Comparative Study of Core Material's Stiffness on Sandwich Panel with Composite Face Sheets beyond the Yield Point

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Abstract: - The study aims to explore the performance of sandwich panels exceeding the yield point stiffness of the core material. Sandwich panels have gained growing attention among designers owing to their excellent corrosion properties, and lightweight, and speedy installation process. They have been applied in numerous industrial sectors, including aerospace, architectural, marine, and transportation. Typically, sandwich panels are composed of a single central core sandwiched by a pair of outer face sheets, where the core is normally developed using softer materials compared to the face sheets. Given that past studies have primarily focused on sandwich panels in the elastic range, this present study explored the performance of sandwich panels exceeding the yield point stiffness of the core material. The univariate search optimization method was utilized to assess the elastic modulus ratio of the core (typically foam) to the face sheet (composite material). The load was elevated in a quasi-static order until the face sheets reached their yield point. Subsequently, the panel was simulated using the finite element analysis commercial package ANSYS APDL, with simply supported boundary conditions used on all sides of the panel. The proposed model was verified by comparing the numerical and experimental data from recent literature. Based on the results, the panel's increased load-carrying capacity corresponded as the core material stiffness exceeded its yield limit. Moreover, the transmission of load to the face sheets increased as the core stiffness decreased. In summary, stiffer core materials caused the sandwich panel to behave more as isotopic face sheets. Thus, the face sheets yielded ahead of the core material.

Key-Words: - Sandwich panels, Core material, Face sheets, Yield limit, Elastic modulus, Composites.

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1 Introduction

Sandwich panels are mechanical structures constructed using two pieces of face sheets made from robust and stiff materials partitioned by a lightweight core. These highly optimized sandwich panels are extensively employed in numerous field applications, such as aerospace, automotive, and navy, given the high stiffness of the face sheets and the low specific weight of the core material. Despite their significant application, sandwich panels are susceptible to various defects and failures due to the considerably differing properties of the core and face sheets. Previous investigation has revealed the impact of the core material stiffness on the mechanical strength of sandwich panels beyond the core material's yield point. A recent study evaluated the elastic modulus ratio of the core material (foam) to the face sheet (metal) using the univariate search optimization approach, [1]. Accordingly, multi-span sandwich panels made with slightly profiled steel facings and polyurethane foam core were identified as the optimal design, which offers cost-effective, minimal variance in the panel types, and potential for a full-scale application that satisfied the conflicting requirements in the market, [2]. In another study, the mechanical strength of sandwich composites made using a hollow glass microsphere containing syntactic foam in an epoxy resin matrix (core material) and hybrid kenaf/glass fibers (face sheet) was assessed, [3]. The study used four distinct face sheet combinations (glass-glass, kenaf-kenaf, kenaf-glass, and glass-kenaf) to develop an acceptable lightweight composite panel for structural applications. Subsequently, a thorough analysis of each design's mechanical performance and failure mechanisms was conducted. Meanwhile, a limited component analysis was carried out to evaluate the stability of a sandwich panel design made of steel with a center that was practically determined, [4]. Polyethylene terephthalate (PET) fiber-reinforced polymer (FRP) composite was used to create the steel-based sandwich beams, with recycled PET (R-PET) from post-consumer plastic bottles serving as the foam core. Using the three-point bending approach, the sandwich beams were studied and experimented with beyond their proportionality limit. A control group with glass FRP facings and a core density of 100 kg/m^3 was used to examine the effects of R-PET at three core densities of 70, 80, and 100 kg/m3.

The present study aims to explore the performance of sandwich panels exceeding the yield point stiffness of the core material. This study is very important because sandwich panels have gained growing attention among designers owing to their excellent corrosion properties, lightweight applications, and speedy installation processes that have been applied in numerous industrial sectors, including aerospace, architectural, marine, and transportation.

The characteristics of the steel were then assessed numerically using ceramic as the interface zone for up to ten individual layers. For the volume portions of K = 2, the FGM was assumed. All 12 of the examined beam specimens showed non-linear load-deflection behavior, as evidenced by the fixed beam geometry during the investigation. Consequently, decreased secant elastic and shear moduli under incremental load capacity were used to build a non-linear analytical model. A parametric assessment of the mechanical strength was carried out under various scenarios after the suggested model was validated, [5]. A previous study considered numerous core models, including hybrid, corrugated, derivative, foam, folded, honeycomb, hierarchical, gradient, truss, hollow, and smart core, along with several composite materials to fabricate novel face sheets, including metal matrix composites, fiber-reinforced composites, and polymer matrix composites, [6]. Additionally, a study performed a delamination test using a double cantilever beam specimen, [7]. The study employed the hand lay-up technique, where two face sheet layers composed of glass fiber composite laminates sandwich a plate/core to modify and enhance the fracture properties of the specimen. Face sheet/core delamination describes the process of separating the core material in a sandwich panel from the face sheet layer. Another research assessed the flexural strength of a sandwich roof panel made of Glass Fiber-reinforced Polymer (GFRP) using ANSYS WORKBENCH, a commercial FEM program. The top and bottom thin GFRP face sheets of the specimen were created using two distinct densities of multilayer polyurethane foam core. As a result, the optimal stacking order for GFRP sandwich panels with diverse multilayer cores was investigated, [8]. This allows for the placement of distinct core material layers on top of one another. A fundamental review that covered the topic of weight reduction in automotive applications was recently published, [9]. The review described a variety of lightweight composite materials with advantageous mechanical characteristics. Concurrently, a recent study created a novel fiber composite sandwich panel for use in constructing buildings and other structural infrastructures, [10]. This panel is made up of a high-strength core material and skins reinforced with glass fiber. To assist technical staff and construction teams grasp a better understanding of this next-generation sandwich panel's behavior for real-world applications, its features have been intensely studied. This innovative sandwich panel was the subject of preliminary research using point loading in one- and two-way spanning floor applications. The findings suggest that the fiber arrangement of the sandwich skins had an impact on the stiffness of the sandwich. One study applied the bioinspired method of hybrid material layers to develop a flimsy material composed of an aluminum face sheet with an interlayer of glass fabric and foam core as an alternative material in automotive, aeronautical, and marine applications, [11]. A GFRP sandwich composite filled with stiff polyurethane foam was created and characterized, according to another study, [12]. The study examined the impact of the volume of epoxy resin, which serves as a binder between the polyurethane core and the GFRP layer, on the mechanical strength metrics of tensile, flexural, and compressive strength. Additionally, one research provided a synopsis of the development of structural insulated panels (SIP) as well as the standard methods and components utilized in SIP fabrication, [13]. The paper also reviewed recent research related to SIPs in terms of their applications and limitations, permitting developers to enhance these materials. Apart from that, static indentation and subsequent unloading were applied and assessed using foam core sandwich beams, [14]. They were considered to be consistently supported by a rigid platen to minimize global bending. Moreover, the flexural analysis of a composite SIP with magnesium oxide board facings was performed using an analytical model that assumed an elastically perfect plastic compressive behavior of the foam core, [15]. To integrate material bi-modularity, a novel bespoke coding process was created, which significantly improved the accuracy of computational results and failure mode prediction. A thorough investigation combining numerical models and laboratory experiments on CSIP beams of varied lengths under three- and four-point bending revealed material model parameters within the non-linear behavior range. Furthermore, finite element analysis was utilized to ascertain the impacts on the characteristics of sandwich composites composed of polymer lamina reinforced with carbon fiber, [16]. The A-shaped cores of the composite sandwich structures exhibit exceptional mechanical characteristics under quasi-static plane compression loads compared to the W-, X-, and Y-shaped cores. Furthermore, a study fabricated two different sandwich panels composed of expanded polypropylene and extruded polystyrene foams as the core materials and aluminum as the face sheet material, [17]. The flexible epoxy-based adhesive was applied to combine the two aluminum face sheets and foam cores under a 20 N static compression load. Using post-mortem imaging, the damage behavior of the fabricated sandwiches was examined, which showed that the sandwiches damaged perfectly plastic deformation. An experimental study developed and evaluated the characteristics of a new type of SIP comprising an insulated foam manufactured from natural rubber loaded with wood particles (core layer) and three commercial wood-composite boards (cement particle, plywood, and fiber-cement) as the surface layer, [18]. Lastly, composite panels with carbon fiber face sheets and Kevlar honeycomb cores in different configurations were evaluated using finite element analysis, [19]. The influence of varying face-sheet thicknesses on the bending rigidity (U), bending stiffness (D), and load-to-deflection ratio of the composite panel was conducted during the analysis.

Geometry and Physical Model of the Sandwich Panel

Generally, the sandwich panel is composed of two composite materials that form the face sheets, with a thickness of t each. A softcore material made of foam with a thickness of c and smoother than the face sheets is sandwiched between the two face sheets. The square-shaped panel has a side length of a and an overall thickness of h. Figure 1 depicts the geometry of the sandwich panel with values a, t, and c of 610 mm, 1.0 mm, and 40 mm, respectively.

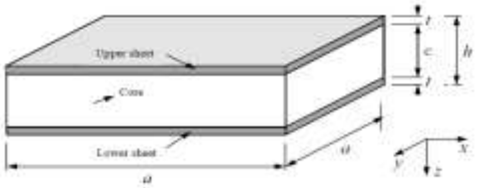


Fig. 1: Schematic diagram of the sandwich panel geometry

Assumptions

This research mainly considers the non-linearity of the sandwich panel materials. Several assumptions were established to elucidate the model without disregarding the physical aspects of the problem, as follows:

1. Both the core and face sheets are perfectly bonded without any delamination occurring between the layers.
2. The face sheets maintain their elastic behavior throughout the loading time due to their substantially greater yield strength and elastic modulus than the core. The analysis halts the moment the face sheets begin to yield.
3. All sides of the panel are supported.
4. The core material is considered to adopt a non-linearity behavior.

Boundary Conditions and Material Properties

Materials that are used as face sheets in sandwich panels should possess desirable properties, including sturdy, durable, and able to withstand the impact of resistance. Additionally, nearly all structural materials that are available as thin sheets can be utilized as the face sheet in sandwich panels. These valuable properties are essential to prevent itself from bending and fracturing through in-plane shearing and out-of-plane compressive load. In this particular case, the composite face sheet can be compared to isotopic materials that fulfill the above conditions. Recent studies have demonstrated the potential applications of composite skins in numerous industrial sectors. For example, these composites are very often employed as panels to minimize weight in aircraft designs. The face sheet material is widely grouped into metal-matrix composites, fiber-reinforced composites, and polymer matrix composites, as listed in Table 1, while the varying softcore materials A, B, C, and D are presented in Table 2.

Table 1. The characteristics of the composite fiber sheets applied in this study

	Elastic modulus (GPa)	Fiber volume fraction (GPa)	Poisson's ratio
Fiber	230	0.785	0.22
	Tensile yield (MPa)	Compression yield (MPa)	Elongation (%)
Carbon fiber	945	686	1.5
Epoxy	79.6	108	14.6

Table 2. Properties of the four isotropic core materials applied in this study

Material	Reference	Young's modulus (MPa)	Poisson's ratio	Shear modulus (MPa)	Shear strength (MPa)	0.2% offset yield strength (MPa)	Strain at yield point (mm/mm)
AirexR63.50 core A	Rao, 2002	37.5	0.335	14.05	0.45	0.637	0.019
H100 core B	Kuang, 2001	138.6	0.35	47.574	1.2	1.5	0.0108225
HerexC70.200 core C	Rao, 2002	180	0.37	65.69	1.6	2.554	0.0162
H250 core D	Kuang, 2001	402.6	0.35	117.2	4.5	5	0.014

The upper and lower face sheet composite material are stacked into several layers of the orthotropic, as illustrated in Figure 2. The load was gradually exerted onto the square-shaped loading area on the top center of the face sheet until the stress strain reached its yield strength (Figure 3). Besides, Figure 4 elucidates the stress-strain curve of the core materials A, B, C, and D. These materials were selected due to their broad applications in many industries.

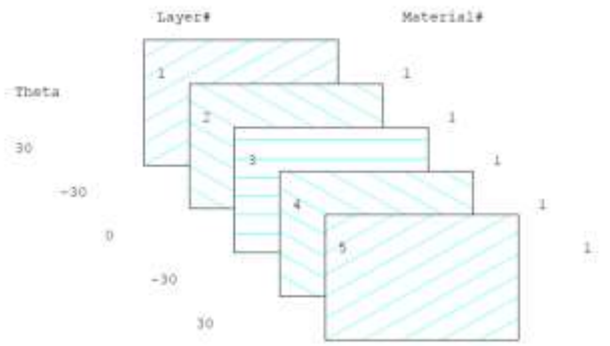


Fig. 2: Upper and lower face sheet composite material and stacking

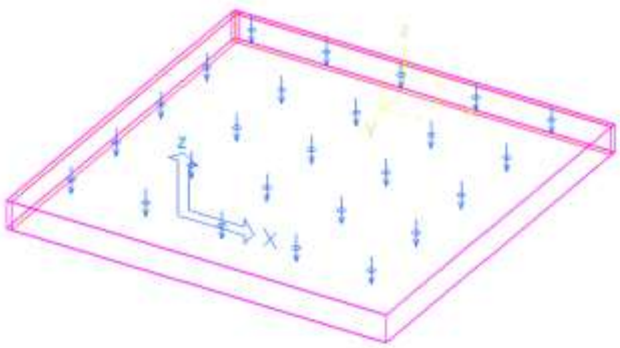


Fig. 3: Load distribution on the center of the upper face sheet

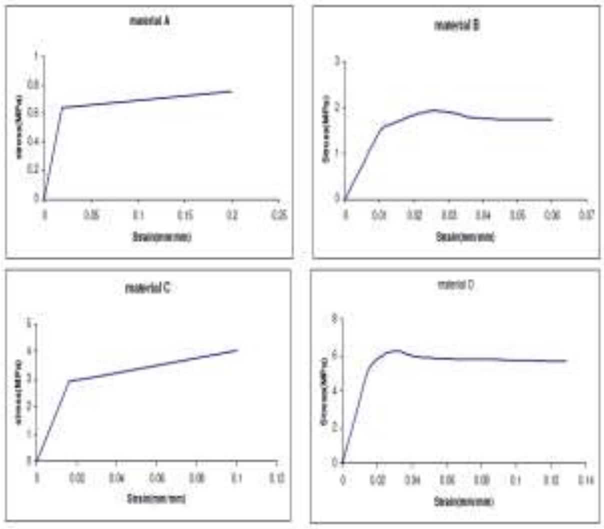


Fig. 4: Stress-strain curve for core materials A, B, C, and D

2 Problem Formulation

2.1 Finite Element Model (FEM)

The ANSYS APDL was used to develop the FEM for the varying proposed sandwich panels and assess their flexural behavior. The isotropic solid element (solid 186) with 3 translational degrees of freedom at each node was utilized to model the light and stiff foam cores. Meanwhile, the orthotropic shell element (shell 281) has 8 degrees of freedom at each node and was applied to model the face sheets. Shell elements were used to achieve effective outputs, making it easier to design thinner components with fewer mesh elements, leading to significant cost-effective computation. To prevent any delamination in the panels, full contact behavior was applied between the sandwich panel components. Following the mesh convergence analysis, sufficient mesh size was equipped to achieve the most reliable findings. The sandwich panel was designed as a simply supported panel, with roller support at one side and pinned support at the other side. Then, the load was equally distributed onto the sandwich panels.

This model was convenient to evaluate thin to moderately thick shell structures. The Shell Element (SHELL 281) model consists of 8 nodes with 6 degrees of freedom at each node comprising translations in the X-, Y-, and Z-axes and rotations about the X-, Y-, and Z-axes. Although the plane elements required a longer computational duration, the primary advantage of the eight-node shell element (rather than SHELL elements) is its notable yielding behavior, the stress/strain profile throughout the plate thickness, and the development of plastic hinges. The stress-strain results are also relatively straightforward to describe. Moreover, the shell elements required lesser computation efforts and faced fewer convergence issues than plane elements.

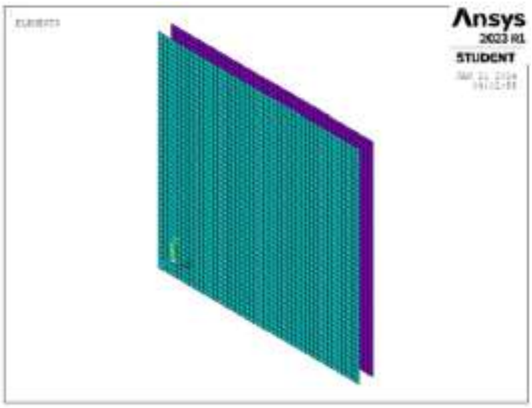


Fig. 5: The FEM mesh of the sandwich panel (upper and lower face sheets)

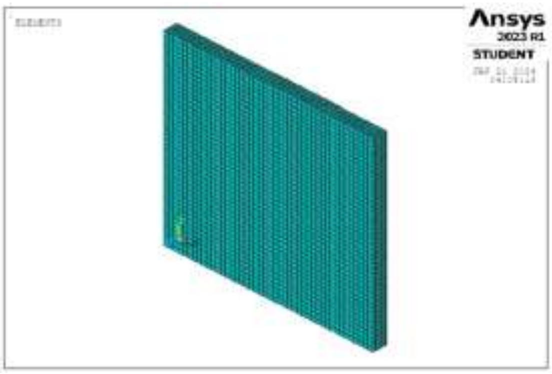


Fig. 6: The FEM mesh of the sandwich panel (core material)

Nevertheless, shell models need more post-processing to describe the findings. Solid 186 was applied to develop the three-dimensional (3D) modeling of the solid structures. The element consists of 21 nodes with 3 degrees of freedom at each node: translation in the X-, Y-, and Z-nodal directions (Figure 5). The element appears to exhibit several behaviors, including creep, huge deflection, immense strain, plasticity, swelling, and stress stiffening. The ANSYS finite element program was utilized to design the sandwich panel. Both the two-dimensional (2D) and 3D simulations were modeled, and the convergence analysis was conducted to measure the consistency.

2.2 Model Validation

In previous literature, FEM was validated by comparing specific cases from the literature. The relative difference in the results was lower than 1%. To verify the FM and its results, experimental validation was performed. The experimental procedure utilized a sandwich panel made of Herex C70-200 as the core material and an E-glass mat (denoted as G300) as the face sheet [20]. The mechanical properties of both the core material and face sheet were obtained during the experiment following ASTM guidelines. Figure 6 shows the relationship between the deflection at the specimen's center point and the applied load for both experimental and FEM procedures, which demonstrates a strong agreement between the results. The maximum relative error was also lower than 6%. The experimental procedures were repeated multiple times, and the average values are shown in Figure 7.

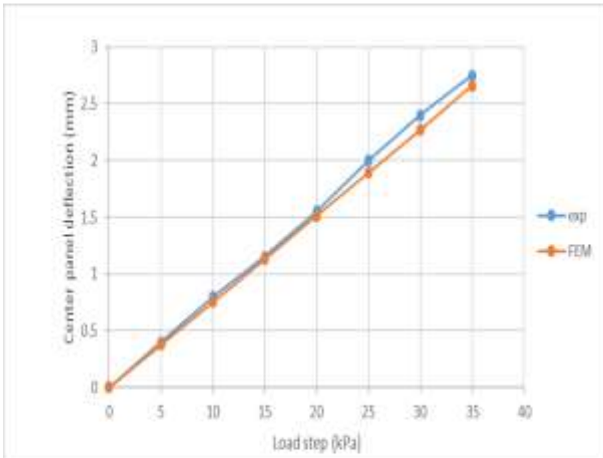


Fig. 7: Comparison of the center panel deflection vs. load step (kPa) between the predicted FEM and the actual experimental result, [20]

3 Problem Solution

The impact of the core stiffness of the sandwich panel was evaluated by varying the mechanical properties of the core material. Materials with non-linear behaviors were considered in this parametric study by applying the ANSYS software, stress and all its components, as well as strain and all its components, such as plastic strain and deformation. It was found that plastic deformation occurred near the panel support (the point at which the boundary conditions were applied), which holds in the physical sense. The load exerted was concentrated on the loading area where the simply supported boundary conditions were applied and became a reaction force. As a result, the area reached the yield stress before other panel parts. The load step on the FEM was halted when any of the face sheets started to yield, which met the designer's requirement to prevent permanent panel distortion. The yielding of the face sheet indicates that non-reversible deformation has taken place. As a result, the applied loading does not exceed the limit and does not lead to the face sheet yielding. The sample displayed the sandwich panel's behavior in terms of each parameter. Thus, the results would help design engineers to achieve (or select) optimal parameters that suit their design.

Figure 8 shows the center of deflection of the entire sandwich panel vs. the load step. It was noticed that the core stiffness increased as the sandwich deflection decreased. Figure 9 and Figure 10 depict that the core stiffness caused the load-carrying capacity (shear and total load) of the panel to rise before the core material reached the shear yield limit (shear strength and yield strength). Meanwhile, the impact of the core stiffness on the upper and lower face sheets is portrayed in Figure 11.

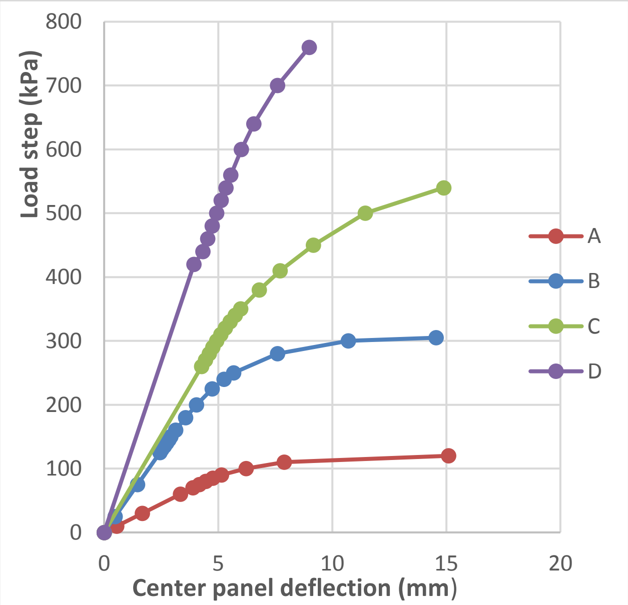


Fig. 8: The center of deflection of the entire sandwich panel (mm) vs. load step (kPa) using varying strength of core material stiffness

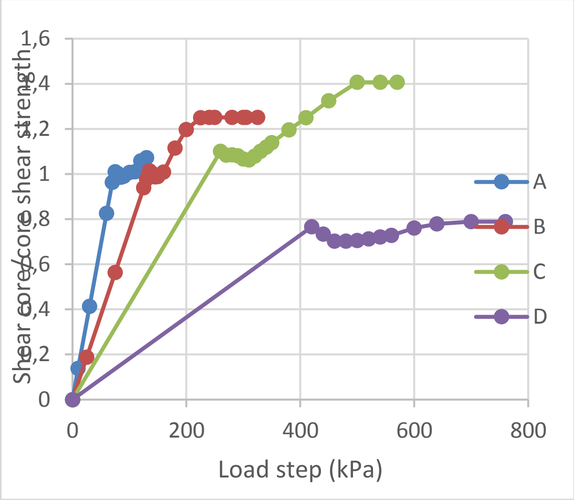


Fig. 9: The maximum core shear stress to the yield shear strength of each core material vs. the load step (kPa)

In general, the upper face sheet was found to start yielding first, followed by the lower face. Besides, the face sheets were able to withstand the tension stresses, noting that the results simulate the actual behavior. According to the Van Misses stresses the two face sheet layers were exposed to tension stresses, whereas the upper layer exhibited a higher value since it was directly exposed to the pressure. Figure 11 presents the impact of the core stiffness on the maximum Von Misses stress for the upper and lower face sheets vs. the load step that causes the sheets to yield just before 130 kPa, 305 kPa, 570 kPa, and 760 kPa when using core materials A, B, C, and D, respectively. The stability of the core material influenced the transfer of stress to the face sheets, increasing their values as they carried the load on the upper and lower face sheets. With the core entering to yielding phase (shifting to plasticity), the rate of increase of the maximum stress diminishes, as shown in Figure 10. In other words, the load was passed to the face sheets, which highlights the key advantage of expanding the load above the core material's yield limit. Note that the different curvatures in Figure 11 for all loads in each core material stiffness were a result of the transformation of the core materials, with both the upper and lower face sheets exhibiting similar behavior.

Figure 12 depicts the contour deflection of the entire sandwich panel under the maximum load step for each core material with the face sheets loaded with carbon fiber composite materials. Additionally, Figure 13 portrays the shear stress contour of the different core materials under the maximum load step.

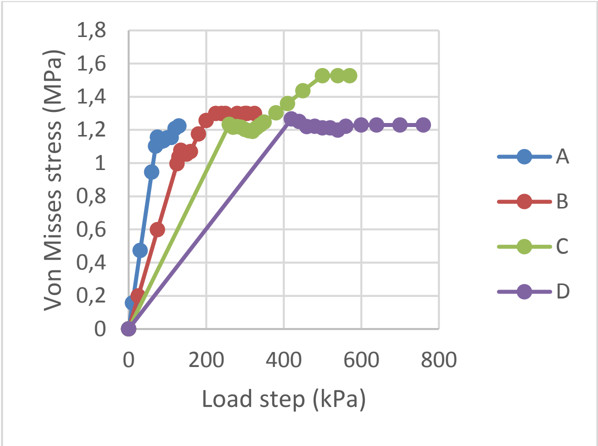
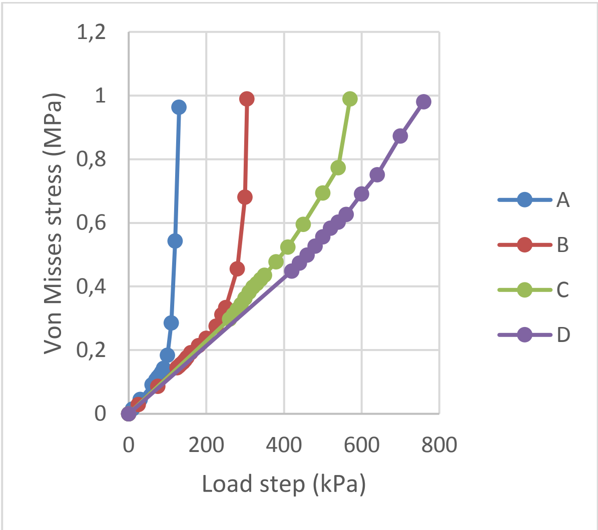
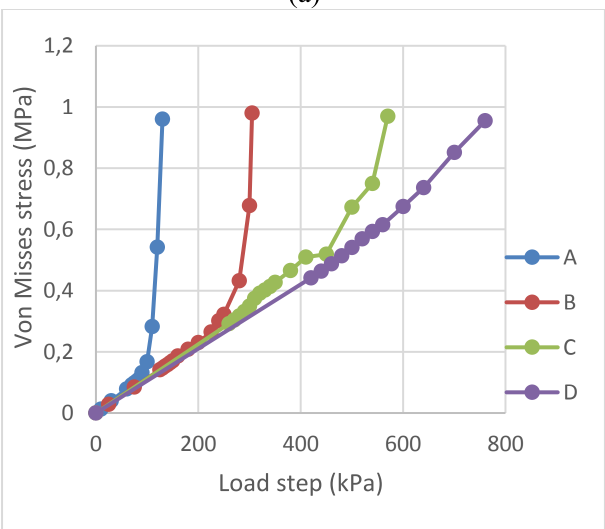


Fig. 10: The maximum core Von Misses stress (MPa) to the yield strength (MPa) for each core material vs. the load step (kPa)



(a)



(b)

Fig. 11: The maximum Von Misses stress (MPa) to the yield strength of each core material vs. the load step (kPa) for the (a) upper face sheet and (b) lower face sheet

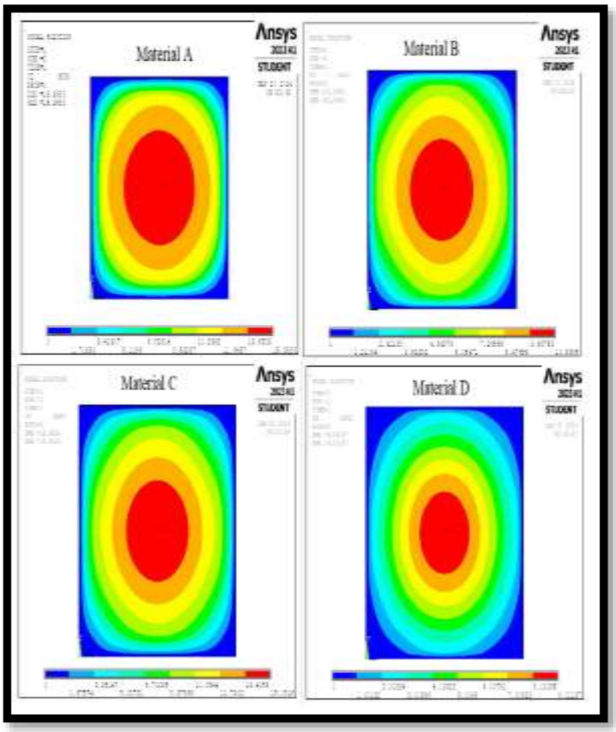


Fig. 12: The contour deflection of the entire sandwich panel under maximum load step using various core materials

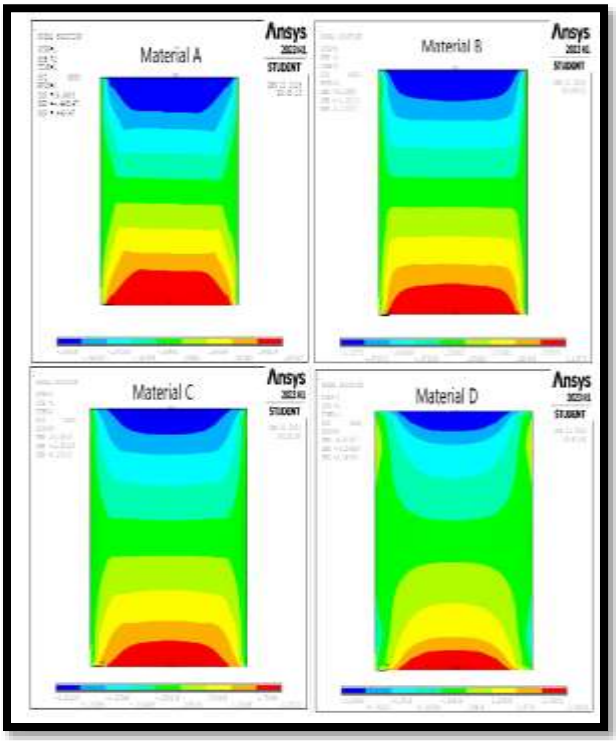


Fig. 13: Shear stress contour of the entire sandwich panel under maximum load step using various core materials

The shear stress contour took place at the edge of all the core materials and showed a similar profile at varying stiffness values. Meanwhile, Figure 14 presents the Von Misses stress contours of the different core materials under the maximum load step. Figure 15 and Figure 16 presents Von Misses stress contour for the upper and the lower face sheets material under maximum load step using different core materials.

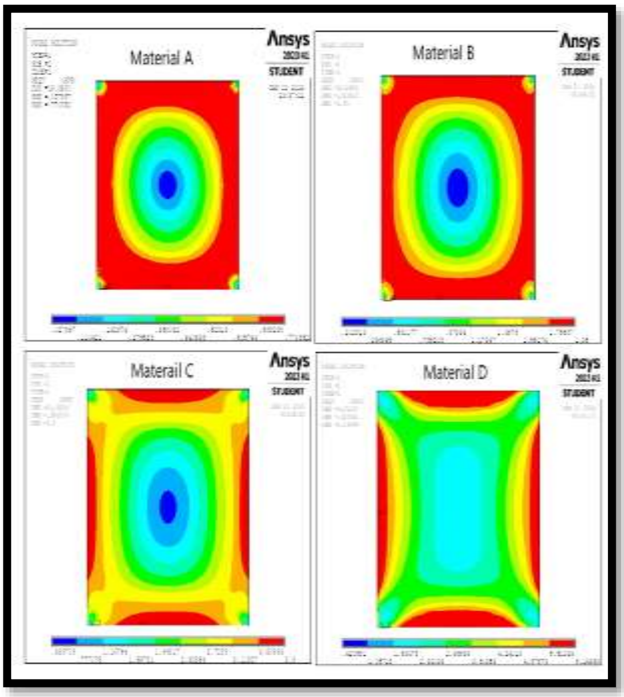


Fig. 14: Von Misses stress contour of the entire sandwich panel under maximum load step using various core materials

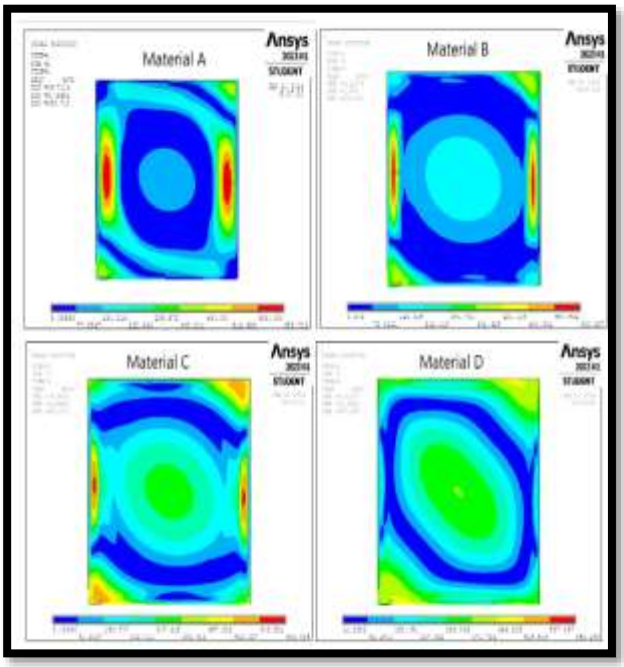


Fig. 15: Von Misses stress contour for the upper face sheet material under maximum load step using different core materials

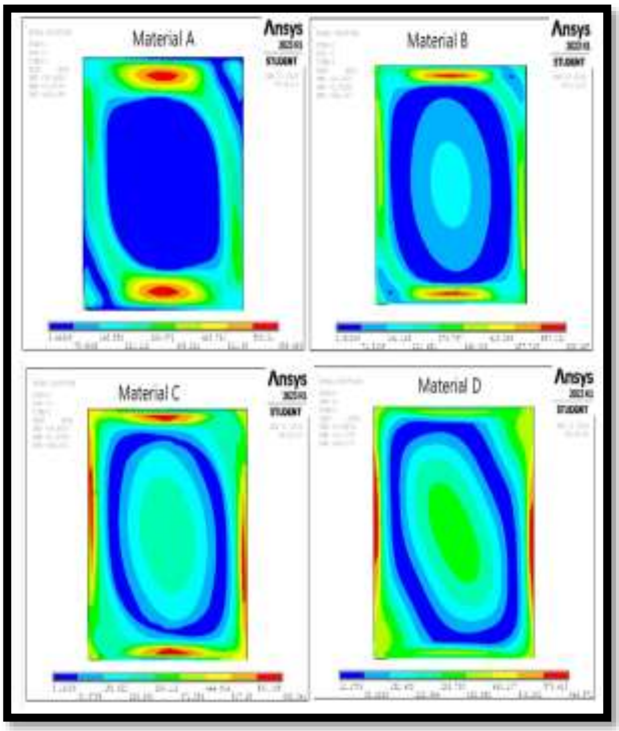


Fig. 16: Von Misses stress contour for the lower sheet material under maximum load step using different core materials

4 Results Discussion

From previous results, the thickness of the core material increases as the load-carrying capacity of the panel increases. This is justifiable because the increase in thickness increases the second moment of the cross-section area of the panel. In addition, the shear stress in the core decreases for the same amount of loading because the shear load is distributed over a larger area as the thickness increases. When the core material reaches the yield point, the shear stress stays constant while the load is being increased. In the yield range, the core material keeps deforming while stress is constant. Increasing the area of loading increases the load-carrying capacity of the panel. The results of this work are generated according to the univariate search optimization technique, [21].

5 Conclusion

This study investigated the performance of sandwich panels beyond the core material yield point. The non-linearity core material of the whole sandwich panel model was generated using the ANSYS software and validated using specific analytical cases from past literature. The accuracy of the model was also examined for certain cases and compared with FEM. Overall, the model showed excellent agreement with past findings, as well as the experimental data in this study when compared to literature as shown in [22]. The increased load-carrying capacity of the sandwich panel corresponds to the impact of the core material as it exceeds the yield limit. Furthermore, the load transferred to the face sheets increased the stiffness of the core materials increased. As such, the sandwich panel tends to behave as an orthotropic composite sheet with greater core material stiffness. As a result, the face sheets yield before the core material.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly for language editing. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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