

Numerical analysis of three-point bending of sandwich panels with different core cross-sections: Finite element study

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Abstract. The development and applications of sandwich structures across various fields, including aerospace, marine, automotive, civil engineering, and building materials, have garnered significant interest. The strength of a sandwich composite material hinges on both its core and the two plates. This study proposes a systematic comparison and numerical analysis of the resistance to imposed displacements and deformations in a sandwich composite structure. We consider three sandwich composites with different core geometric structures (square, hexagon, and circle-square) while considering various factors, such as the geometric structure of the core and the fiber orientation of the laminated plates, among others. The numerical results indicate that the sandwich structure with a circle-square core exhibits higher strength than the other two options, namely square and hexagonal (honeycomb) cores.

Keywords: displacement; honeycomb; fiber orientation; finite element method; laminated plates; sandwich structure

1. Introduction

Sandwich panels are increasingly used in structures in various engineering fields, such as aerospace, marine, and automotive, due to their development over the last few decades. Improving the durability and strength of a sandwich structure under different loads has prompted researchers to focus on the geometric shape of the core, and the honeycomb sandwich structure has always been a significant topic for researchers (Luat *et al.* 2021, Zheng *et al.* 2022, Kamarian and Song 2023, Alambeigi *et al.* 2023, Zhu 2023). Several studies have been undertaken in this context. The dynamic response characteristics of corrugated sandwich panels were investigated experimentally and numerically by Rejab and Cantwell (2013). The results showed that corrugated sandwich panels exhibit good impact resistance. Kueh *et al.* (2023) proposed a sandwich beam consisting of four essential parts comprising carbon-fiber-reinforced polymer top and bottom laminates embedding a two-layer core of laterally arched solid hot-melt adhesive material and aluminum honeycomb. The study beam gave improved impact resistance compared with existing designs. Sun *et al.* (2016) studied experimentally

and numerically in-plane compression of a sandwich structure with a hexagonal honeycomb core reinforced with periodic grids. Their results showed that the honeycomb core reinforced with grids can improve the performance of the sandwich structure. The impact energy absorption and dynamic stiffness obtained depend on the geometric parameters; impact energy and dynamic stiffness as a function of the geometric parameters of the structure enable the evaluation and prediction of safety-relevant parameters of sandwich structures under impact loading and ensure cost-effectiveness (Zeleniakienė *et al.* 2010). This finite element simulation was carried out to study the behavior under impact loading of the sandwich composite based on woven glass fibers and a hexagonal polypropylene honeycomb core. Liu *et al.* (2019) conducted a numerical study on a sandwich panel with a hexagonal honeycomb core filled with circular tubes. The results showed that the hexagonal honeycomb core sandwich panel filled with round tubes had better impact resistance than the conventional hexagonal honeycomb core sandwich panel. Li *et al.* (2020) conducted comparative forced vibration studies of a nonlinear cubic system to verify the accuracy and precision of the homotopy analysis method. The effects of thickness/length ratio, width/length ratio, and transverse excitation on the nonlinear primary response were investigated for honeycomb sandwich panels. In addition, many researchers have concluded that the compression properties of honeycomb structures in three axial directions

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under various loading rates were significantly different (Baran and Öztürk 2020, Shen *et al.* 2022, Liu *et al.* 2021, Ma *et al.* 2021). Huang *et al.* (2016) investigated experimentally by considering aluminum sandwich structures with hexagonal honeycomb cores subjected to water-based impulsive loading are investigated. Their results show that the effect of the relative density of the core significantly influences the explosion resistance of sandwich panels under different loading conditions. Georges *et al.* (2023) have introduced an analytical model to study lattice cores based on spacers made up of periodic representative volume elements (RVE) of 3D uprights in sandwich panels. The analysis and comparison of the local impact resistance of a series of honeycomb cores (re-entrant hexagon, semi-re-entrant hexagon, convex, and hexagon) with different Poisson's ratios under the impact of a spherical projectile at different velocities have been dealt with by Gong *et al.* (2022) and Luo *et al.* (2021). Gupta and Pradyumna (2022) present an in-depth numerical study, including the effects of honeycomb cell geometric parameters, curvilinear fiber path angles, and boundary conditions on the nonlinear dynamic response of auxetic sandwich panels with a negative Poisson's ratio. In addition to the studies summarized above, numerical modeling of a problem, regardless of the discipline, is an essential milestone in the solution process. Examining the solution proposals provided after analyzing the issues in various disciplines on a numerical basis will offer readers a different perspective (Haeri and Sarfarazi 2016, Sarfarazi *et al.* 2017, 2024, Alqahtani *et al.* 2024, 2025, Fu *et al.* 2024, Al-Hdaibat *et al.* 2025a, b, c, Khan *et al.* 2024).

This article deals with the finite element comparison of three sandwich composites with different geometric core structures (square, hexagon, and circle-square) from the point of view of resistance to imposed displacements and deformations, considering several factors such as the geometric structure of the core, the orientation of the laminated plate fibers—among others. Studies examining sandwich composites with different geometric structures with the same parameters for different scenarios have not yet been detailed enough in the literature. The authors based their originality on this deficiency and aimed to provide a confirmatory reference for future studies in the literature.

2. Materials and methods

2.1 Geometric model

Our geometric model is a sandwich panel measuring $300 \times 85 \times 24$ mm³ made of two graphite/epoxy composite sheets of eight crossed plies [+ θ ; - θ] cross-stacked plies (0°; 10°; 20°; 30°; 40°; 45°; 50°; 60°; 70°; 80°; 90°) and a core of different geometries, whose properties are cited in Table 1 and of a soul. The sandwich panel is rested on two supports and subjected to an imposed displacement of 1 mm in the middle, along the Y-axis. In this study, we have three different models depending on the geometric type of core used (square, hexagonal, and circle-square) (Fig. 1).

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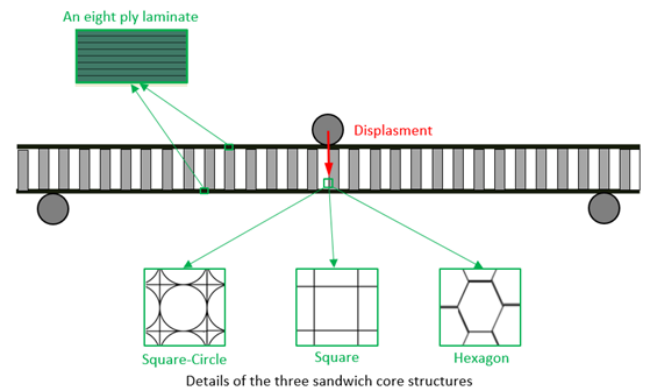


Fig. 1 Geometric model

Table 1 Mechanical characteristics of the material

Symbols	Parameters	Values
ρ [g.cm ⁻³]	Mass Density	2.62
E1 [MPa]	Longitudinal modulus of composite	0.369
E2; E3 [MPa]	Transverse modulus of composite	23.24
G12; G23 [MPa]	Composite shear modulus	0.161
G31 [MPa]	Composite shear modulus	

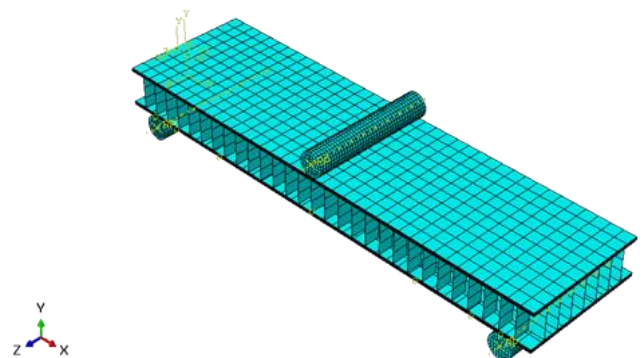
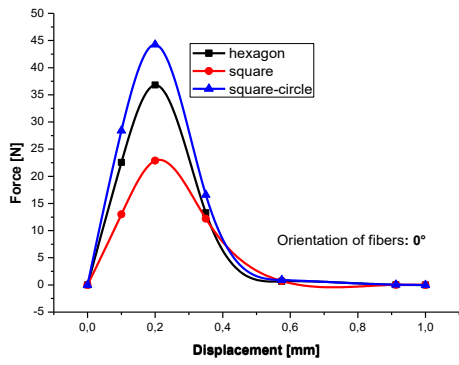


Fig. 2 Mesh structure of the study model

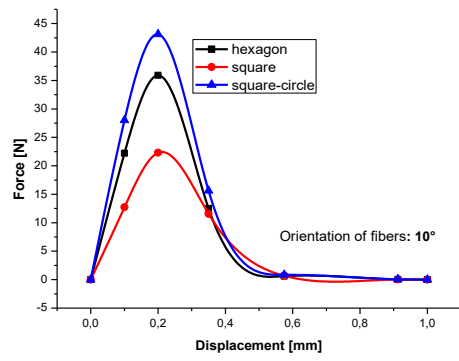
plies (0°; 10°; 20°; 30°; 40°; 45°; 50°; 60°; 70°; 80°; 90°) and a core of different geometries.

2.2 Mesh assembly

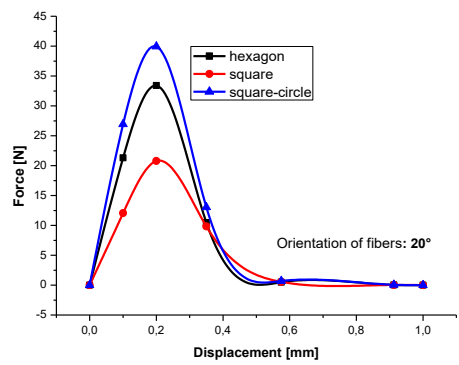
The finite element method has developed depending on technological developments and has become one of the numerical methods used in many fields today. In this respect, there are many implementations of FEM in the field of engineering (Abdelmadjid *et al.* 2020, Madenci 2021, Uzun Yaylacı 2024, Moulgada *et al.* 2023, 2024, Gul and Aydogdu 2023, Wang *et al.* 2023, Shen *et al.* 2024, Benouis *et al.* 2024, Yaylacı *et al.* 2024a, b, Sekban *et al.* 2024a, b, c, Selvamani *et al.* 2024a, b, Kurt *et al.* 2024, Güvercin *et al.* 2025, Yemenoglu *et al.* 2025). Similarly, numerical solutions of sandwich panel analysis using the finite element method have been published in many studies. To obtain successful results, the geometry of the problem was modeled with the help of a package program containing the finite element method. Subsequently, finite element analysis



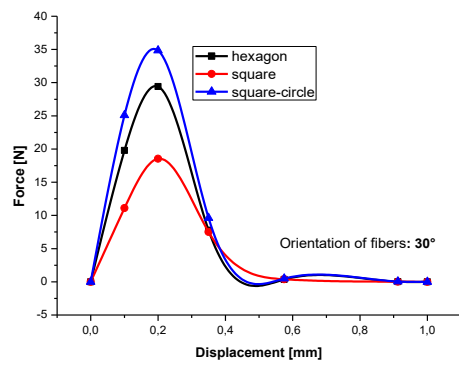
(a) $\theta=0^\circ$



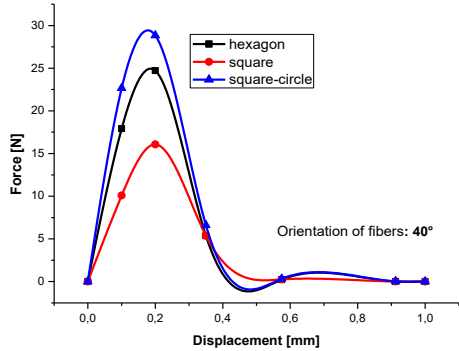
(b) $\theta=10^\circ$



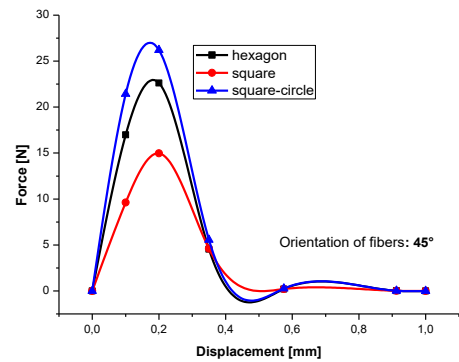
(c) $\theta=20^\circ$



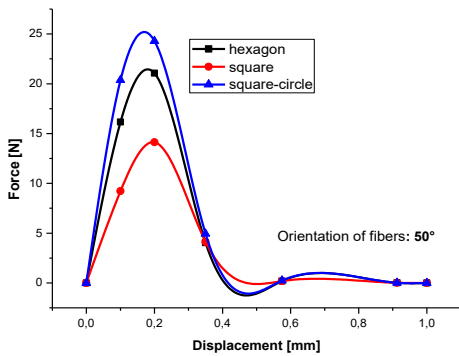
(d) $\theta=30^\circ$



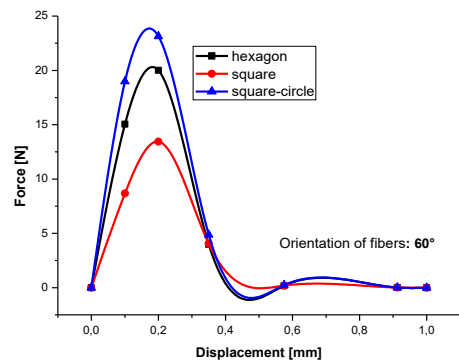
(e) $\theta=40^\circ$



(f) $\theta=45^\circ$



(g) $\theta=50^\circ$



(h) $\theta=60^\circ$

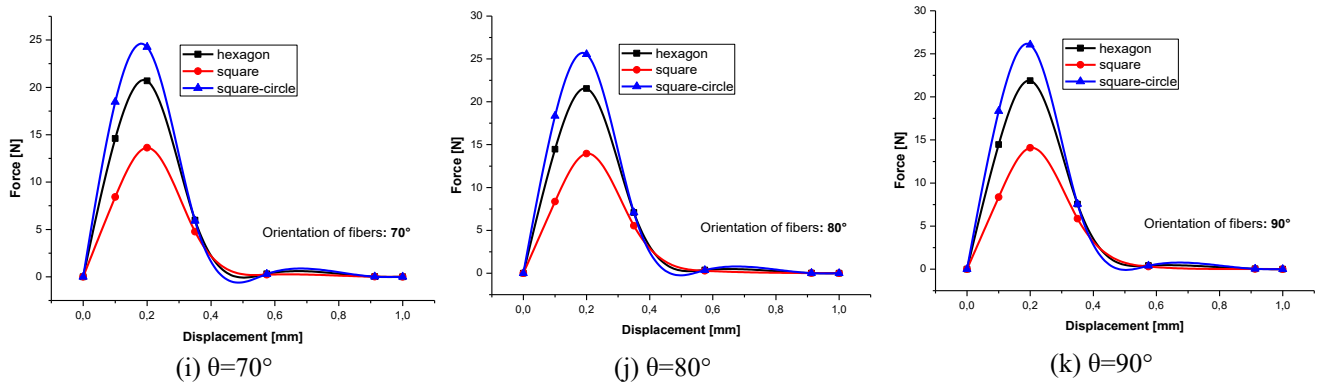


Fig. 3 Variation of force as a function of displacement of different sandwich panels for different fiber orientations ($\theta=0^\circ$; $\theta=10^\circ$; $\theta=20^\circ$; $\theta=30^\circ$; $\theta=40^\circ$; $\theta=45^\circ$; $\theta=50^\circ$; $\theta=60^\circ$; $\theta=70^\circ$; $\theta=80^\circ$; $\theta=90^\circ$)

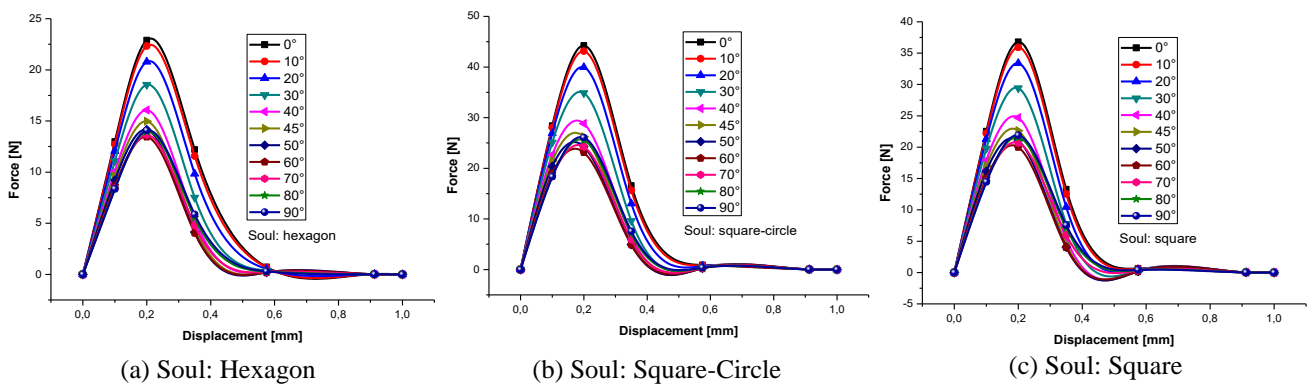


Fig. 4 Variation of force versus displacement for different fiber orientations ($\theta=0^\circ$; $\theta=10^\circ$; $\theta=20^\circ$; $\theta=30^\circ$; $\theta=40^\circ$; $\theta=45^\circ$; $\theta=50^\circ$; $\theta=60^\circ$; $\theta=75^\circ$; $\theta=80^\circ$; $\theta=90^\circ$) and different sandwich panels (circle-square, square and hexagonal)

was carried out on the model under appropriate boundary conditions. To simulate the behavior in three-point bending and the influence of the different geometries of the core, as well as the orientation of the fibers of the composite plates of the sandwich panel, was used the calculation code “Abaqus” version 6.17 for the analysis of composite structures using the finite elements method (Manigandan *et al.* 2022, Ghatage and Sudhagar 2023). This code is a complete system, integrating the calculation functions and functions for building models (pre-processors) and processing results (post-processor). The mesh structure is of type C3D8R with eight linear nodes and 39949 elements (Fig. 2).

3. Results and discussion

3.1 Influence of sandwich panel core geometry on the force-displacement curve

Fig. 3 (a, b, c, d, e, f, g, h, i, j and k) shows the variation of force versus displacement for the three sandwich panels for the different fiber orientations ($\theta=0^\circ$; $\theta=10^\circ$; $\theta=20^\circ$; $\theta=30^\circ$; $\theta=40^\circ$; $\theta=45^\circ$; $\theta=50^\circ$; $\theta=60^\circ$; $\theta=70^\circ$; $\theta=80^\circ$; $\theta=90^\circ$). The curves have the same gaits and possess a corresponding maximum; the force increases with increasing displacement to reach a maximum (displacement = 0.2 mm) and decreases with increasing displacement to the minimum (displacement = 0.6 mm), then becomes stable until the end. We also note

that the core with the circle-square geometric shape achieves a higher peak force for the same imposed displacement than the other two cores with square and hexagonal geometric shapes.

3.2 Influence of fiber orientation on the force-displacement curve

Fig. 4 (a-c) shows the variation in force as a function of displacement for the different fiber orientations ($\theta=0^\circ$; $\theta=10^\circ$; $\theta=20^\circ$; $\theta=30^\circ$; $\theta=40^\circ$; $\theta=45^\circ$; $\theta=50^\circ$; $\theta=60^\circ$; $\theta=70^\circ$; $\theta=80^\circ$; $\theta=90^\circ$) for the three sandwich panels. The curves have the same shapes and possess a corresponding maximum. We also note that the maximum force is reached at a fiber orientation of 0° for a displacement of 0.2 mm for all three sandwich panels.

3.3 The effect of composite plate material on the force-displacement curve for different core geometries

Fig. 5 (a₁, a₂, a₃, b₁, b₂, b₃, c₁, c₂, and c₃) illustrates the variation of the force as a function of the displacement of different sandwich panels for different orientations of the fibers ($\theta=0^\circ$; $\theta=45^\circ$; $\theta=90^\circ$) and different materials of the composite plate. We note that the geometry of the core (circle-square) has better resistance compared to the two other geometries (square and hexagon), and this is whatever the nature of the material of the plate is considered.

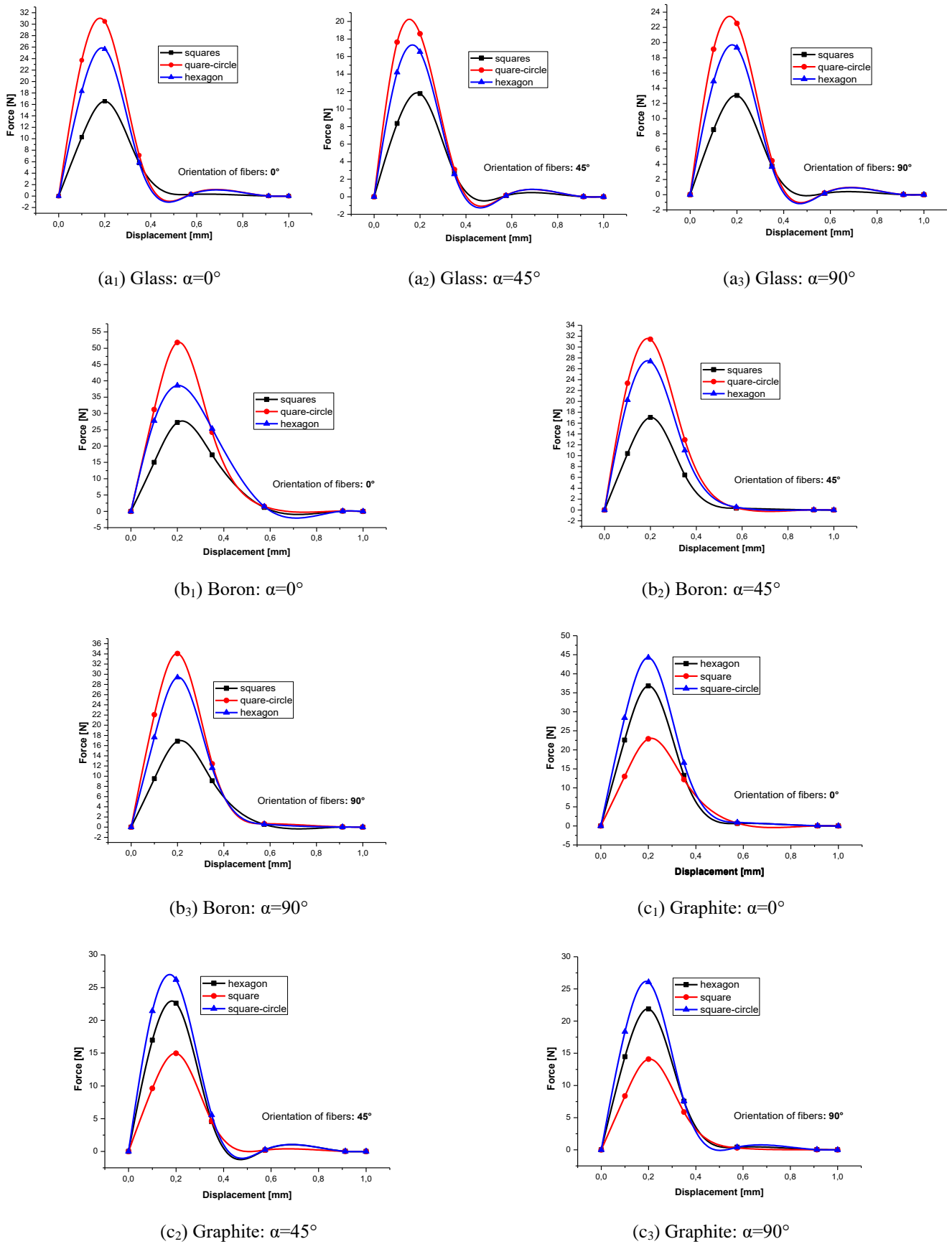


Fig. 5 Variation of the force as a function of the displacement of different sandwich panels for different fiber orientations ($\theta=0^\circ$; $\theta=45^\circ$; $\theta=90^\circ$) and different materials of the composite plate

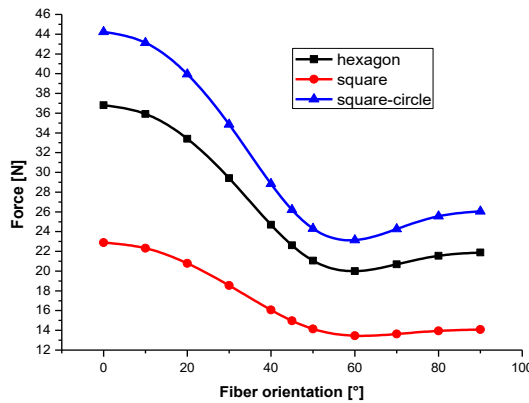


Fig. 6 Geometric model Variation of maximum force as a function of different fiber orientations ($\theta=0^\circ$; $\theta=10^\circ$; $\theta=20^\circ$; $\theta=30^\circ$; $\theta=40^\circ$; $\theta=45^\circ$; $\theta=50^\circ$; $\theta=60^\circ$; $\theta=75^\circ$; $\theta=80^\circ$; $\theta=90^\circ$) and for different sandwich panels (circle-square, square and hexagonal) and for a displacement of 0.2 mm

3.4 Variation of maximum force as a function of fiber orientation

Fig. 6 illustrates the variation in maximum force as a function of fiber orientation for the three sandwich panels. According to the numerically obtained results from the finite element method, the maximum force occurs at a fiber orientation of 0° for a displacement of 0.2 mm for all three sandwich panels. It can also be seen that the force decreases with increasing orientation, reaching a minimum at a fiber orientation of 60° and then increasing slightly for all three sandwich panels. We also note that the sandwich panel with a circle-square core geometrically has the maximum strength for all fiber orientations.

4. Conclusions

According to the numerical results obtained using the finite element method, the sandwich structure with a circle-square geometric core achieves a higher maximum force than the other two cores with square and hexagonal geometric shapes for the same imposed displacement, irrespective of the fiber orientation and the composite plate materials considered. This maximum force occurs at a fiber orientation of 0° for a displacement of 0.2 mm for all three sandwich panels. Additionally, it can be observed that the force decreases with increasing fiber orientation, reaching a minimum at 60° and then increasing slightly for all three sandwich panels.

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