JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

FABRICATION OF SANDWICH COMPOSITE ROOFING PANELS AND ITS ANALYSIS USING ANSYS SOFTWARE

[1]Syed Mudassir, [2]Mithun Vinayaka Kulkarni

[1,2]College of Engineering and Technology, Department of Engineering, Mechanical Engineering Section, University of Technology and Applied Sciences, Salalah, Sultanate of Oman

Abstract: Sandwich composite materials are considered a special class of composite materials due to their high stiffness-to-weight ratio. Sandwich structures are composed of two fiber-reinforced plastic (FRP) skins that sandwich a low-density rigid foam core, providing high flexural stiffness and improved high specific energy absorption capability. The increasing need for new cost-effective and reliable materials is evident in automotive, aerospace, marine industries, and various domestic applications such as roofing panels. The performance of sandwich composite laminates (SCL) depends entirely on the properties of their constituent materials and flexural stiffness determined by the geometry of the component. Analytical procedures, such as implementing Finite Element Analysis (FEA), have been employed to investigate effects and compare experimental results with analytical findings. In evaluating the static performance of SCL, a simple sandwich roofing panel is being designed, fabricated, and tested under static bending conditions

Keywords: Composites, Sandwich structures, roofing panels, FEA/FEM, FRPs, Polyurethane foam

1. INTRODUCTION

In the contemporary era of construction and architecture, the quest for innovative, sustainable, and efficient building materials has become imperative. With a growing emphasis on energy efficiency, environmental sustainability, and structural performance, researchers and engineers are continually exploring novel materials and design methodologies. One such promising avenue is the development of Sandwich Composite Roofing Panels (SCRP)[1], which combines diverse materials in a layered structure to achieve a synergistic blend of strength, insulation, and durability. Roofing systems play a pivotal role in the overall performance and sustainability of buildings. Traditional roofing materials, while effective in providing shelter, often fall short in meeting the multifaceted demands of modern construction[2]. As climate change concerns and energy efficiency standards escalate, there is a growing need for roofing solutions that not only ensure structural integrity but also contribute to thermal insulation, acoustic performance, and overall sustainability. The Sandwich Composite Roofing Panels, emerging as a promising alternative, bring together the advantages of diverse materials in a composite structure. The design of Sandwich Composite Roofing Panels involves the strategic integration of various materials to create a layered structure. The choice of materials for the outer and inner layers, as well as the core material, is a critical aspect of the design process. Materials with high strength-to-weight ratios, such as fiberglass, carbon fiber, and aluminum, are commonly employed for the outer layers to ensure structural integrity. The core, which is sandwiched between the outer layers, often consists of lightweight and insulating materials like foam or honeycomb structures[3]. This layering not only enhances the mechanical properties of the panels but also enables the optimization of thermal and acoustic performance. The primary objective in the design and development of SCRP is to achieve superior structural performance and load-bearing capacity[4]. The layered composition imparts unique mechanical properties, such as increased stiffness and strength, to the roofing panels. The synergy between the different layers allows for a more efficient distribution of loads, reducing the overall weight of the structure without compromising its strength. This not only contributes to the longevity of the roofing system but also has potential implications for the overall sustainability of the building. Sandwich Composite Roofing Panels offer significant advantages in terms of energy efficiency, particularly in maintaining thermal comfort within buildings. The insulating properties of the core material contribute to temperature regulation, reducing the need for excessive heating or cooling. This not only enhances the comfort of occupants but also leads to potential energy savings, aligning with the global drive towards sustainable construction practices[5][6]. In this work, design, fabrication and analysis using ANSYS a Finite Element Analysis (FEA) software has been carried out.

2. LITERATURE REVIEW

The evolution of Sandwich Composite Roofing Panels (SCRP) showcases an interdisciplinary effort to enhance structural efficiency. Historically, sandwich composites have evolved from niche military applications to mainstream engineering solutions. Feichtinger's pioneering studies laid the groundwork for modern composite applications [7], while Kueh 's research provided a deeper understanding of the mechanical behaviour under compressive loads [8]. The literature classifies fibers into natural and synthetic, offering diverse mechanical properties and applications [8]–[11]. Synthetics like glass, carbon, and Kevlar are particularly noteworthy for their superior strength and durability. The matrix component's role in load transfer and environmental protection of the fibers is well-established, with polymers, ceramics, and metals providing distinct advantages [12]. Katzman et al. have also explored the mechanical behaviours of composites, focusing on stiffness, strength, and energy absorption [10]. The significance of core materials like polyurethane foam is emphasized for their specific energy absorption capabilities, which is critical for applications requiring energy efficiency [13]. The advantages of sandwich composites, including their high flexural stiffness and thermal insulation, are well-documented [14]. However, challenges persist with adoption, including costs and manufacturing complexities. The industry is working towards cost-effective manufacturing techniques and enhanced understanding of material behaviour. Future research is directed towards the long-term durability and environmental resistance of composites [15]. Several researchers have elaborated on diverse types of sandwich structures and their corresponding core materials, shedding light on their unique properties and applications. Polymeric foam cores offer advantages such as cost-effectiveness and ease of fabrication, demonstrating shockwave absorption, blast mitigation, and crashworthiness ideal for space applications. Variations in polymer types impact the behavior of sandwich structures, emphasizing the preference for uniform-density polymer cores in achieving high performance.

Metallic foam cores, notably aluminum-based, offer enhanced energy absorption in sandwich structures, particularly when combined with composite face sheets. Unlike polymer foam cores, graded metallic cores outperform uniform density cores, showcasing high blast resistance and crashworthiness. However, their drawbacks include high density and complex processing methods. Honeycomb cores stand out for their exceptional performance in dynamic loading scenarios within space applications, displaying superior shockwave absorption and low-velocity impact resistance. Graded honeycomb cores exhibit higher efficiency than uniform density ones, offering substantial energy absorption capabilities determined by design parameters and strain rate. The utilization of balsa wood cores in sandwich structures aligns with ecological sustainability efforts, delivering cost-effective solutions with high thermal insulation. However, challenges like intricate processing, low water durability, and impact resistance persist, despite their widespread application in marine and civil structures. Tubular cores and corrugated structures demonstrate promising attributes in blast resistance and shock/crash sustainability, offering notable energy absorption capacities. Origami and meta/auxetic cores, developed through innovative fabrication techniques like 3D printing, present possibilities to overcome debonding issues between face sheets and cores during shock/impact events [6]. These discussions underscore the diverse array of core materials available for sandwich structures, each possessing unique characteristics and tailored applications across various industries, while also highlighting their inherent limitations and ongoing research efforts to address these challenges. There are various manufacturing techniques employed for creating sandwich composite structures, detailing methods like hand lay-up, prepreg techniques (including vacuum bagging and autoclave), resin injection processes, compression-based methods, continuous processes like pultrusion, and advanced methods such as 3D and 4D printing. However, among all, the most preferred is the hand lay-up technique.

3. Estimation of Fiber and Volume fraction

In order to determine the volume fraction of fiber and matrix, the burn test has been conducted. In static loading, sandwich composite laminates (SCRP) are tested in the horizontal position with the face being flat, as it is commonly used as structural panels for the roof, floor, walls, bridge decks, etc.

3.1 Estimation of Volume Fraction

The volume fraction measures the volume of fiber and matrix contained within the composite. It is evident that the stiffness of the composite depends on the volume fractions of the fiber and matrix. Lightweight and soft composites result from a low volume fraction, whereas heavy and stiff composites result from a high volume fraction. Determining the fiber volume fraction relies on variations in thermal properties between the fiber and matrix. Glass fiber exhibits excellent thermal resistance compared to epoxy resin. Therefore, the burning test is a suitable method for determining the fiber volume fraction. By heating the specimen in a furnace at 800°C, the matrix is burned off, as depicted in Fig. 1a and b. The volume fractions of the fiber and matrix are presented in Table 1.

(a) Laminates placed inside the furnace (b) Laminates before and after the burn test

Fig. 1: Determination of fibre - volume fraction

Table 1: Fiber – Volume fraction

Fiber orientations	The volume fraction of fiber	The volume fraction of the matrix
$[0^0/90^0/90^0/0^0]_{2s}$	0.55	0.45
$[0^0/45^0/90^0/-45^0]_{2s}$	0.53	0.47

3.2 Estimation of Material Properties

The estimation of the Young's modulus of the composite laminate in both the direction of load application and the transverse direction can be derived from the classical laminate theory. To streamline this process, the Classical Laminate Theory software is utilized, mitigating the need for laborious manual calculations. Material properties for various orientations of glass fiber have been determined using the classical laminate theory calculator and Table 2 presents the material properties corresponding to different orientations of E-glass/epoxy laminate.

Table 2 Material properties of different orientation E-glass/epoxy laminate.

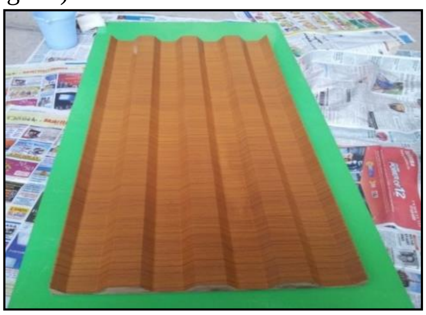
Material Properties	E-glass/epoxy laminate	
	$[0^0/90^0/90^0/0^0]_{2s}$	$[0^0/45^0/90^0/-45^0]_{2s}$
Young’s modulus, Exx (GPa)	33.42	31.85
Young’s modulus, Eyy(GPa)	19.97	19.94
Shear modulus,Gxy (GPa)	8.78	9.33
Major Poisson’s ratio, Vxy	0.27	0.27
Minor Poisson’s ratio, Vxy	0.06	0.06

4. Sandwich Roof Panel Fabrication

The sandwich roof panel, designed and tested under static bending, features a simple structure tailored for various applications previously outlined. Material selection for fabricating these roof panels was based on optimal results derived from static flexural tests. The chosen skin orientations for this application comprise $[0^0/90^0/90^0/0^0]_{2s}$ and $[0^0/45^0/90^0/-45^0]_{2s}$, utilizing polyurethane foam as the core material. Notably, the disbonded face-sheet deflects out-of-plane during testing. To capture this phenomenon accurately, a laser displacement gauge was mounted in a rig, facilitating measurement of the out-of-plane displacement at the disbond center. This setup not only determined the onset of buckling but also recorded the maximum disbond height throughout the loading process.

4.1 Procedure to Prepare GFRP Roofing Panel

- Mold Preparation: Apply wax polish to both the mold and wooden planks (Fig. 2a – 2b), ensuring smooth surfaces. Subsequently, apply polyvinyl alcohol (PVA) using soft sponges. It is recommended to apply PVA 15-20 minutes after wax polishing.
- Gel Coat Preparation: In a clean empty bucket, take 2000 ml of gel coat and add 100-150 grams of white color pigment, stirring thoroughly for even distribution. Introduce 2% accelerator (cobalt naphthenate), i.e., 40 ml for the 2000 ml gel coat, and stir the composition for 2-3 minutes. Then, separately measure 1000 ml and add 2% catalyst (methyl ethyl ketone peroxide) to the gel coat, color, and accelerator composition.
- Gel Coat Application: Apply the gel coat composition to the mold and wooden planks within a 15-20 minute window to avoid premature solidification (Fig. 2c).
- Layering Process: After allowing the gel coat to dry and adhere firmly, accurately cut E-Glass fibers as per the foam dimensions (500 mm X 1000 mm) and place them over the foam material (Fig. 2d & e).
- Compression Molding: Place a wooden plank previously coated with gel coat over the fiber-epoxy resin-coated foam panel (Fig. 2f). Apply an anvil weighing 50-60 kg evenly over the plank for compression molding (Fig. 2g). Ensure an even distribution of weight across the area.
- Curing: Leave the setup undisturbed for 24 hours. Carefully remove the final SCRP product using chisels and hammers (Fig. 2h).



(a) Mold

(b) Wooden plank

(c) Gel coat applied to mold and planks

(d) Cut glass fibre

(e) Fiber glass placed on the PU foam core

(f) Wooden plank used to support the mold.

(g) Anvils placed for compression

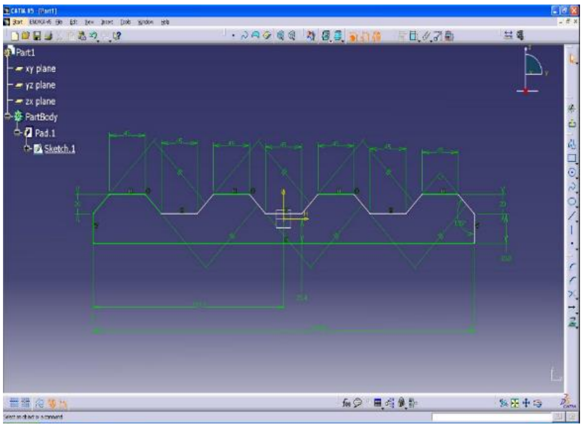
(h) Fabricated panel

Fig. 2: SCRP preparation

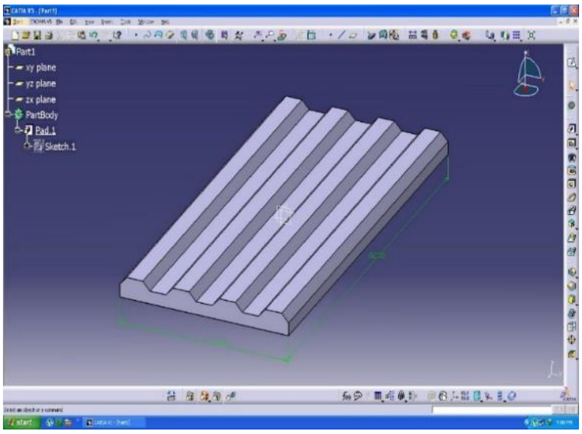
5. Modelling and Finite Element Analysis

5.1 Modelling

The sandwich composite roof panels are created and analysed through a combination of modelling in CATIA V5 and subsequent static deflection test analysis using ANSYS software. Fig. 3a and 3b depicts the CAD model.



(a) Mold profile creation



(b) CAD model of the mold

Fig. 3 CAD Model of the Mold

5.2 FINITE ELEMENT ANALYSIS for Sandwich Composite Roofing Panels (SCRP).

The finite element analysis (FEA) for the Sandwich Composite Roof Panels (SCRP) was conducted using ANSYS 10.0, focusing on static deflection analysis under diverse load conditions outlined in the experimental results. A meshed model of the SCRP, exemplified in Fig. 4, enabled the exploration of outcomes for loads ranging from 49.1 N to 343.35 N, specifically considering polyurethane-based orientations: $[0^0/90^0/90^0/0^0]_{2s}$ and $[0^0/45^0/90^0/-45^0]_{2s}$. The corresponding results are graphically presented in Fig. 5–12 and detailed in tables 3 and 4.

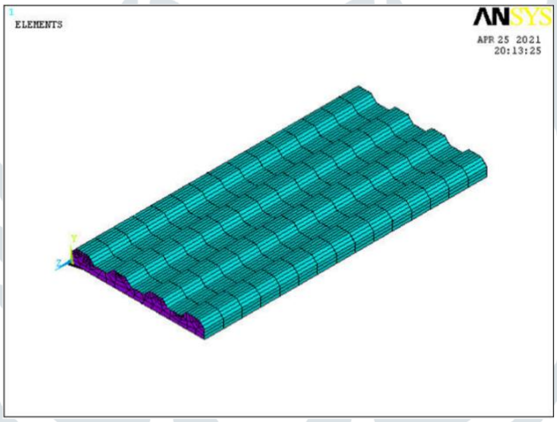


Fig. 4: Meshed Model of SCRP

The SCRP roofing panels were virtually subjected to 3-point bending, simulating two distinct skin orientations, $[0^0/90^0/90^0/0^0]_{2s}$ and $[0^0/45^0/90^0/-45^0]_{2s}$, using FEM. The FEM analysis involved various load ranges based on experimental data. However, it's important to note that the roofing panels weren't tested to complete failure.

For modelling SCL in ANSYS, the shell-99 linear layered element was selected for its capability to model composite structures with up to 250 layers, optimizing computational efficiency. This element type comprises 8-noded elements, with four nodes at corners and four at mid-sides, offering six degrees of freedom (DOF) per node—three for rotation and three for translation. The FEA input parameters were meticulously defined to ascertain the maximum deflection for the two distinct orientations of SCRP.

The geometry of the roofing panel, including layer count, orientation of each layer, constraints, and boundary conditions, was imported from CATIA V5. The two supporting points at either end of the panel were fixed at Z=0 translation, with a static bending load applied in the opposite direction. Material properties, specifically for various E-glass/epoxy laminate orientations, were previously discussed. The load values applied to each roofing panel were extracted from experimental tests, and the resulting deflections were recorded for plotting curves. These experimental deflection values were then compared to the results obtained from FEM analysis for comprehensive evaluation.

6. RESULTS AND DISCUSSIONS

6.1 FEA results discussion

This section is centred on determining the optimal orientation sequence of skin and foam core among the selected materials for the given SCRP composition.

Table 3: FEM Deflection Results for PU $[0^0/90^0/90^0/0^0]_{2S}$ SCRP

Load in (N)	FEM Deflection in mm
49.05	1.35
98.1	1.64
147.15	1.88
196.2	2.18
245.25	2.88
294.3	3.14
343.35	3.71

Table 3 implies that the fibres in the composite layers are oriented at 0° and 90° angles alternately, which should provide balanced stiffness in two orthogonal directions. The data shows a progressive increase in deflection with increasing load, which is a typical mechanical response. The non-linearity of the deflection (Fig. 6) with respect to the load suggests that as the load increases, the composite experiences greater deflection for the same increment of load, indicating a decrease in stiffness, possibly due to the beginning of material non-linearities or damage mechanisms such as matrix cracking or fiber-matrix debonding.

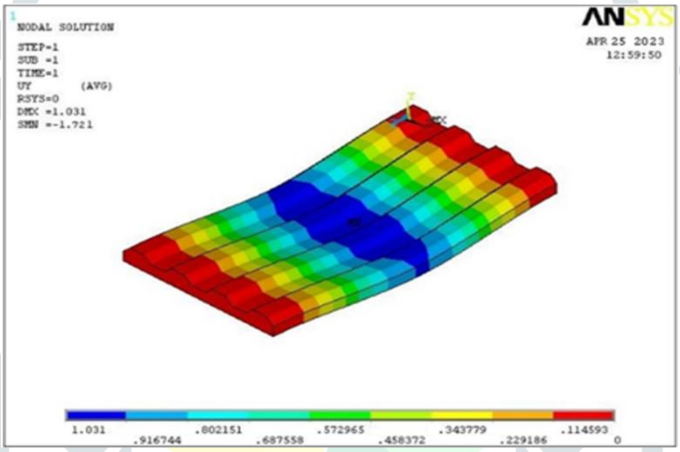


Fig. 5: Deflection for 49.05 N.

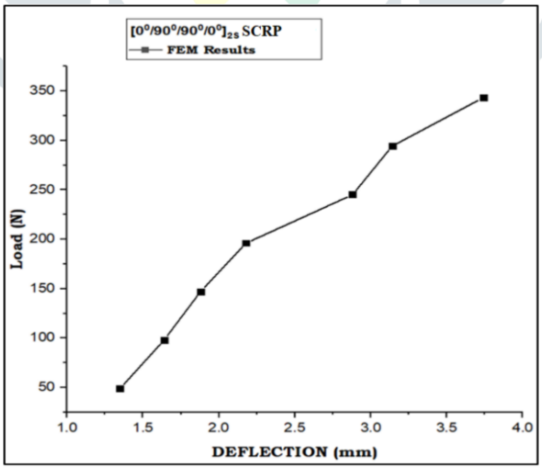


Fig. 6: Load Vs Deflection for PU $[0^0/90^0/90^0/0^0]_{2S}$ SCRP.

Table 4: FEM Deflection Results for PU [00/450/900/-450]2s SCRP

Load in (N)	FEM Deflection in mm
49.05	1.03
98.1	1.65
147.15	1.80
196.2	2.10
245.25	2.51
294.3	3.18
343.35	3.68

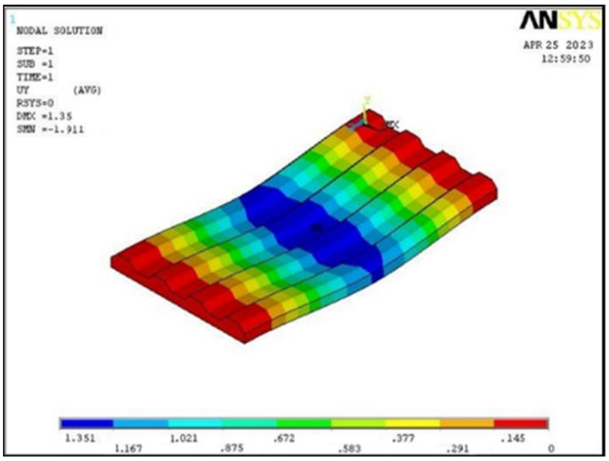


Fig. 7: Deflection for 49.05 N.

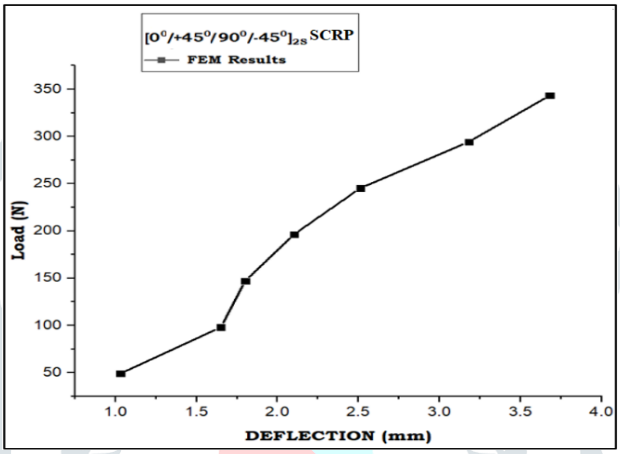


Fig. 8: Load Vs Deflection for PU [0°/45°/90°/-45°]2s SCRP.

In this layup, the fibers are oriented at 0°, +45°, 90°, and -45°, which is a common layup to increase shear and in-plane strength. The deflection results for the same loads show a different pattern compared to the previous layup, with generally lower deflections for lower loads, suggesting that this layup is stiffer in the initial loading stages. However, at higher loads, the deflections become comparable to the first layup, suggesting similar deformation characteristics under higher loading. The angles +45° and -45° are known to contribute to shear and torsional strength. This layup configuration may provide improved performance under torsional loads or when shear forces are dominant. The different orientations of the fibers may influence the failure modes of the composite. For example, the [0°/+45°/90°/-45°]2s layup might exhibit more distributed damage before final failure, which could be indicated by the deflection behavior under increasing loads. Comparing the two layups, the [0°/+45°/90°/-45°]2s SCRP may offer better multi-axial performance, while the [0°/90°/90°/0°]2s SCRP might offer better performance against bending in one principal direction.

6.2 Experimental Results on Sandwich Roof Panels (SCRP) discussion

To ensure the FEM model's accuracy, it would be important to compare these results with experimental data. Any significant differences would require revisiting the model assumptions, material properties, and boundary conditions used in the simulations.

The static deflection test was conducted under simply supported boundary conditions on SCRP for different loads. The preparation of sandwich roof panels was based on the skin orientation ($[0^0/90^0/90^0/0^0]_{2s}$ and $[0°/45°/90°/-45°]_{2}$s) and polyurethane core material behaviour identified from flexural tests. Experimental results for these SCRP are listed in tables 5–6, while Load Vs deflection curves are represented in Fig. 9–10. Comparison between experimental and FEM results is presented in tables 7–8 and illustrated in Fig. 11–12.

Table 5: Experimental Results for [00/450/900/-450]2s SCRP

Load in (N)	Experimental Deflection in mm
49.05	0.91
98.1	1.5
147.15	1.85
196.2	1.92
245.25	2.58
294.3	3.24
343.35	3.72

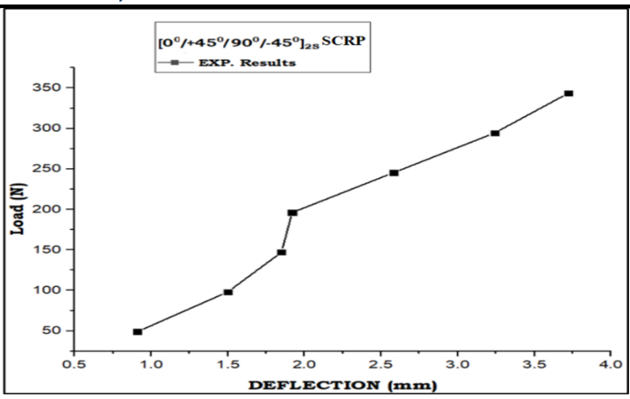


Fig. 9: Load Vs Deflection for [0°/45°/90°/-45°]2s SCRP.

From Table 5 and Fig. 9, the deflection increases nonlinearly with the load applied, which indicates that the material is exhibiting typical viscoelastic behaviour where the deflection rate decreases as the load increases. The initial stiffness seems to be quite high, as lower loads result in relatively small deflections. However, the stiffness decreases as the load increases, which could be due to the material transitioning from the linear elastic region into a nonlinear region where plastic deformation or damage begins to occur.

Table 6: Experimental Results for $[0^0/90^0/90^0/0^0]_{2S}$ Polyurethane based SCRP

Load in (N)	Experimental Deflection in mm
49.05	1.42
98.1	1.79
147.15	1.94
196.2	2.25
245.25	2.98
294.3	3.40
343.35	3.82

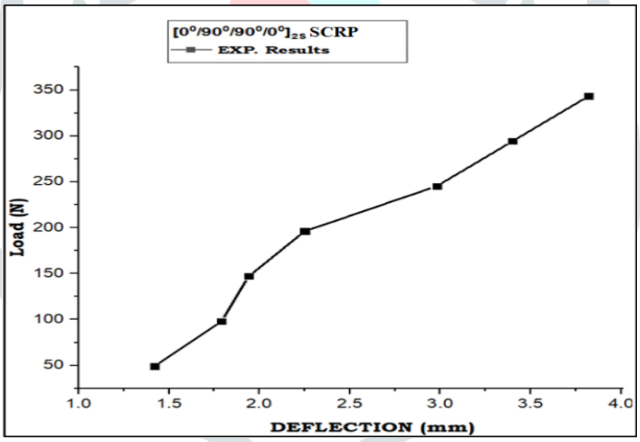


Fig. 10: Load Vs Deflection for $[0^0/90^0/90^0/0^0]_{2s}$ SCRP.

Similar to Table 5, there is a nonlinear relationship between load and deflection. This layup configuration seems to exhibit greater deflections for the same loads when compared to the [0°/45°/90°/-45°]2s layup, suggesting that this layup may be less stiff or more compliant in the direction of the applied load.

Table 7: Comparison of Experimental and FEM Deflection Results for [0°/45°/90°/-45°]2S Polyurethane based SCRP

Load in (N)	Experimental Deflection in mm	FEM Deflection in mm
49.05	0.91	1.03
98.1	1.5	1.65
147.15	1.85	1.80
196.2	1.92	2.10
245.25	2.58	2.51
294.3	3.24	3.18
343.35	3.72	3.68

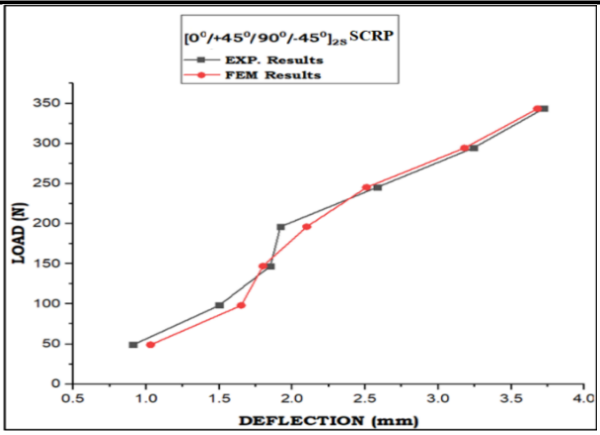


Fig. 11: Experimental and FEM Result Comparison for [0°/45°/90°/-45°]₂s SCRP.

As seen from table 7 and Fig. 11, the FEM results tend to overpredict the deflection slightly for most load cases except for the load of 147.15 N, where the experimental and FEM results are almost identical. The trend of the FEM results is consistent with the experimental data, suggesting that the model is capturing the material behaviour accurately, though there is a systematic discrepancy that could be due to assumptions in the model or variations in the material properties.

Table 8: Comparison of Experimental and FEM Deflection Results for $[0^0/90^0/90^0/0^0]_{2S}$ SCRP

Load in (N)	Experimental Deflection in mm	FEM Deflection in mm
49.05	1.42	1.35
98.1	1.79	1.64
147.15	1.94	1.88
196.2	2.25	2.18
245.25	2.98	2.88
294.3	3.40	3.14
343.35	3.82	3.72

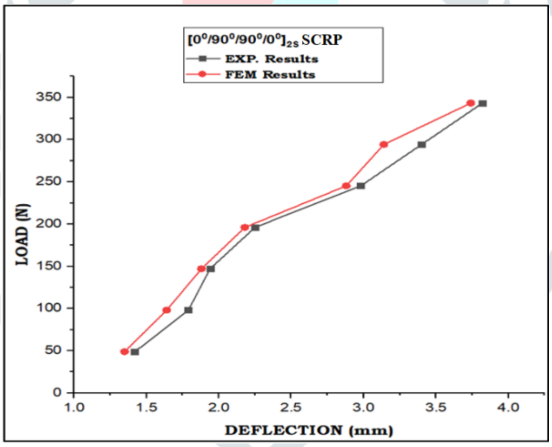


Fig. 12: Experimental and FEM Results Comparison for $[0^0/90^0/90^0/0^0]_{2S}$ SCRP.

As with Table 8, the FEM model overpredicts the deflection in most cases, but the discrepancy is less pronounced here than with the [0°/45°/90°/-45°]₂s layup. The overall trend of the FEM closely follows the experimental curve, indicating that the FEM model is generally representative of the physical behaviour of the material.

Both layups show increasing deflection with increasing load, a behaviour typical of composite materials under load. The nonlinear increase in deflection suggests a reduction in stiffness, which is common in composite materials as they approach their yield point or the onset of damage.

The different deflections observed in the two layup configurations under similar loads demonstrate how fibre orientation affects the mechanical properties of the composite material. The [0°/90°/90°/0°]2s layup generally shows higher deflections than the [0°/45°/90°/-45°]2s layup, which may suggest it is less effective at resisting bending loads.

7. CONCLUSIONS

- The sandwich composite roofing panels (SCRP) are fabricated with two skin orientations, $[0^0/90^0/90^0/0^0]_{2S}$ and [00/450/900/-450]2s, along with a polyurethane core, and subjected to testing under five distinct static loads.
- The results obtained from both experimental and FEM analyses suggest close alignment between load Vs. deflection values. This alignment can be attributed to the geometric design of the roofing panels, meshing techniques, element types, and boundary conditions. Additionally, it may be influenced by the precise percentage mixture of resin and hardener.

- Analysis of the obtained results indicates that the FEM deflection values for the $[0°/45°/90°/-45°]_{2s}$ skin orientation of polyurethane core-based sandwich composite roofing panels exhibit lower deflection compared to experimental results.
- The $[0°/45°/90°/-45°]_{2s}$ orientation of the SCRP demonstrates superior performance when compared to the $[0^0/90^0/90^0/0^0]_{2s}$ orientation of SCL.

REFERENCES

[1] M. Mohamed, S. Anandan, Z. Huo, V. Birman, J. Volz, and K. Chandrashekhara, 'Manufacturing and characterization of polyurethane based sandwich composite structures', Compos. Struct., vol. 123, pp. 169–179, 2015, doi: 10.1016/j.compstruct.2014.12.042.

[2] B. Mintz, A. G. Chowdhury, A. Mirmiran, N. Suksawang, and R. Kargarmoakhar, 'Design, Development, and Testing of a Composite Roofing System', J. Compos. Constr., vol. 20, no. 2, p. 04015052, 2016, doi: 10.1061/(asce)cc.1943-5614.0000605.

[3] S. Mudassir, M. Vinayaka Kulkarni, and S. Sivamani, 'Modelling and fabrication of synthetic-natural fibre sandwich structure for fish feeder hull', Mater. Today Proc., Feb. 2023, doi: 10.1016/J.MATPR.2023.02.141.

[4] E. Indutries, 'Roof Sandwich Panel'. https://emaarllc.com/roof-sandwich-details.php (accessed Dec. 08, 2023).

[5] Mithun Vinayaka Kulkarni, 'Composites Overview', in Structural Composite Materials: Fabrication, Properties, Applications and Challenges, Boppana Satish Babu, C. G. and Ramachandra, and K. K. Palani, and and R. S, Eds. Singapore: Springer Nature Singapore, 2024, pp. 3–21. doi: 10.1007/978-981-99-5982-2_1.

[6] A. Kausar, I. Ahmad, S. A. Rakha, M. H. Eisa, and A. Diallo, 'State-Of-The-Art of Sandwich Composite Structures: Manufacturing—to—High Performance Applications', J. Compos. Sci., vol. 7, no. 3, 2023, doi: 10.3390/jcs7030102.

[7] K. A. Feichtinger, 'Test Methods and Performance of Structural Core Materials -1. Static Properties', J. Reinf. Plast. Compos., vol. 8, no. 4, pp. 334–357, 1989, doi: 10.1177/073168448900800402.

[8] A. B. H. Kueh, S. H. Abo Sabah, D. N. Qader, S. H. Drahman, and M. Amran, 'Single and repetitive low-velocity impact responses of sandwich composite structures with different skin and core considerations: A review', Case Stud. Constr. Mater., vol. 18, p. e01908, Jul. 2023, doi: 10.1016/J.CSCM.2023.E01908.

[9] S. Sathish, K. Kumaresan, L. Prabhu, S. Gokulkumar, S. Dinesh, and N. Karthi, 'Experimental Testing on Mechanical Properties of Various Natural Fibers Reinforced Epoxy Hybrid Composites', Indian J. Sci. Technol., vol. 11, no. 25, pp. 1–6, 2018, doi: 10.17485/ijst/2018/v11i25/122231.

[10] H. A. Katzman, R. M. Castaneda, and H. S. Lee, 'Moisture diffusion in composite sandwich structures', Compos. Part A Appl. Sci. Manuf., vol. 39, no. 5, pp. 887–892, 2008, doi: 10.1016/j.compositesa.2008.01.005.

[11] M. A.-M. F. Avile´s, 'Moisture Absorption in Foam-Cored Composite Sandwich Structures', Polym. Polym. Compos., vol. 16, no. 2, pp. 101–113, 2008, doi: 10.1002/pc.

[12] J. Pflug, X. Y. Fan, B. Vangrimde, I. Verpoest, P. Bratfisch, and D. Vanderpitte, 'Development of a sandwich material with polypropylene/natural fiber skins and paper honeycomb core', Proc. 10th Eur. Conf. Compos. Mater., no. January, p. 331, 2002.

[13] M. Akil Hazizan and W. J. Cantwell, 'The low velocity impact response of foam-based sandwich structures', Compos. Part B Eng., vol. 33, no. 3, pp. 193–204, Apr. 2002, doi: 10.1016/S1359-8368(02)00009-4.

[14] Y. Chen et al., 'Manufacturing Technology of Lightweight Fiber-Reinforced Composite Structures in Aerospace: Current Situation and toward Intellectualization', Aerospace, vol. 10, no. 3, 2023, doi: 10.3390/aerospace10030206.

[15] B. CASTANIE, C. BOUVET, and M. Ginot, 'Review of composite sandwich structure in aeronautic applications', Compos. Part C Open Access, vol. 1, p. 100004, Aug. 2020, doi: 10.1016/J.JCOMC.2020.100004.