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Effect of Physical and Geometrical Factors on Low Velocity Impact Characteristics of Sandwich Plates Made up of Composite Face Sheets and Flexible Foam Cores

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Abstract


The use of composite sandwich plates in aerospace, marine, and lightweight civil engineering structures has become common practice as these materials exhibit favorable stiffness-to-mass ratios and excellent energy absorption capabilities. Nevertheless, there exists a lack of understanding of their non-linear behavior in the context of Low Velocity Impact (LVI) loads, especially concerning the effects of physical and geometrical characteristics on impact performance. In the current research, a new fully three-dimensional non-linear finite element formulation for the analysis of LVIs of sandwich plates, consisting of composite face sheets and flexible foam cores, is introduced using the ABAQUS platform. Contrary to the plate theory-based conventional approach, the proposed formulation uses three-dimensional elasticity theory. The influence of different physical and geometrical parameters on LVI resistance is investigated. The numerical analysis shows that a decrease in the stiffness of the composite face sheets or foam core causes a reduction in contact force and absorbed energy, while increasing local deformation and time of impact occurs. Moreover, an alteration of impactor shape from spherical to cylindrical shape enhances the contact stiffness and causes an increase in peak impact force greater than 100% at the expense of displacement and impact time reduction. It is also found that thinning of core thickness lowers bending stiffness of the sandwich panel, which results in a significant increase in impact force and deflection. The findings presented here could be useful in designing impact-resistance sandwich structures and also could be used as a basis for further theoretical and experimental researches.

Keywords: Low velocity impact, Sandwich structures, Composite face sheets, Flexible core, Physical and geometrical parameters.

1 | Introduction

Composite sandwich panels have been widely studied for applications in aerospace, marine, automobile, rail, and civil engineering industries due to their superior stiffness-to-weight ratios, high specific strength, and high energy dissipation capability [1–4]. In these structures, two thin and stiff composite face sheets were bonded

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to a lightweight core material, such as polymeric foams or honeycomb structures. By separating the two composite face sheets through a thicker core material, the bending stiffness of the structure could be increased while keeping the structural weight very low [5], [6]. As a result of such advantages, sandwich structures have become increasingly popular in the design of lightweight structures with exposure to dynamic loads.

Among many different loading cases, Low-Velocity Impact (LVI) can be regarded as one of the most important threats to sandwich structures when it comes to their manufacture, maintenance, accidental tool drops, runway Foreign Object Debris (FOD), and in-service dynamic loading conditions [7–9]. Contrary to the high-velocity impact phenomenon, LVI could cause considerable damage mechanisms, such as matrix cracking, fiber breaking, core crushing, localized indentation, and debonding of the face sheets/core without showing any noticeable visible damage [10–12]. Such invisible impact damage, namely BVID, can seriously deteriorate the mechanical behavior of the structures.

Initial studies on LVI response focused primarily on simplified analytical and equivalent single layer models. Fundamental insight into impact behavior in composite materials was gained by the pioneering work of Abrate [13] and Beaumont et al. [14]. Lee et al. [15] have studied dynamic response of composite sandwich plates with Mindlin plate theory, whereas Herup and Palazotto [16] presented elasticity-based Hertzian contact formulation for analysis of sandwich structures under impact loading conditions. Finite element methods based on simplified elastic foundation assumptions for the core material were used by Palazotto et al. [17] for studying LVI response.

With increasing development in computational mechanics, complex numerical and experimental techniques were introduced during the period 2016 to 2020. Various authors explored the effect of corrugated core, foam filled core, and advanced cellular core on energy absorption and impact resistance [18–21]. Studies using experimental and numerical methods showed that core shape, core density, and face sheet properties had significant effect on contact force evolution and failure mechanisms under impact conditions [22], [23].

In the past few years, a lot of work has been done towards the progressive damage approach, advanced contact laws, and high-fidelity finite element analysis. Residual compressive strength analysis after LVI was carried out by Wang et al. [24] for honeycomb sandwich structure. Multi-core composite sandwich structures were tested under LVI by Pandey et al. [25]. In their study, the effect of geometrical properties on energy absorption capability was emphasized. Higher resistance towards impact under dynamic loading was achieved by Tao et al. [26] using bio-inspired honeycomb sandwich structure. Recent works include damage analysis [27–30], use of elastomers in sandwich structures, auxetic core structure, and efficient simulation for impact response.

However, despite all the significant developments made by researchers in past researches, there exist certain drawbacks that have to be addressed. In particular, most models developed thus far are based on equivalent plate theories, Hertzian contact approximation, or reduction techniques, which might fail to take into account accurate three-dimensional stress fields and changing contact stiffness as a function of the time variable during impact loadings. Moreover, while several studies considered new core configurations and their effect on progressive damage propagation, no research work attempted a comprehensive analysis of face-sheet stiffness, foam core compliance, geometry of the impacting object, and thickness of the core on the dynamics of sandwich plates.

Specifically, the influence of the geometrical shape of the impactor on the contact stiffness evolution and deformation characteristics has not yet been well explored in current literature. Furthermore, many contemporary works consider only honeycomb-core structures and analyze progressive damage behavior under LVI loadings, whereas only a few attempts have been made towards developing nonlinear three-dimensional models to predict the LVI behavior of composite sandwich panels with flexible foam cores.

Thus, the current work proposes a full three-dimensional nonlinear finite element model to analyze the LVI response of composite sandwich panels with flexible foam cores through ABAQUS simulation. As opposed to the typical method based on plate theory, the proposed approach considers the exact three-dimensional

linear elastic theory as its foundation. Such an approach allows predicting localization behavior and accounting for contact stiffness evolution without resorting to the analytical definition of the contact law.

The novelty in this research work stems from the systematic non-linear analysis conducted to understand the transient impact responses of sandwich plates under the coupled influences of various physical and geometric parameters. The effects of material properties of composite face-sheets, foam density of the core layer, shape of the impactor, and thickness of the core on the contact forces, absorbed energy, local displacements, and duration of impact have been studied in detail. Moreover, the finite element model developed here has been validated with experimental data.

2 | Numerical Modeling

A square panel of size $76.2 \times 76.2 \text{ mm}^2$ was chosen for the current work. The outer composite faces were made up of six layers each, where the thickness of one layer was 0.264 mm. On the other hand, the core was designed by only one layer whose thickness was 12.7 mm. The sandwich panel had the stacking sequence of $[0_2/90_2/0_2/\text{core}/0_2/90_2/0_2]$, which led to the total thickness of the panel as 15.868 mm.

The current analysis was conducted by modeling the sandwich panels using three-dimensional solid elements instead of the traditional two-dimensional plate elements. That means that all results presented here did not come from classical/lord-order theories, but rather directly resulted from the three-dimensional theory of elasticity (*Fig. 1*).

All the boundaries of the sandwich plate considered are simply supported. Different types of mathematical models have been suggested by researchers for the same. In the current investigation, the mathematical model presented by Reddy [31] for a simply supported boundary condition will be used:

$$\text{at } x = -\frac{a}{2}, x = \frac{a}{2} : v = w = \frac{\partial w}{\partial y} = 0, \quad (1)$$

$$\text{at } y = -\frac{b}{2}, y = \frac{b}{2} : u = w = \frac{\partial w}{\partial x} = 0, \quad (2)$$

where u , v , and w represent the displacements along the x -, y -, and z -directions, respectively. Sandwich panel is modeled through eight-node linear brick continuum shell elements (SC8R), in which there are three degrees of freedom for translation at each node (*Fig. 2*).

Material and geometric properties of the investigated sandwich panel are presented in *Table 1*.

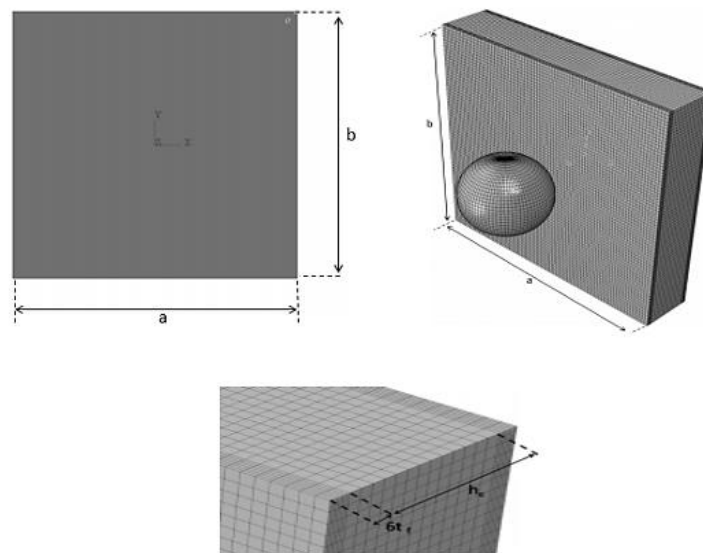


Fig. 1. Geometrical model of the sandwich panel.

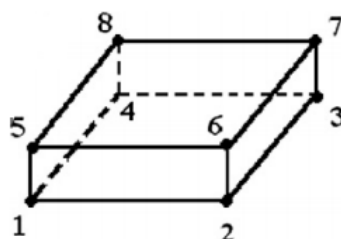


Fig. 2. Eight-node linear brick continuum shell element (SC8R).

Table 1. Mechanical and geometrical properties of the sandwich panel components.

Property	Face Sheet	Foam Core
Material	Carbon fiber	Polymethacryimide foam
E_{11} (GPa)	54	0.18
E_{22} (GPa)	54	0.18
E_{33} (GPa)	4.84	0.18
G_{12} (GPa)	3.16	0.07
G_{13} (GPa)	1.87	0.07
G_{23} (GPa)	1.87	0.07
ν_{12}	0.06	0.286
ν_{13}	0.313	0.286
ν_{23}	0.313	0.286
ρ (kg/m ³)	1511	110
h_c (mm)	–	12.7
t_f (mm)	0.264	–
a (mm)	76.2	76.2
b (mm)	76.2	76.2

The projectile is considered to be a rigid spherical body with a diameter of 25.4 mm and a weight of 1.8 kg impacting the sandwich structure at a speed of 3.7 m/s, resulting in the impact energy of 12.32 J. The projectile is represented in the FE model using four-node three-dimensional rigid elements (R3D4).

In order to obtain a numerically stable model and reach the mesh independence of the solution, a mesh sensitivity analysis was performed through a series of analyses with gradually decreased element sizes (*Fig. 3*).

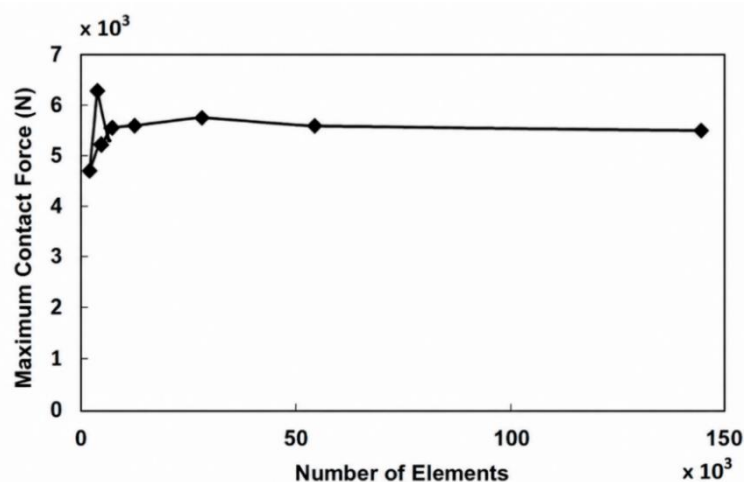


Fig. 3. Mesh convergence study for the maximum contact force with respect to the number of finite elements.

To prove the validity of the obtained results, numerical values are compared with the results provided by experiments in [14], as shown in Fig. 4. The above figure indicates that there is a high level of agreement between experimental and numerical results.

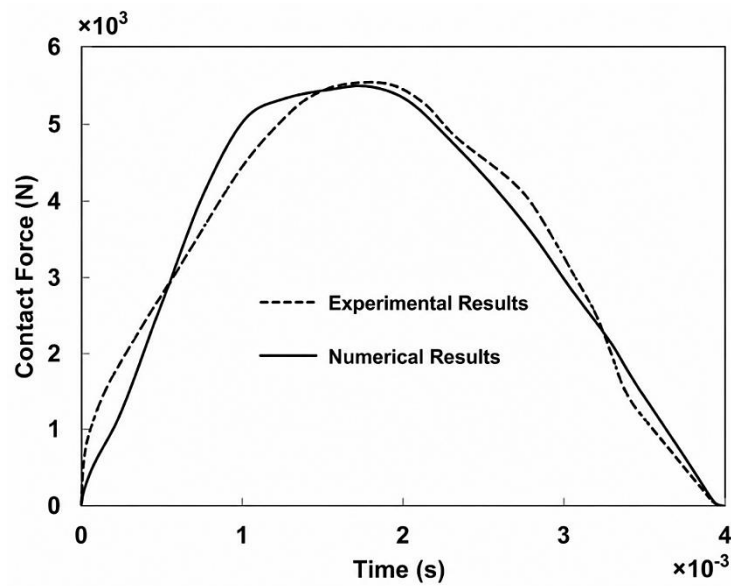


Fig. 4. Validation of the numerical model against the experimental results reported in [14].

3 | Effect of Composite Face-Sheet Material

In order to determine the effect of the composite material used in the face sheet of the sandwich panel on its impact behavior, the material of the facesheet was altered from carbon epoxy to glass epoxy composite. The physical properties of the glass epoxy facesheets used are given in Table 2. The results for such cases are depicted in Figs. 5–7 and presented in Table 3.

From the aforementioned findings, it can be deduced that using weaker composite materials in the facesheets will lead to a decrease in both the magnitude of the contact force and the absorbed energy owing to the low stiffness of the contacting region. On the other hand, both the central deflection at the impact point and contact time increase drastically because of the increased plasticity and reduced resistance to bending of the face sheets.

Consequently, the softening of the sandwich panel causes a longer interaction time between the impacting body and the panel, which increases the absorption of the impact energy by the structure.

Table 2. Mechanical properties of the glass/epoxy composite lamina.

Parameter	Value
E11 (GPa)	32.062
E22 (GPa)	10.789
E33 (GPa)	10.789
G12 (GPa)	11.92
G13 (GPa)	11.92
G23 (GPa)	4.68
ν_{12}	0.344
ν_{13}	0.344
ν_{23}	0.344
ρ (kg/m ³)	1796
t_f (mm)	264
a (mm)	2/76
b (mm)	2/76

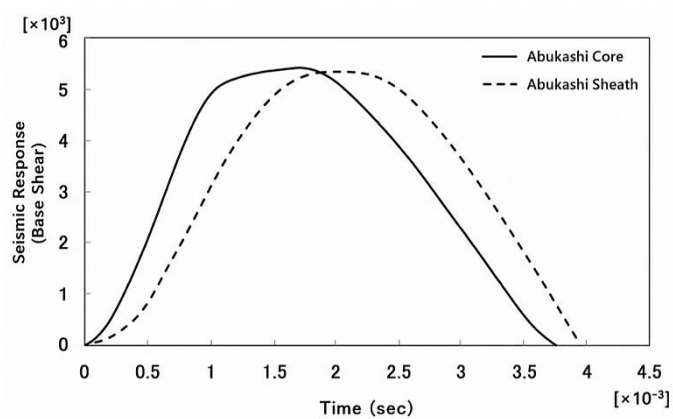


Fig. 5. Influence of composite face-sheet material on impact force.

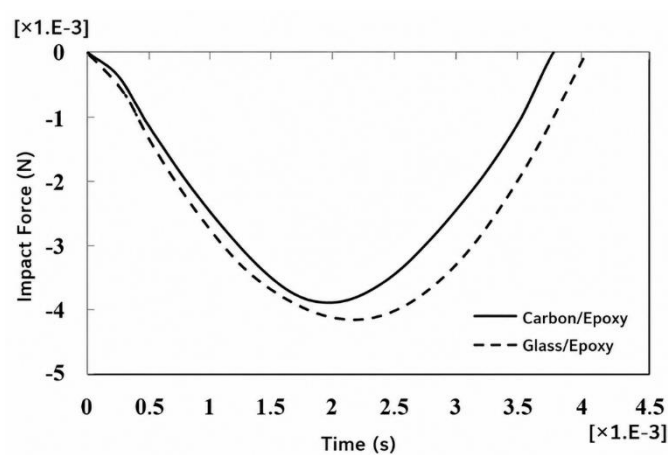


Fig. 6. Influence of composite face-sheet material on deflection at the impact location.

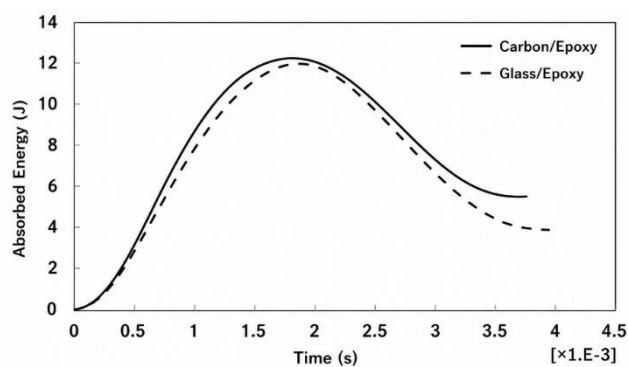


Fig. 7. Influence of composite facesheet material on structural energy absorption.

Table 3. Effect of composite facesheet material on impact response.

Composite Facesheet Material	Maximum Impact Force (kN)	Impact-Point Deflection (mm)	Absorbed Energy (J)	Contact Duration (ms)
Carbon/Epoxy	5.376	3.90	5.225	3.75
Glass/Epoxy	5.278	4.11	3.754	4.00

4 | Effect of Sandwich Panel Core Material

In order to examine the influence of core on the impact behavior of sandwich composite panels, the core was replaced with another type of core; that is, a low-density foam core instead of a high-density foam core. The characteristics of the new core used are provided in *Table 4*. The analysis findings are given in *Figs. 8-10* and *Table 5*.

From the results, it can be seen that the low density of the core lowers the stiffness of the contact zone. As a result, the impact load and absorbed energy in the panel become smaller, while the contact deformation becomes larger.

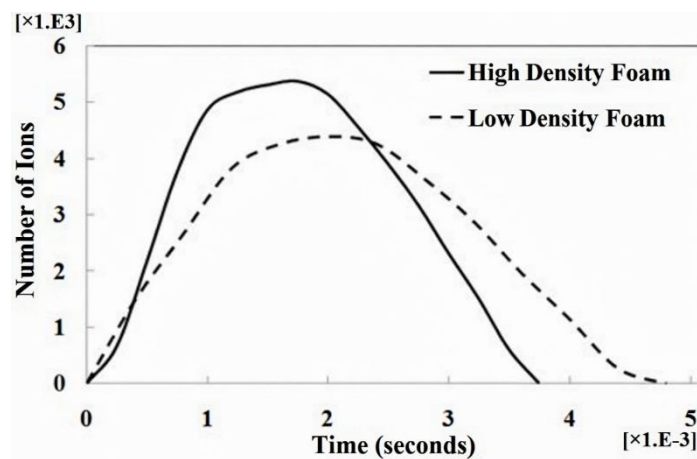


Fig. 8. Effect of core material on impact force.

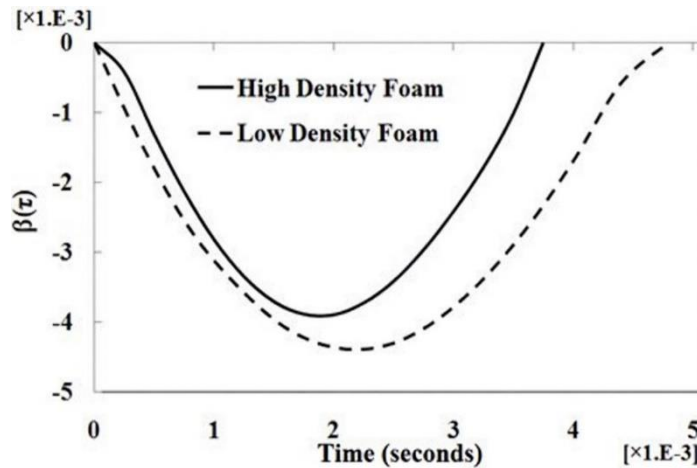


Fig. 9. Effect of core material on deflection at impact location.

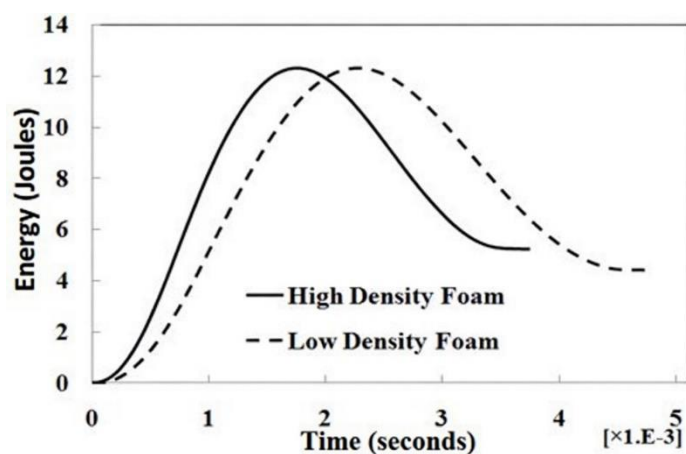


Fig. 10. Effect of core material on energy absorbed by the structure.

Table 4. Properties of the low-density foam core.

Parameter	Value
E11 (GPa)	0.072
E22 (GPa)	0.072
E33 (GPa)	0.072
G12 (GPa)	0.024
G13 (GPa)	0.024
G23 (GPa)	0.024
ν_{12}	0.499
ν_{13}	0.499
ν_{23}	0.499
ρ (kg/m ³)	51
hc (mm)	12.7
a (mm)	2.76
b (mm)	2.76

Table 5. Effect of core material on impact response.

Core Material	Maximum Impact Force (kN)	Impact-Point Deflection (mm)	Absorbed Energy (J)	Contact Duration (ms)
High-density foam	5.376	3.90	5.225	3.75
Low-density foam	4.395	4.36	4.431	4.80

5 | Effect of Impactor Geometry

To study the role of impactor shape on the impact behavior, the rigid spherical impactor was substituted by a cylindrical impactor whose dimensions, including the diameter, mass, and speed, were the same as those of the spherical impactor. The impactor shape influence on the impact behavior was thus examined. The analysis outcomes for the cylindrical impactor are illustrated in *Figs. 11–13*.

From the analysis outcomes given in *Tables 6* and *7*, it is evident that using a cylindrical impactor rather than a spherical impactor increases stiffness significantly. Therefore, the impact force is greatly increased while the impact point deflection and contact time are substantially reduced.

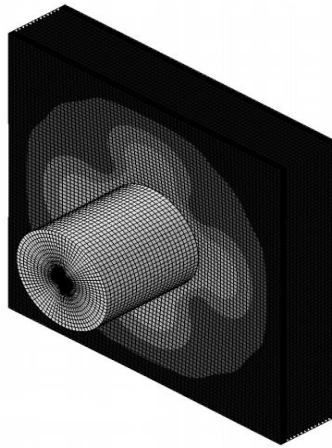


Fig. 11. Stress distribution obtained from the cylindrical impactor analysis.

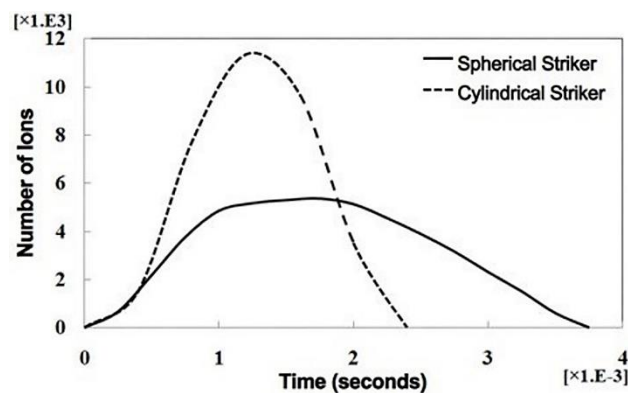


Fig. 12. Effect of impactor geometry on impact force.

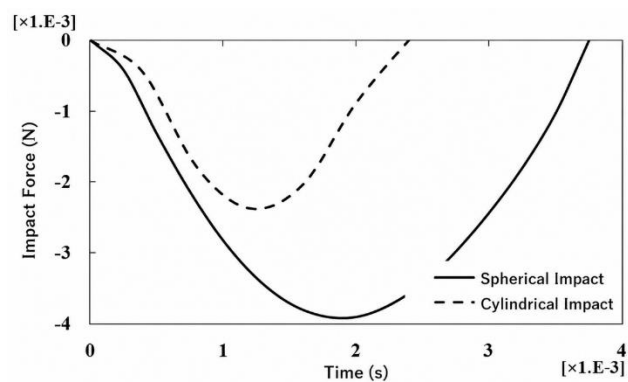


Fig. 13. Effect of impactor geometry on deflection at impact location.

Table 6. Effect of impactor geometry on impact response.

Impactor Shape	Maximum Impact Force (kN)	Impact-Point Deflection (mm)	Contact Duration (ms)
Spherical	5.376	3.90	3.75
Cylindrical	11.346	2.37	2.40

Table 7. Percentage changes of various parameters in the case of a cylindrical impactor compared to the initial case of a spherical impactor.

Increase in Impact Force (Percent)	Decrease in Deflection at Impact Location (Percent)	Decrease in Collision Duration (Percent)
111.05	39.23	36

6 | Effect of Core Thickness

To test the impact of sandwich panel thickness on the impact load, initially the thickness of the core was decreased to half its value. In another study, the core was completely taken out, and both facesheets of composite material were joined together to make a single layer of composite material.

The results obtained through the study have been provided through *Figs. 14-16* and *Table 8*.

From the above figures, it is clear that decreasing the thickness of the core decreases the moment of inertia of the section. Thus, the impact load increases, while the energy absorbed by the panel decreases.

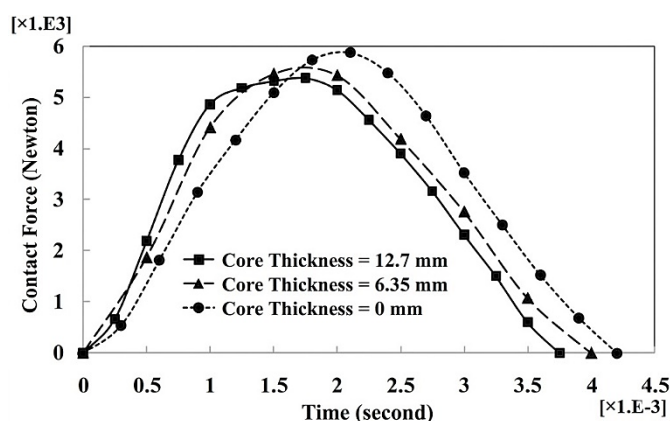


Fig. 14. Effect of core thickness on impact force.

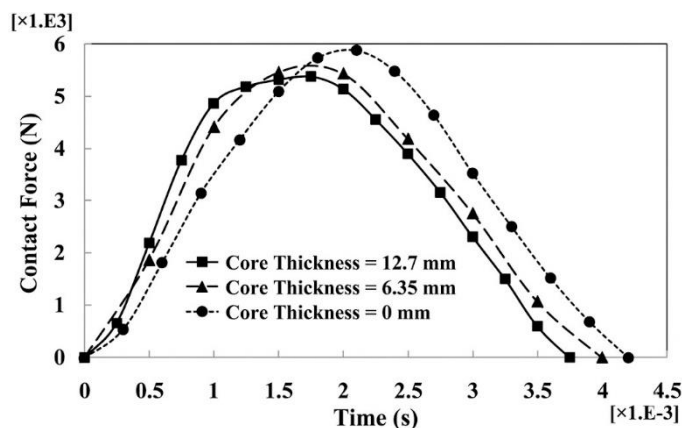


Fig. 15. Effect of core thickness on deflection at impact location.

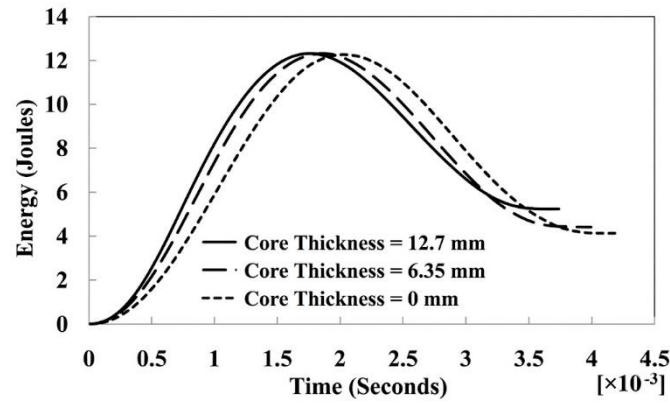


Fig. 16. Effect of core thickness on energy absorbed by the structure.

Table 8. Values of various parameters for different core thicknesses.

Core Thickness (mm)	Maximum Impact Force (kN)	Deflection at Impact Location (mm)	Absorbed Energy (J)	Collision Duration (ms)
7.12	376.5	90.3	225.5	75.3
35.6	457.5	22.4	400.4	4
0	876.5	72.4	110.4	20.4

7 | Conclusion

Numerical analysis was conducted using a nonlinear model describing the response of sandwich composites with facesheets made of composite materials and an elastic core subjected to LVIs. Different physical and geometrical factors influencing the response were considered. Since these results were derived from three-dimensional elasticity theory, they may be used as reference benchmarks in future studies.

To verify the accuracy of the numerical calculations, the computed results were compared against experimental data available in [14]. Excellent agreement was observed.

The key conclusions of this paper include:

- I. Use of weaker materials for facesheets or the core material leads to a softer contact region. Accordingly, the impact force and absorbed energy decrease, whereas impact-point deflection and contact time increase.
- II. Converting from the spherical impactor to a cylindrical impactor makes the contact region much stiffer. This causes a significant increase in the impact force, while impact-point deflection and contact time become smaller.
- III. The reduction in the core thickness reduces the sectional area moment of inertia of the core. Therefore, the impact force and impact-point deflection increase, whereas the contact time increases and absorbed energy decreases.

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