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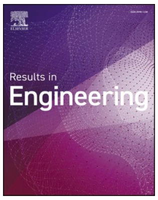

Experimental and numerical investigation of multi-layered honeycomb sandwich composites for impact mechanics applications

A. Al Ali[a], E. Arhore[a], H. Ghasemnejad[a,*], M. Yasaee[b]

[a] *Centre for Aeronautics, Cranfield University, MK43 0AL, UK*
[b] *Magma Global, Portsmouth, PO6 4PX, UK*

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ABSTRACT

This project aims to investigate the design of a multi-layered sandwich composite and its performance under impact loading conditions. An experimental and numerical assessment was performed to conclude the effect of increasing the layers of sandwich panels. Three specimens of four different sandwich panel configurations were manufactured to be tested. The skin of the sandwich panels comprises a twill carbon-reinforced epoxy resin, whereas the core consists of a 2D Nomex honeycomb core. The panels are then subjected to transverse impact loading to investigate their impact behaviour. These experimental results are then used to verify numerical models constructed in LS-Dyna. The models of the honeycomb-reinforced sandwich panels are investigated using MAT-054 and MAT-142 material cards in LS-Dyna to find the most economical computational approach. Finally, the energy absorption characteristics calculated during the experimental and numerical work are used to conclude the multi-layered sandwich composite's performance and provide design recommendations. The findings suggest that by increasing the core and shell numbers through the thickness of the panel, the specific energy absorption capability will increase.

1. Introduction

Nowadays, composite materials are introduced into almost every industry. One of the benefits of using composites is the wide range of property values attained with them and the ability to tailor their properties depending on the application they are utilised for. In addition, composites exhibit higher strength-to-weight and modulus-to-weight ratios than traditional engineering materials such as metallic alloys. These features can reduce a system's weight by up to 30 % with weight savings that equate to energy savings or improved efficiency. In addition, advanced composites have other useful properties, such as high creep resistance and good dampening characteristics. Composites are even used to repair metallic airframes because of their superior fatigue performance [1].

One widely used composite material form is in a sandwich configuration. Hoff and Moutner [2] proposed one of the first articles devoted to sandwich composites where he describes them as composites that are distinguished using a multilayer structure composed of one or more high-strength outer layers referred to as skin and one or more low-density inner layers referred to as a core. The same definitions are still used today with some variations of this type of structure [2]. Composite sandwich panels with two relatively stiff face sheets separated by a lightweight core are attractive for industries where mass reduction is critical. Sandwich panels are widely used in the transport, aerospace, automotive, naval, and defence industries. They are well-known for their high bending and shear resistance. As a result of the growing industry interest in the use of sandwich panels in recent years, a significant amount of research and development on the impact characteristics of sandwich composites have been conducted.

The development of lightweight composite sandwich panels with high-impact resistance has motivated the interest of many researchers. Many engineering structures are susceptible to impact damage. An example is bird strikes on wing structures in aerospace vehicles which can introduce significant damage and loss of functionality of the overall vehicle.

The response of sandwich composites to impact is similar to Whipple shields, which are used for hypervelocity protection of space vehicles. Whipple shields are designed for protection against high-velocity space debris. The system shielding consists of multiple walls separated by distance. The front wall is commonly referred to as the bumper, and its primary function is to disperse projectiles into a cloud of material that expands as it moves across the standoff. The impactor's energy and

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* Corresponding author.
E-mail address: Hessam.Ghasemnejad@cranfield.ac.uk (H. Ghasemnejad).

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momentum are distributed over the rear wall, which must be thick enough to withstand blast loading from the fragment cloud and stop its further propagation. Modern Whipple shields are stuffed with foam and honeycomb cores to increase the crashworthiness of space vehicles [2].

To the knowledge of the author, the first study aiming for analytical modelling of the low-velocity impact behaviour of composite panels was that of Sun and Chattopadhyay [3], who computed the equivalent stiffness for a supported monolithic composite plate out of the equations developed by Whitney and Pagano [4], whereas the contact force was considered as of Hertzian-kind. However, the existence of nonlinear terms in the contact force governing dynamic equations proved to hinder its implementation, thus necessitating numerical resolution. Another approach was used by Shivakumar et al. [5], which consisted of the use of a two-degrees-of-freedom (TDOF) equivalent spring-mass system that accounted for the monolithic laminate's membrane, shear and bending stiffnesses, plus the contact stiffness, to capture the dynamic response of the event. Although it simplified the implementation compared to previous studies and good agreement was obtained with respect to existent data under certain conditions, the definition of the equivalent stiffnesses was based on isotropic plate theory, where the inputted properties were computed from the actual anisotropic composite ones. Thus, its implementation was limited to the then-dominant quasi-isotropic laminates.

Ouadday et al. [6] studied experimental characterization and modelling of the impact behaviour of a multi-functional dual-core sandwich panel designed for the rehabilitation of hydroelectric turbines. The experimental results showed that for the tested impact energy range, the sandwich panel absorbs approximately 50 % of the impact energy. Although the top facesheet and the ATH/epoxy core govern the initial impact behaviour, the recoverable compression deformation of the XPS foam core is the major energy absorption mechanism. This statement is well supported by the numerical simulation. Zhang et al. [7] investigated a series of air explosion experiments on the 3D polyurea-coated auxetic lattice sandwich panels in order to combine the advantages of auxetic materials and polyurea. The results showed that the dynamic response of the 3D polyurea-coated auxetic lattice sandwich panel could be divided into four stages: the shock wave action stage, the auxetic effect stage, the overall deformation stage, and the oscillation stage. Mani et al. [8] employed hybrid sandwich polymer structures in various secondary aerospace applications like antennas, solar panels, tailplanes, wings, doors, and control structures owing to their wide range of advantages. Their investigation explored the better functionality of sandwich polymer panels' impact strengths during barely visible low-velocity impact (LVI) analysis.

Wu et al. [9] and He et al. [10] systematically investigated the response and damage behaviour of CFRP-aluminium honeycomb sandwich panels under low-velocity impact using experiment and simulation, which included the effects of honeycomb edge length, unit cell size, and face sheet thickness. The results indicated that the impact curve with different impact energy can be divided into single-peak type, platform area after single-peak and double-peak, and the face sheet thickness had a significant effect on the impact resistance, while the thickness of honeycomb wall and edge length had less effect on the stiffness and impact load.

Yefei Zhu a, Yuguo Sun [11] performed analytical and experimental investigations on the low-velocity impact response of multilayer foam core sandwich panels with composite face sheets. Considering the reinforcement of face sheets by foam cores, an energy-based analytical model for multilayer sandwich panels was developed to predict contact forces, impactor displacement and energy absorption. According to their results, Adjusting the local stiffness close to the top face sheet can further improve the energy absorption of multilayer sandwich panels; however, the maximum contact force will be increased. This finding suggests that the design of multilayer foam core sandwich panels needs to carefully consider the requirements according to the cases in engineering applications. Goswami and Becker [12] have investigated sandwich plates using Finite element methods under in-plane loading. From the analysis, they found that significant stress concentration at cell walls which leads to cracks. For different crack lengths energy release rate has been analysed using the fracture mechanics technique and observed that for small formations the significant energy release rate is high.

More appropriate and extensive research was conducted by Hoo Fatt and Park [13], who developed a variational-based formulation for modelling both the indentation and the global response of the sandwich panel. This approach relied on the minimization of the potential energy, and the crushed/non-crushed core bizonal domain was considered within the equations, not needing a discretional input of the boundary definition. Results from this modelling technique were found to be close to reality. However, due to the neglect of the differentiated unloading path for the indentation of a sandwich panel, results lacked accuracy when considering the post-peak-force response. Moreover, the definition of the upper facesheet deformed shape lacked further justification, as it was not included within the potential energy minimization. Based on this latter work, some further studies, such as those from Malekzadeh et al. [14] and Khalili et al. [15], were conducted in an attempt to increase the applicability and accuracy of the analysis through the use of the improved higher-order plate equations (IHSAPT) and three-degrees-of-freedom spring-mass-dashpot systems. To that end, the formulation was developed within [14], where it was proven that this method delivered results closely matching those available in the literature, whereas the study in Ref. [15] depicted the effects that different parameters have on the impact response. Moreover, in a later study, Malekzadeh et al. [16] also introduced more general descriptions of the facesheets behaviour, where both membrane and plate terms are simultaneously considered, as well as the in-plane loading effect. It was found that the application of in-plane stresses on the panel had a noticeable effect on the contact duration and the peak force. This behaviour supports the interest in the use of non-conventional core geometries in an aim to improve the low-velocity impact performance of sandwich panels. Eventually, one of the most recent studies concerning the low-velocity impact modelling of sandwich structures was performed by Arachchige and Ghasemnejad [17], who proposed a new formulation that accounted for the uneven distribution of stiffness across curved sandwich panels.

Hou et al. [18] conducted an experimental study in which it was proved that non-conventional hollow-core geometries, such as those auxetic-like, may improve the impact performance and increase its robustness. Therefore, it has been vehemently shown that the characterization of low-velocity impacts in composite components is of large interest within the scientific community, with special attention paid to its analytical modelling. Zhu et al. [19] investigated the bending performance of a new type of composite sandwich panels with pultruded profile cores, and multiaxial glass fibre-reinforced polymer (GFRP) facial sheets and webs between the profile cores. The results show that wrapping multiaxial fibre cloth can change the brittle failure characteristics of the pultruded profiles and that the multiaxial FRP surface and uniaxial pultruded profiles can operate effectively. Xie et al. [20] studied the flexural properties of polyethylene terephthalate (PET) foam-filled lattice composite sandwich panels subjected to four-point bending (FPB). The effects of different face sheets and core thicknesses on the flexural properties of the sandwich panels were analysed. Experimental results indicated that the glass fibre-reinforced polymer (GFRP) webs can effectively prevent the sandwiches from catastrophic failure, the failure modes of the structures are dominated by foam shear, top face sheet compressive, and top face sheet-core debonding. Increasing the face sheet and PET foam thickness can effectively improve the ultimate load of the panels by 88.9 % and 115.6 %, respectively. Sun et al. [21] investigated bending performances at different loading rates for carbon fibre/honeycomb sandwich panels toughened by short aramid fibre tissues and carbon fibre belts. The carbon fibre belts were stitched across the pores of the honeycomb core for interfacial improvements. According to their results, the crack isolation phenomenon was found to be the main mechanism for avoiding interfacial damage of the sandwich specimen.

There have been many studies conducted on the behaviour of traditional sandwich composites to impact. However, these are typically conducted on standard two outer skin with single low-density core configuration. The main idea of this research is related to lightweight design and to how the impact resistance of sandwich structures can be improved without significant weight penalty. Both the aerospace and automotive industries would benefit from the outcomes of this research by improving the out-of-plane stiffness and higher energy absorption capability in comparison with the existing designs. To the best of the authors' knowledge, there are no studies on the performance of multi-layered sandwich composites to impact events. Therefore, this research paper focuses on the performance of different arrangements of multi-layered sandwich panel structures under drop height impact loading conditions. We investigate the performance of these various arrangements using experimental and numerical methods. With numerical models, the aim will be to seek accurate, low-cost, and efficient solutions for analysing the performance of multi-layered sandwich composites in order to better understand the ability of the structure to absorb energy and its energy absorption behaviour.

2. Experimental studies

Four different sandwich panel configurations were made of CFRP and Nomex Honeycomb to be studied in the scope of this project. The mass of the specimens was fixed as the experimental constant, whereas the specimen dimensions were variable. Fig. 1 depicts the difference in the overall Nomex honeycomb and CFRP layers between the five different configurations studied. In this paper, the difference between the impact performance of standard sandwich composite (Fig. 1 – S1) will be with those of multi-layered design (Fig. 1 – S2 – S4). A monolithic composite (Fig. 1 – Base Model) is also investigated to aid in the development of numerical models.

Since the density of the Nomex honeycomb core is too small relative to the density of CFRP, the number of layers of CFRP has the highest influence on the mass of the overall sandwich panel structure. In this case, the number of CFRP layers was used as the control to normalise the mass amongst all designs in Fig. 1. Fig. 2 depicts all the proposed designs in this research. Case (S1) is made up of two CFRP skins and a Nomex honeycomb core. Each CFRP skin laminate has ten plies, resulting in a skin thickness of 2.5 mm. As a result, the overall specimen thickness is 15 mm.

Case (S2) consists of two skins and 3 core layers. The skins consist of 8 plies of CFRP laminate, whereas the core consists of 2 Nomex honeycomb cores and one 4 plies CFRP laminate in the middle resulting in a 25 mm thick specimen. This design aims to understand the effect of adding a layer of CFRP and HC to the core of the sandwich panel.

Similar to the case study (S2), case (S3) consists of two skins and 3 core layers. However, in this case, the effect of thinner CFRP skins and thicker CFRP core is applied. Resulting in skins consisting of 6 plies of CFRP laminate, whereas the core consists of 2 Nomex honeycomb cores and one 8 plies CFRP laminate in the middle resulting in a 25 mm thick specimen. This case study aims to understand the effect of having a different arrangement of layers of that in case (S3). Moreover, to understand the effect of having a thicker CFRP core laminate. The effect of adding another honeycomb core to the sandwich panel is applied. Case (S4) consists of two 6 plies CFRP skins and 3 Nomex honeycombs and 4 plies of CFRP core layers resulting in a 35 mm specimen thickness.

2.1. *Sandwich panels manufacturing*

This section presents the manufacturing process that was conducted to produce the sandwich panel specimens used in the experimental part of this study. There are three common methodologies to manufacture sandwich composite panels. The first methodology is co-curing which is when the whole sandwich panel is cured in one curing process, where both skins are bonded with the core with or without the aid of an adhesive film. The second methodology is co-bonding, which involves two curing processes. While one skin is curing, the other skin is bonded to the core. The third method is known as secondary bonding, and it involves three curing processes in which the two skins are cured individually, then joined to the core using adhesive and cured for the third time. In this paper according to the recommendations in the literature [14–21], the third methodology was found to produce the most consistent output and highest performance. Therefore, CFRP plies were cut and attached to prepare for curing. Fig. 3 shows the produced sandwich panels after the curing and trimming process.

2.2. *Experimental results and discussions*

In this study, the impact test is approached in terms of high energy using a hemispherical impactor. The test is carried out at Cranfield Impact Centre's drop tower testing facility. Fig. 4a indicates the testing facility and the hemispherical impactor used for the test. Fig. 4b depicts the testing procedure. First, the impact velocity is calibrated using the kinetic energy principle after determining the desired energy of the heavy-weight impactor. After that, the impactor is dropped on the specimen, and the impact begins. During the impact, information on impact force, displacement, and velocity is measured using sensors. The impactor comes to a halt when it reaches a metallic piece set beneath the specimen to absorb the remaining energy.

The impactor, target, and impact velocity parameters are all considered in this experimental setup. A hemispherical impactor with a diameter of 20 mm and a weight of 46 kg is employed. The impactor velocity is set to 2.5 m/s producing ~143.75 J of impact energy. This corresponds well to the ballistic limit of similar structures found in the literature, comparable to a steel ball bearing weighing 7 g moving at

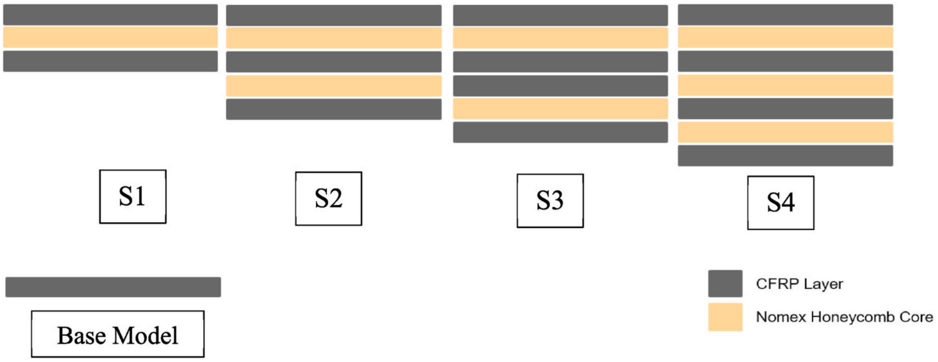

Fig. 1. Sandwich panel configurations, S1) single core sandwich, S2) double core sandwich, S3) double core with twin skin in between and S4) triple core with two laminates in between.

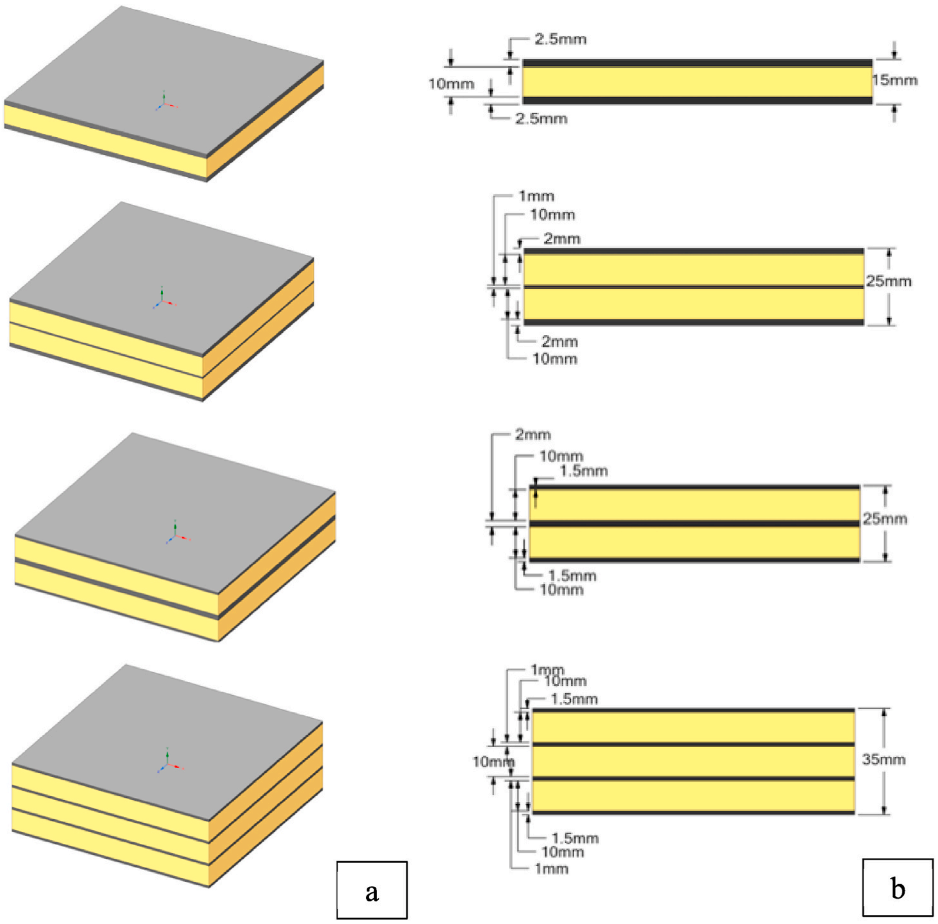

Fig. 2. Various designs of sandwich panels have a) an isometric view and b) a side view.

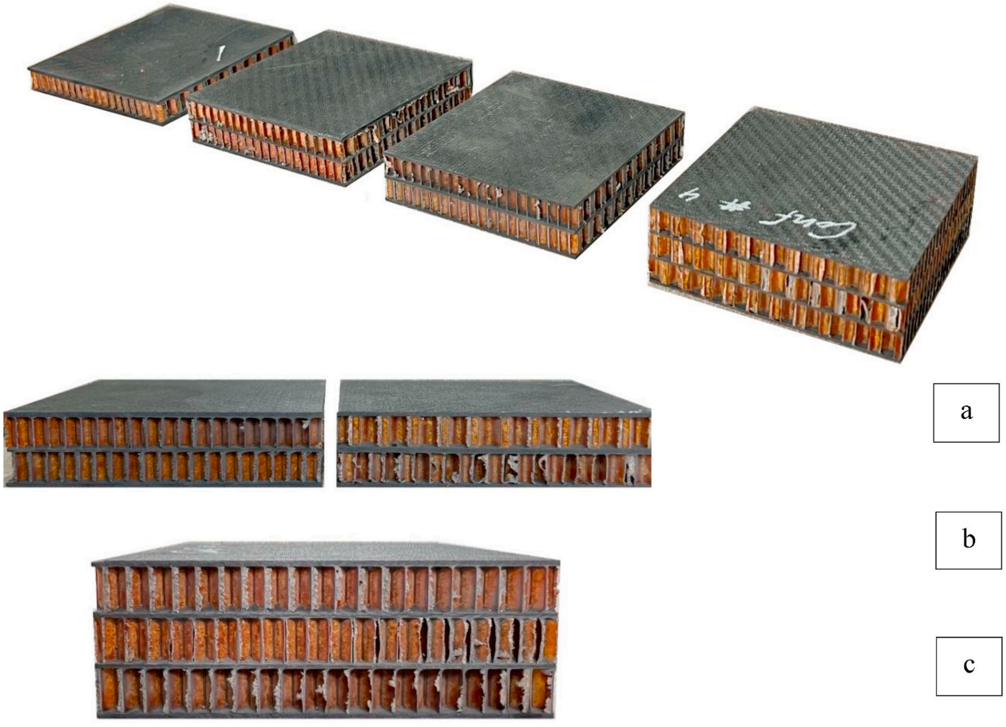

Fig. 3. a) Isometric view of various designs of sandwich panels from CFRP and Nomex materials, b) side views of designs S2 and S3 and c) side view of design S4.

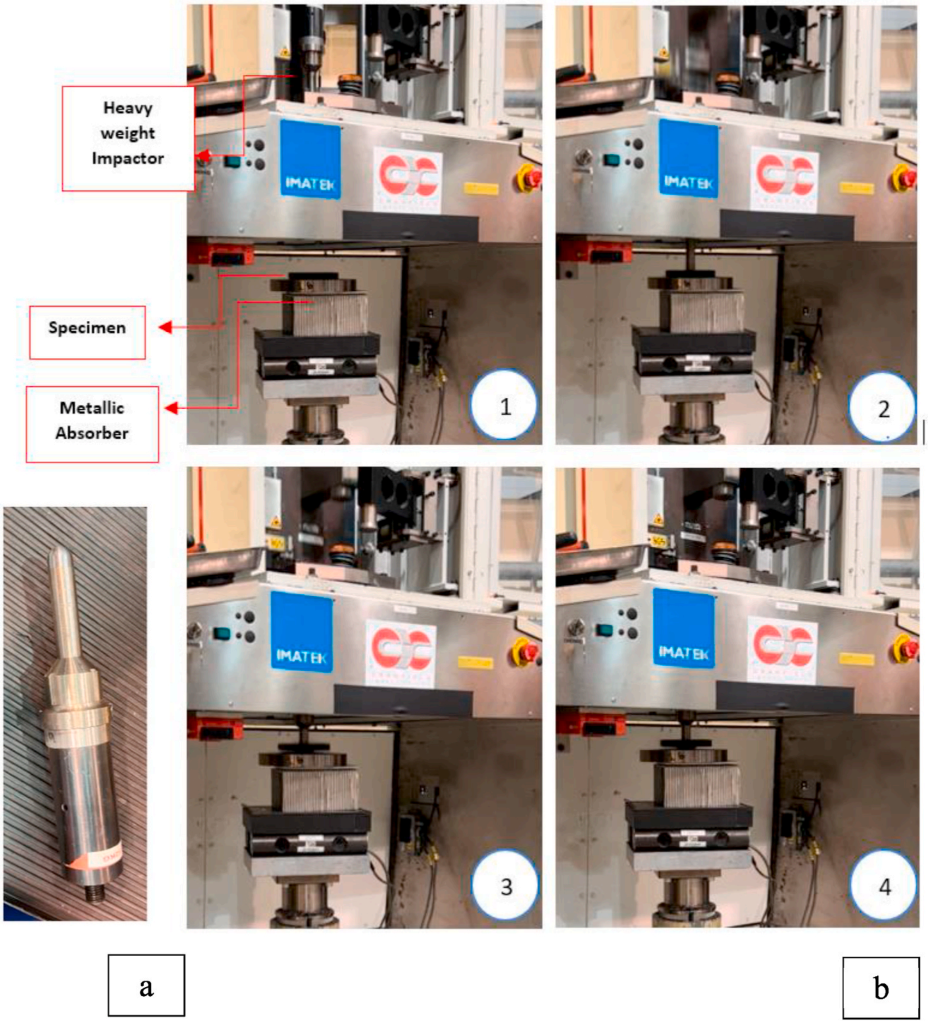

Fig. 4. Various stages of high energy impact test at Cranfield Impact Centre, a) hemispherical impactor and b) drop tower test facilities.

207 m/s with an energy of ~150J.

The impacted specimens for various designs are shown in Figs. 5–8. All four configurations of sandwich panels have a nearly identical fracture mechanism. When the top skin fractures, it behaves similarly to the monolithic composite, with a hole approximately the size of the impactor diameter and no other visible damage. However, when cutting the samples across the centre of the fracture, delamination in the top skin in all configurations is visible. This again can be interpreted as the sliding and shear between the laminate plies due to the impact. In addition, debonding between the core and the bottom side of the top skin can be visible.

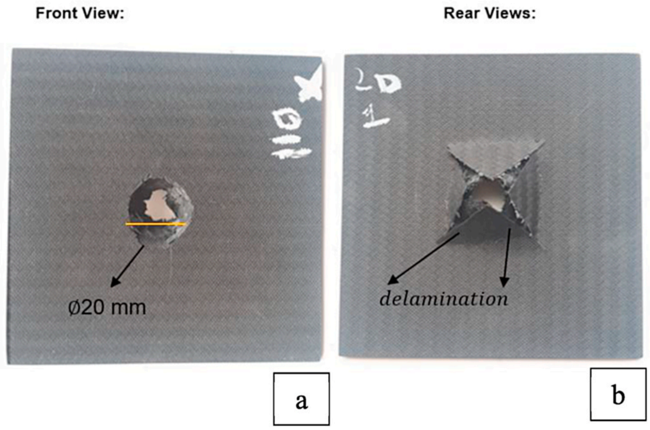

Fig. 5. Monolithic composite panel after impact - a) side view and b) rear view.

Debonding and fracture of core cells are visible when moving across the thickness of the sandwich panel where the impact occurred. Impact damage causes debonding between the core and the skin near the fracture. As a result, the adhesive between the core cell walls and the core and skins fail.

Delamination of the middle layer is visible in configurations with a middle laminate, such as configurations S2, S3, and S4. However, delamination is clearly more visible in design S3. This is due to the layer's thickness which indicates high energy absorption. Finally, the back of the sandwich panels shows a protrusion nearly the size of the impactor. The protrusion is made up of compressed core fragments. Furthermore, it contains fibre bits because of the delamination of each composite layer during the impact. This protrusion is comparable to that seen in monolithic composites. Debonding between the core and the bottom skin is visible in the cross-section. Furthermore, shear and sliding of plies cause delamination along the thickness of the skin layer.

The energy absorption capacity of each specimen is calculated using the previously extracted data. Fig. 9 indicates the residual velocity, energy absorption, and specific energy absorption of the specimens of each case study. Configuration **S4** showed the highest energy absorption because it resulted in the lowest residual velocity. Configuration **S3** has a higher specific energy absorption than configuration **S2**. Configuration

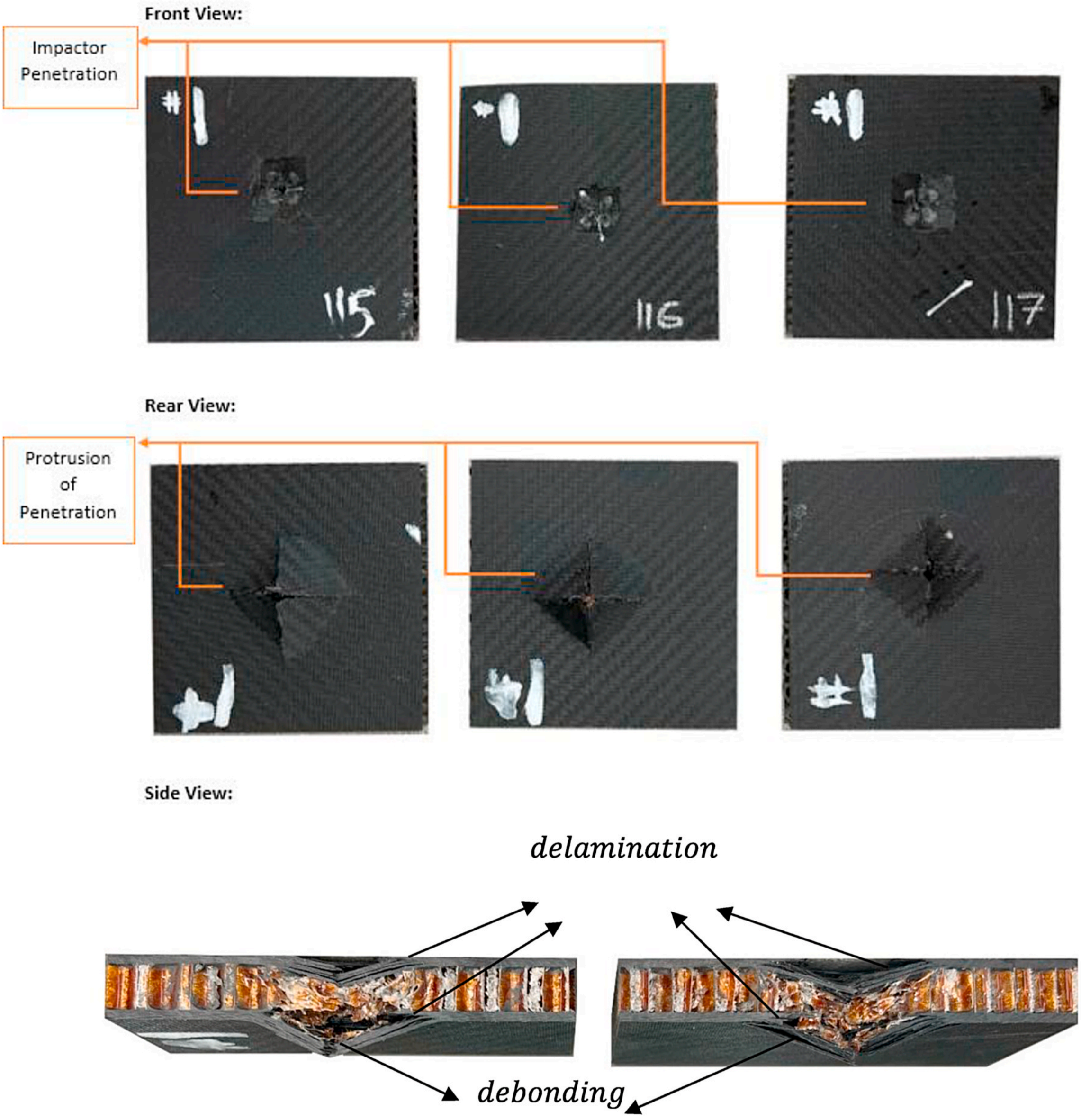

Fig. 6. Sandwich composite panel – Design **S1** - after impact a) side view and b) rear view.

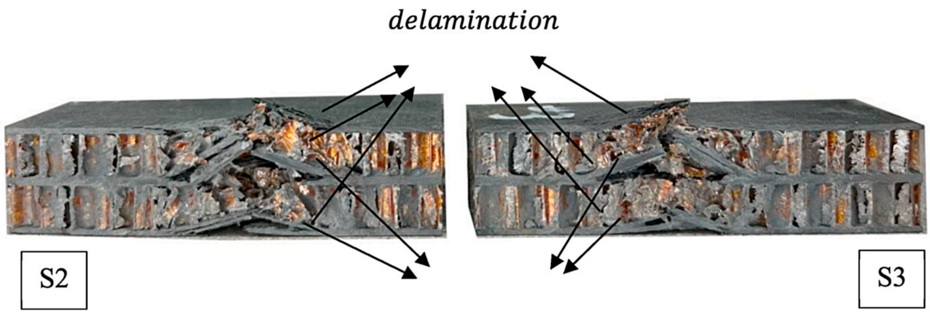

Fig. 7. Side view of the sandwich composite panel – Designs **S2** and **S3** - after impact.

S3 outperforms Configuration **S2** because it contains less crushed mass, resulting in nearly the same specific energy absorption. Furthermore, as demonstrated by the Base Model, sandwich composite panels have a higher energy absorption capacity than monolithic composites.

3. Finite element modelling of the multi-layered honeycomb sandwich panels

For the objectives of this study, numerical simulations were performed using LS-Dyna software. LS-PrePost V4.7.7 was used to set up the model and analyse the results, while LS-Run R2 was used to run the

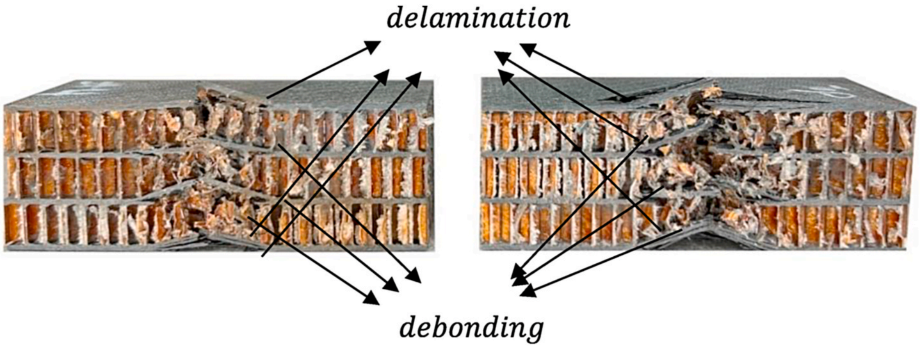

Fig. 8. Side view of the sandwich composite panel – Design **S4** - after impact.

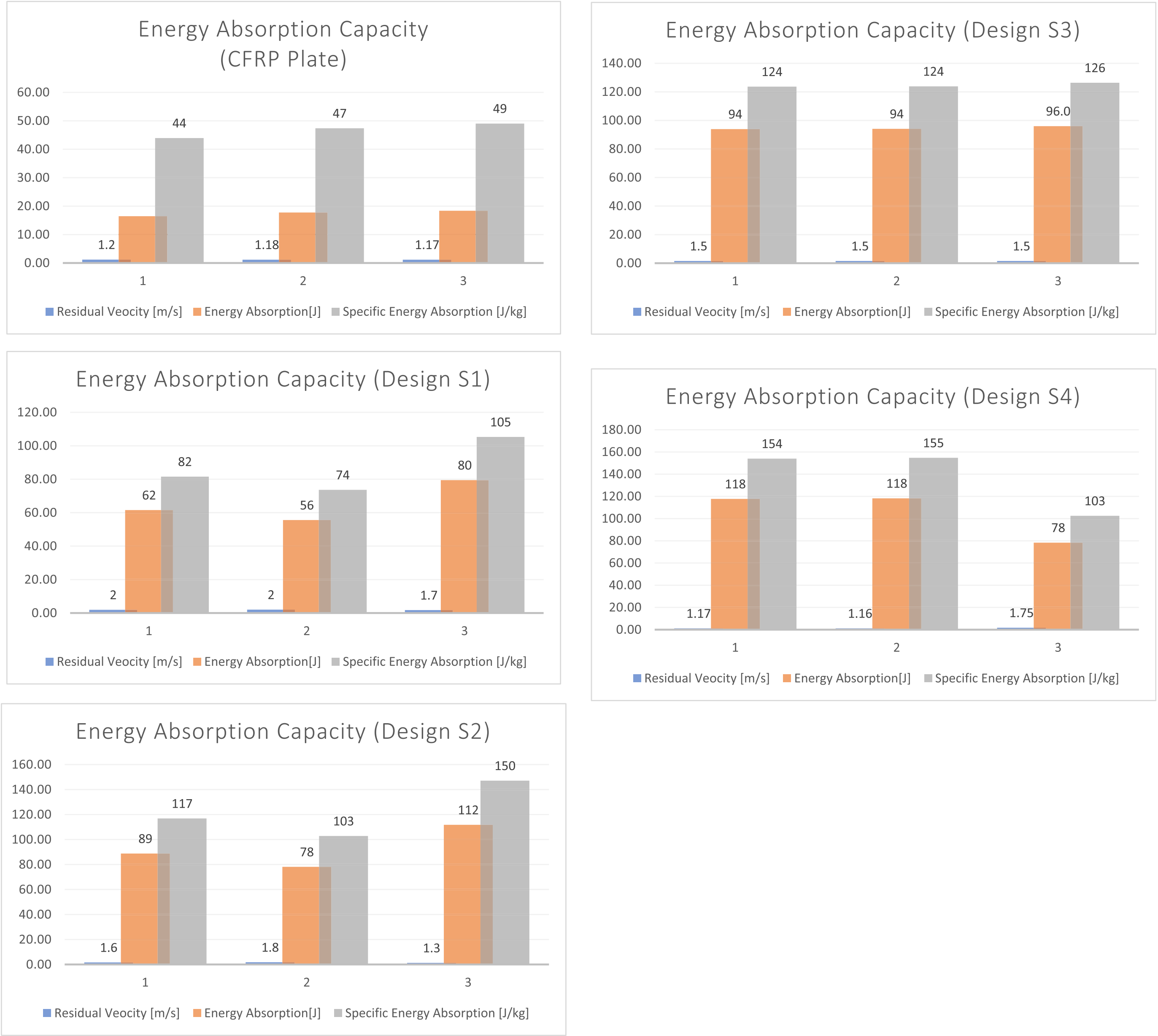

Fig. 9. Results for energy absorption capacity for various designs of sandwich panels – 3 tests for each design. The specific energy absorption has been tripled from 47 J/kg (CFRP) to 138 J/kg (Design S4).

simulation. The impactor has a cylindrical shape and weighs about 46 Kg. The impactor's geometry is modelled using solid elements and rigid sections. The hemispherical impactor's geometry was modelled as a sphere. The weight was also adjusted based on the density of the sphere. The spherical impactor geometry was modelled using a rigid material model of MAT 020.

The honeycomb was made from solid elements and material model MAT-142 was assigned to the geometry. As the material card is anisotropic, the directional material properties in relation to the global coordinate system were considered for this material model. The skins were modelled as shell elements, and then MAT-54 was assigned to their geometries as composite parts. According to mesh sensitivity analysis, a 2.5 mm hex mesh was assigned to the geometry of the core and skins. A ten-element mesh was maintained along the thickness of the geometries, allowing to capture of accurate results. Fig. 10 illustrates the assigned mesh to the geometries. To replicate the setup described in this paper, the edges of the core and skin were fixed in all directions. In terms of contact definition, the impactor and core and impactor and skin bodies denoted as A, B, and C in Fig. 10, were assigned automatic-surface-to-surface and automatic-single-surface contacts, respectively. This will define the impact instance and prevent interference between bodies. Contact A was chosen because the honeycomb body tends to lose contact when the impactor begins to penetrate its body. A tiebreak contact was assigned between the skins and core to simulate the adhesive between them. An automatic-single-surface-tiebreak was used between the top skin, represented by D, and a node-to-surface-tiebreak contact was assigned between the nodes at the top of the bottom skin and core, represented by E. This ensures that the tiebreak is activated at the top skin when impact occurs and prevents the tiebreak from becoming lost at the bottom skin. Finally, an initial velocity was applied to the nodes of the impactor with an initial impact velocity is 2.5 m/s (see Fig. 11).

4. Validation of finite element studies

The FE results are plotted alongside experimental data to aid in understanding the FEA performance. A good agreement was observed between load-displacement from the experiment and FEA, as shown in Figs. 12 and 13. As a result, the FEA calculated specific energy absorption values are close to the experimental values with an error of less than 10 %. Our model can predict the overall force–displacement behaviour for every four designs. However, due to multi-damage and debonding at interfaces during experimental results, FE results cannot predict that specific behaviour and it comes to the higher value of loads at the end of the process. This phenomenon is observed for designs S1 and S2. For designs S3 and S4, fragmentation of cores and skins added extra resistance to the experimental samples which is again not predicted in FE models. This would be the main reason for discrepancies between numerical and experimental results in a particular case for design S4. Finally, it is concluded that the existing damage models are not capable of predicting the out-plane damage and failure in composite structures in particular case of sandwich panels. The difference between experimental and numerical results is significant when the core thickness increases.

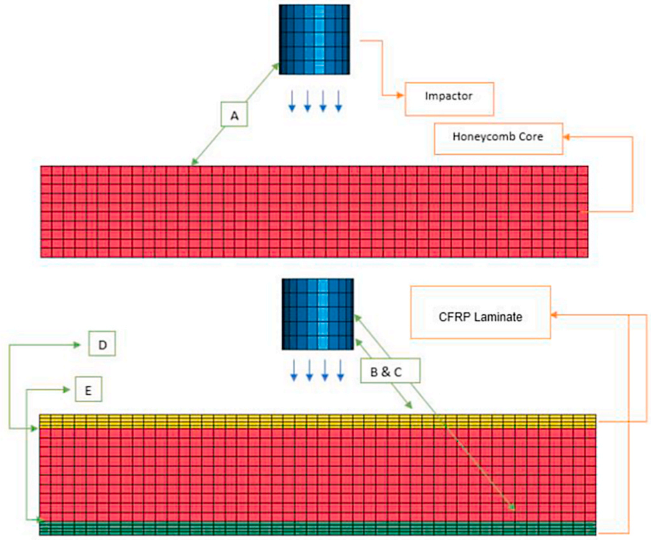

Fig. 10. Mesh and boundary and loading conditions for sandwich panel with Design **S1**.

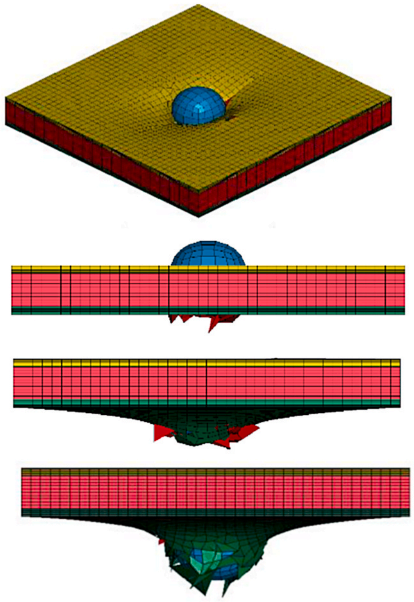

Fig. 11. Various stages of the impact of the striker on the sandwich panel with Design **S1**.

5. Conclusion

This research allowed us to have a better understanding of the behaviour of multi-layered composite panels. Various layer configurations of multi-layered sandwich composites were manufactured and tested under high-impact energy. The results of the experiments revealed that different layer arrangements of sandwich composites have different impact resistance capabilities. Specific energy absorption increased in specimens with a greater number of cores. Additionally, multi-layered sandwich specimens with cores made of thicker laminates had greater absorption capabilities. The design of multi-layered sandwich panels caused a double peak in load-displacement diagrams, indicating each core's effect in absorbing the impact energy. In addition, the FEA modelling techniques of honeycomb-reinforced sandwich composites under high energy impacts were investigated using the LS-Dyna software. The MAT-142 material model was investigated, and the produced data was similar to the results obtained from the experiments. However, the discrepancies between FEA and experimental results for design S4 are significant which is related to the capacity of the model to predict multi-damage and debonding at interfaces between cores and skins.

According to experimental results, there is no unexpected behaviour during the impact tests. As it was predicted, the energy absorption increases by increasing the number of cores and skins in different designs. The outcomes of this research will contribute to the impact resistance of vehicular structures. Increasing cores and skins through the thickness of structures introduces various damage and failure scenarios in particular cases arrangements of cores within a sandwich panel affect the number

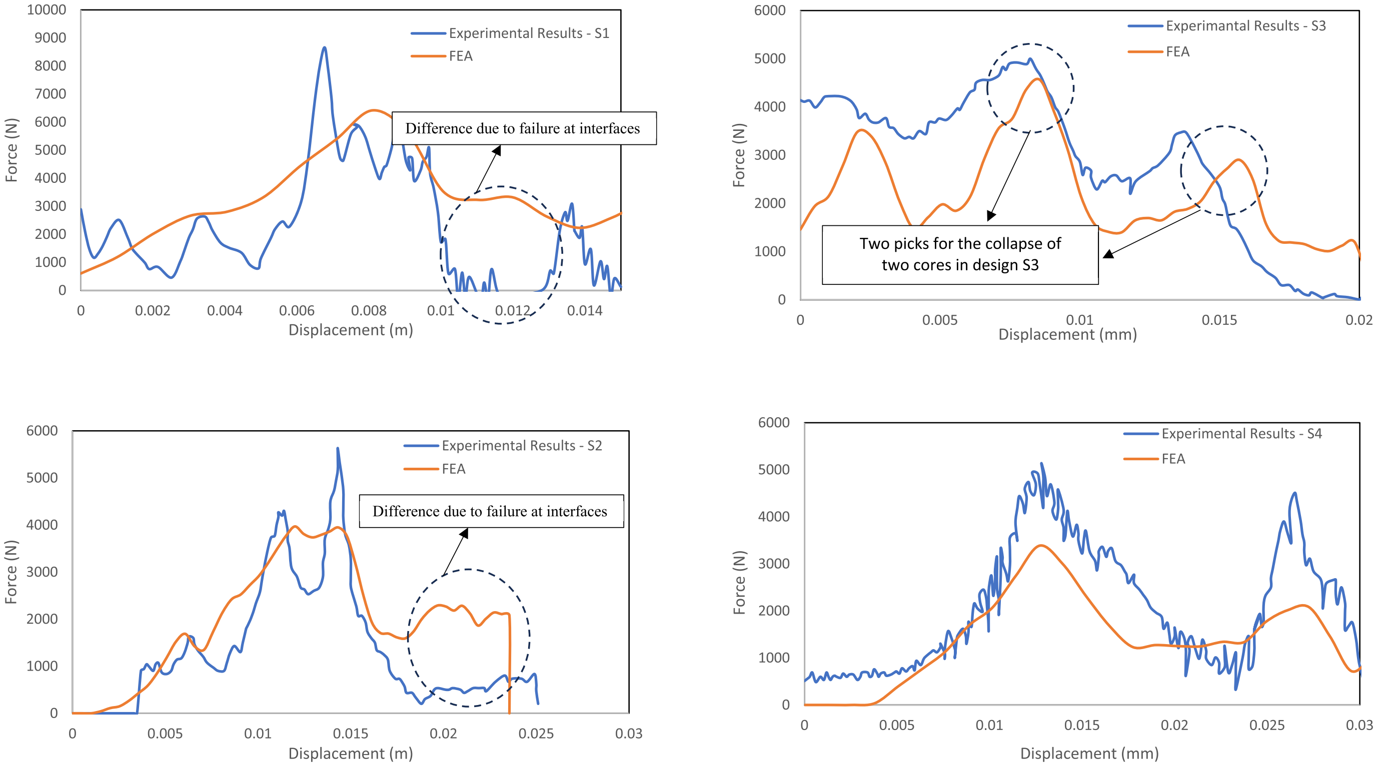

Fig. 12. Comparison between load–displacement results – Cases S1 – S4.

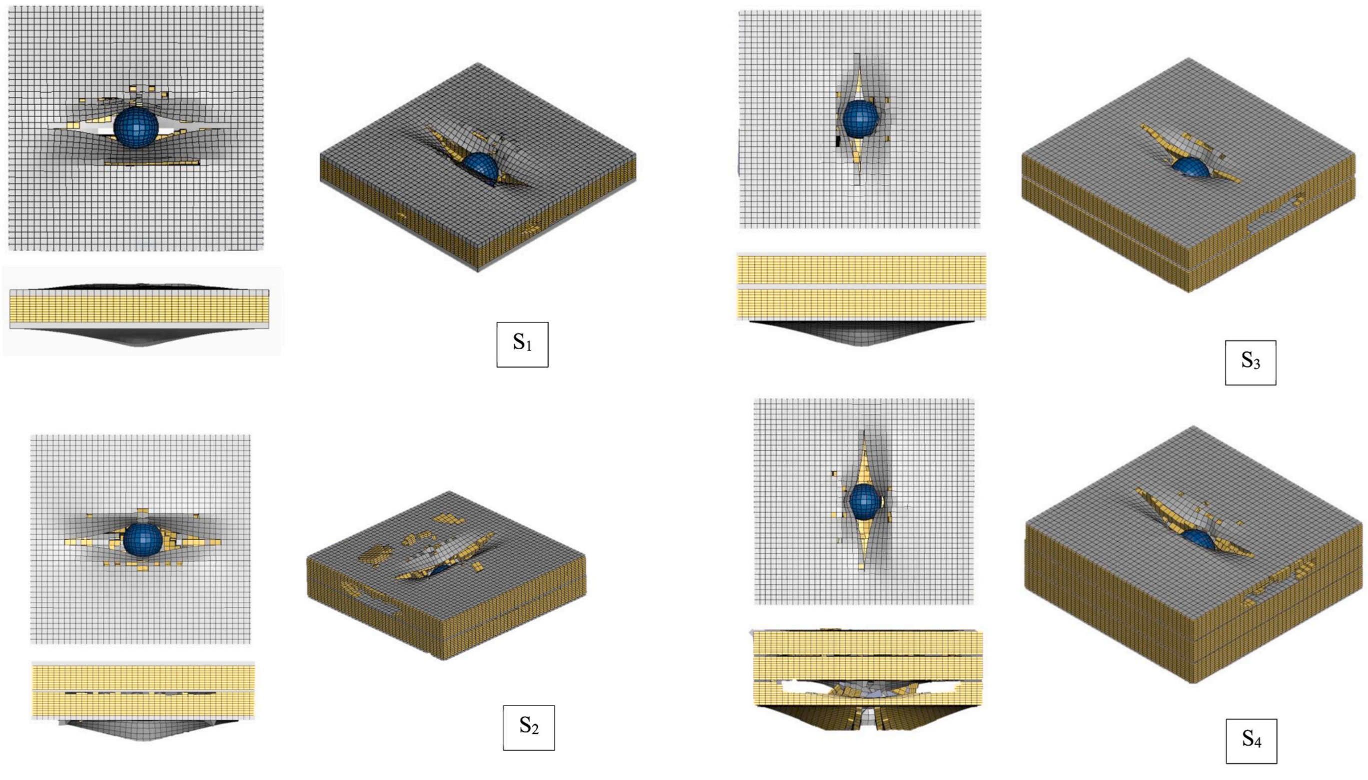

Fig. 13. Various stages of Finite Element simulation for 4 configurations **S1 – S4.**

of pick loads in force history during the impact event. The specific energy absorption has been tripled from 47 J/kg (CFRP) to 138 J/kg (Design S4). Authors recommend studying this behaviour further to predict various failures in multi-layered sandwich composite panels.

Funding

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Competing interest

No competing interest is declared.

CRediT authorship contribution statement

A. Al Ali: Writing – original draft, Methodology, Investigation. **E. Arhore:** Software, Methodology. **H. Ghasemnejad:** Writing – review & editing, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M. Yasaee:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization.

Declaration of Competing interest

Submission of this article implies that the work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Data availability

Data will be made available on request.

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Al Ali, A.

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