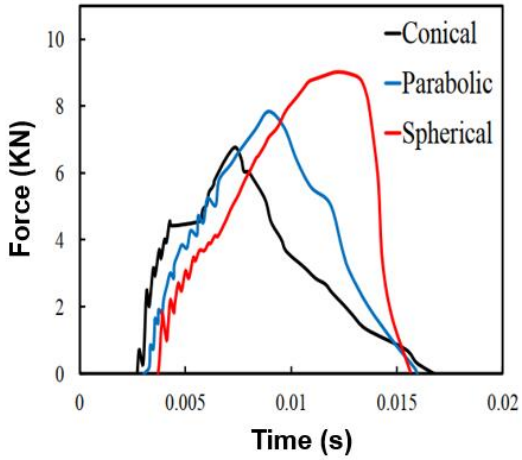

Fig. 7 Comparison of force-time diagram for three different impactors with aluminum layer

In general, it can be concluded that the greater the radius of the impact of the impactor, the maximum force of impact with the sample increases and decreases in contrast to the time of impact. To evaluate the effect of sandwich plate surface type, as described in the previous section, impact tests were performed on three types of aluminium surface, orthogonal composite and quasi-isotropic composite. The results of force-time diagrams with a spherical striker are shown in Fig. (8).

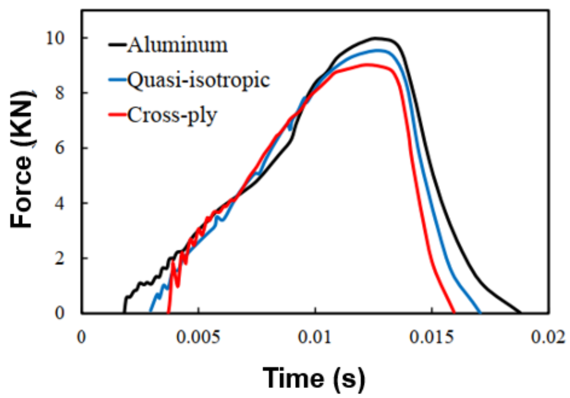

Fig. 8 Comparison of force-time diagrams for three types of face layers with spherical impactor

In this diagram, it can be seen that the aluminium surface of the sandwich plate has the highest amount of impact force and the orthogonal composite surface has the lowest impact force. Due to the mechanical properties of the aluminium layer and the shape of the spherical impact geometry, the least amount of projectile penetration occurred in the sample, which results in the highest impact force and impact time. The quasi-isotropic and orthogonal composite surfaces are then exposed to the maximum impact force and lower impact time. It should be noted that in order to evaluate the performance of different surfaces in impact load, different parameters must be considered, which will be mentioned in the continuation of the article. However, due to the approximately 30% reduction in face-sheet weight, reduction of production costs and economic justification and other unique properties of composite materials, composite face sheets can be used. In the force-time diagrams in Figures 7 and 8, several fluctuations are observed in the initial part of the diagram. Due to the fact that in measuring the impact force from the load cell connected to the data device is taken, with the beginning of the impact process and impact of the impact inside the surface of the plate and the aluminium foam core and considering the porous structure of the core as well as the composite surface, gradual damage occurs. These gradual damages reduce the resistance of the plate, which leads to a sudden drop in the force diagram. As the impact of the striker continues and the force increases, the effect of local damage disappears and the force-time diagram continues until the total damage of the plate or zero impact force. From the force-time diagram, using the relation (1), the impactor acceleration is obtained:

$$F(t) = ma(t) \tag{1}$$

Where m is the impactor mass. The following equation is used to obtain the velocity-time relation:

$$V(t) = V_0 - \int a(t)dt \tag{2}$$

Where $V0$ is the velocity of the projectile at the moment of impact with the screen. By reintegrating Equation (2), the displacement relation in terms of the impact time of the impactor can be obtained according to Eq (3).

$$\delta(t) = \int V(t)dt \tag{3}$$

On the other hand, the amount of energy absorbed by the plate is obtained from the area below the force-displacement diagram. In order to more accurately investigate the performance of the samples in the impact load and also due to the lack of effect of their thickness and weight on the amount of absorbed energy, in this study Specific Energy Absorbed (according to Equation 4) in terms of J/g is used.

$$(SAE) = \frac{E}{w} \tag{4}$$

Where E is the energy absorbed (J) and w is the sample weight (g). Figures 9 and 10 compare the maximum impact displacement, the maximum impact force of the impactor, and the amount of specific energy absorbed by the sandwich plate with the aluminium surface for three types of impactors: spherical, parabolic, and conical.

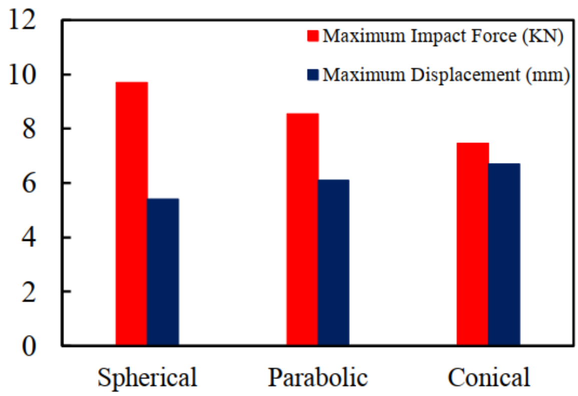

Fig. 9 Maximum impact force and displacement of sandwich plate with aluminum skin layer caused by different impactor

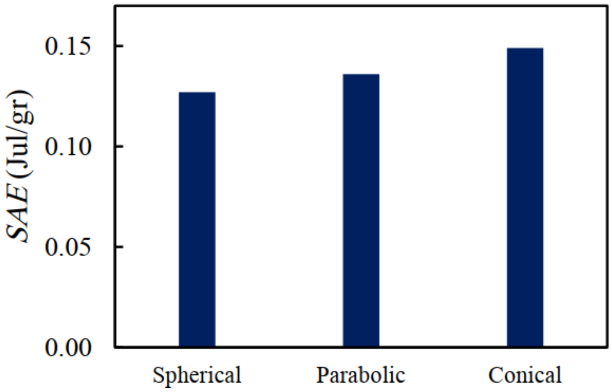

Fig. 10 specific energy absorbed of the sandwich plate with aluminum skin layer caused by different impactor

As can be seen, the larger the radius of curvature of the impactor (the wider the impactor head), the lower its displacement and the greater the impact force. On the other hand, by increasing the radius of curvature of the impactor, the amount of energy absorbed by the plate also decreases. This behaviour of the sandwich plate against different shock absorbers is due to the increase of the impact of the impactor in order to reduce its curvature. In this way, all the kinetic energy due to the speed of impact of the impactor on the plate is spent on the penetration of the projectile into its foam core, and therefore the surface of the sandwich plate plays the least amount of resistance. As mentioned earlier, this study also examined the effect of sandwich plate surface behaviour on impact resistance behaviour. Figures 11 and 12 show the maximum impact displacement, maximum impact force, and the amount of specific energy absorbed by the sandwich plate with three different types of aluminium, orthogonal and quasi-isotropic surface, and the use of spherical impact, respectively.

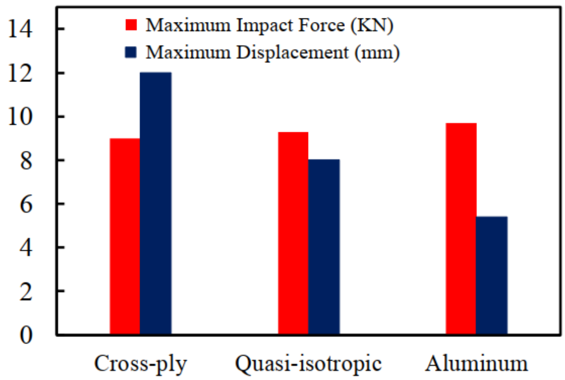

Fig. 11 Maximum Impact Force and Displacement of sandwich plate with different types of skin layer using spherical impactor

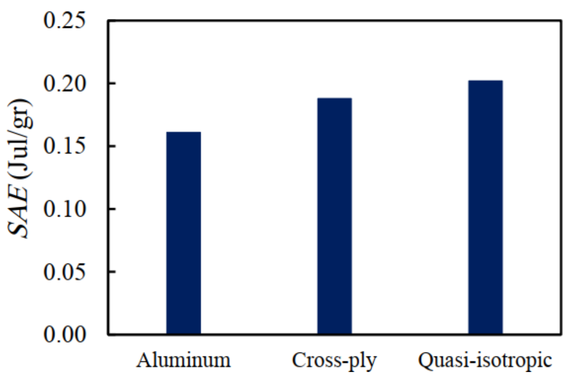

Fig. 12 specific energy absorbed of a sandwich plate with different types of skin layer using spherical impactor

The above diagrams show that the highest displacement of the sandwich plate belongs to the orthogonal composite (cross-ply) surface and the lowest belongs to the aluminium surface. Also, the aluminium surface has the most impact force in this case. Due to the different weights of the produced samples (Table 3), the highest amount of specific energy absorption of the projectile collision occurred in the sandwich plate with quasi-isotropic, orthogonal, and aluminium surfaces, respectively. Figure 13 shows the force-displacement diagram using a spherical shock absorber for both quasi-isotropic and aluminium composite surfaces. This diagram is obtained by using the information of the force-time diagram by applying relations (1) to (3). As mentioned earlier, this diagram deals with shock displacement and does not provide information on the displacement of a composite part. As can be seen, at the beginning of the graph, the behaviour is almost linear, which increases with the impact of the impactor. The slope of this initial linear part of the force-displacement diagram can be interpreted as the flexural stiffness of the sheet. In the second part of the graph and in a small part, with the increasing impact rate of the impactor, the amount of force is almost constant. Until in the final part, which is related to the test load, the impactor no longer penetrates the sample, and with the separation of the impactor from the sample, the applied force is gradually reduced to zero. It should be noted that the maximum difference between the impact force and the amount of special energy absorbed by the sandwich plate with three different surfaces is about 4%.

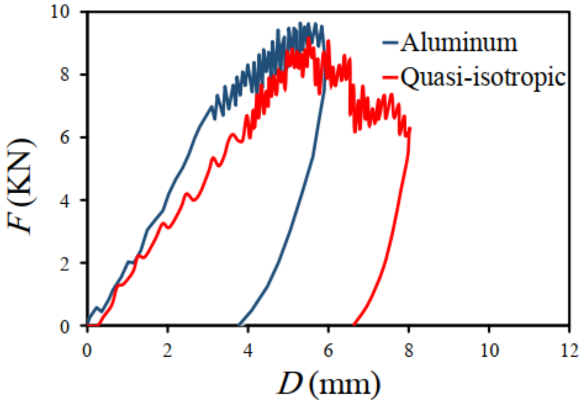

Fig. 13 Comparison of force-displacement diagrams for two types of skin layer (pure aluminum and quasi-isotropic composite) with spherical impactor

This difference in the three procedures indicates that the orthogonal and quasi-isotropic composite surfaces have a higher specific energy of absorption than the aluminium surface and therefore can be a suitable alternative for making sandwich plates under impact load. In addition, the reduction of structural weight, strength against abrasion, fatigue, thermal resistance, and other distinctive properties of composite materials can encourage the designer to use these surfaces in the design of energy-absorbing structures. Figure 14 shows images of sandwich samples with different surfaces that have been subjected to a drop impact test using a spherical hammer. Since the analysis of sample damage and the mechanism of their destruction is not the subject of this article, it is sufficient to report only a sample of it. As can be seen, the spherical impactor on the plate with aluminium and quasi-isotropic surfaces is inserted from the upper surface but is stopped in the foam core. As can be seen in the figure, the surface damage of a sample with an isotropic surface is greater than the surface damage of a sample similar to an orthogonal surface. This phenomenon is due to the greater impact force in this case (Fig. 12). Also, the separation of the surface from the core is seen in the orthogonal sample, which has not been observed in the case of the isotropic analog. Also, in evaluating the impact depth of the impactor in this case, the highest penetration depth belongs to the plate with orthogonal surface and the lowest is related to the plate with aluminium surface, which can be seen in Fig. (11).

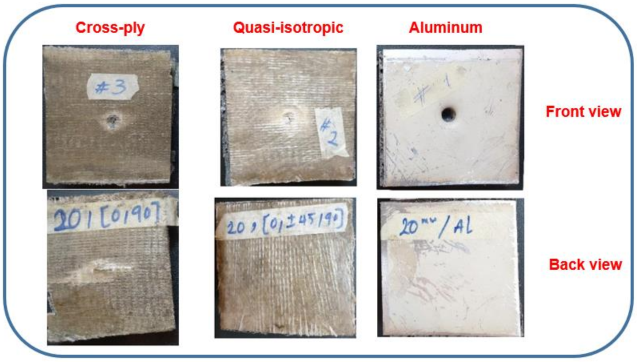

Fig. 14 Front and back view of the specimens after testing by a spherical impactor

6. Conclusion

In this paper, the effect of the impact geometric shape and the porcelain layer on the behaviour of the sandwich composite plate was investigated. For this purpose, three types of conical, parabolic, and spherical impact geometric shapes as well as three types of aluminium surface, orthogonal composite, and quasi-isotropic composite with a thickness of 2 mm were used. 20 mm thick aluminium foam was used as the core of the sandwich plate. All experiments were prepared at room temperature and according to the relevant standard and performed using the drop weight method. The following can be mentioned as a summary of the results:

- In aluminium sandwich plates, the highest impact force is related to the spherical impactor and the lowest is related to the conical impactor. In other words, by reducing the radius of impact of the impactor, the maximum impact force is also reduced. Therefore, in applications of energy absorbers where the impact geometric shape is spherical, the maximum impact force is very high that should be considered in the design of structures.
- In sandwich plates with aluminium surfaces, the conical shock absorber displacement is more than other types of shock absorbers due to the possibility of penetrating the plate and the spherical type has the lowest impact penetration depth. It can be said that the sharper the impactor, the higher its displacement due to the impact with the screen. Therefore, in the design of energy-absorbing structures, the impact depth of the impactor is considered a very effective factor, and this parameter is a function of its radius of curvature.
- The rate of absorption of specific kinetic energy due to the impact of the impactor on the plates with the aluminium surface with the conical impactor is the highest and the lowest value for the spherical impactor. Therefore, in the design of structures in which the amount of energy absorption is more important and also the impactor has a conical geometry, the use of this type of sandwich plate is recommended.
- Using a spherical impactor, the maximum and minimum impact forces are observed in sandwich plates with orthogonal aluminium and composite surfaces, respectively. Also, in this case, the amount of impact displacement on the plate with the orthogonal composite surface is the highest and with aluminium surface is the lowest. Therefore, if the least amount of displacement is more important in the design of sandwich plates, the use of aluminium surface is recommended.
- Considering the comparison of the amount of specific energy absorbed in the plates with aluminium, orthogonal and quasi-isotropic surfaces, it can be concluded that if the amount of specific energy absorption is more important in the design of energy absorber, composite surfaces can be used as an alternative to aluminium. Among the composite surfaces studied in this research, the isotropic quasi-isotope surface has a better performance in this regard. Weight reduction, reduction of production costs, and increase of other mechanical properties (wear resistance, corrosion, etc.) are other characteristics of using composite surfaces in the design of sandwich structures under impact load.

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