International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 9 Issue 9 September - 2025, Pages: 18-22

Flexural Behavior of E-Glass/Epoxy–PVC Foam Sandwich Composites for Railway Applications

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Abstract: *Sandwich composite materials are increasingly used in industrial applications due to their excellent strength-to-weight ratio and favorable mechanical performance. This study investigates the application of sandwich composites in railway vehicle bodies to enhance speed, passenger comfort, seating capacity, and fuel efficiency by reducing overall structural weight. The selected materials include woven E-glass reinforced with a thermoset epoxy matrix and polyvinyl chloride (PVC) foam as the core. The composites were fabricated using hand lay-up, vacuum bagging, and autoclave curing. Test specimens were manufactured with isotropic, flat sandwich configurations, comprising face sheets with lay-up and PVC foam cores of 3 mm and 6 mm thickness. Mechanical characterization was tested and conducted. Results from three-point bending tests showed that the 6 mm core specimens exhibited superior flexural stiffness, and maximum load capacity compared to the 3 mm core specimens. These findings confirm that increasing core thickness significantly improves the structural performance of composite sandwich panels, making them a suitable option for lightweight and high-performance railway vehicle applications.*

Keywords— Sandwich composite; E-glass; Mechanical characterization; Failure Mode.

1. INTRODUCTION

Composites are becoming an attractive alternative to standard metallic solution for mass transport applications. Lightweight composite materials are primarily specified because they can be used to produce cost- effective[1]. For transportation modes there are several factors that have to be taken under consideration, e.g. travel time, ride comfort and price Advantages that are often pointed out for rail transportation are for example the ability to work or read during travel, that connections often place the passenger in good proximity to city centers and for shorter to intermediate travels[2]. Sandwich structures have important applications in the naval, railway and aerospace industry. Their high strength/weight ratio and high Stiffness/weight ratio plays a vital role in their applications[3].

Rail vehicle bodies were made of stainless steel and constituted by stainless steel sheets welded onto a strength-providing structure.

In a study by Takeichi, M., et al. Railway car body structures has a panel assembly forming at least part of a side, the roof, an end or the floor plate, each panel has inner and outer spaced metal sheets and a cellular metal core bonded to the sheets and maintaining them spaced apart [4]. On author hand Tieberghien, P. et al. A rail vehicle body is made of stainless steel, wherein: the length members of the chassis and the roof battens are made of stainless steel, are constituted by section members that are continuous along the entire length of the body [5].

Development of materials used in the train cars bodies structure according to Saranac, R. Started in the 1970's by using Aluminum Railcar Design and Useful Life–Fatigue assessment. The use of aluminum in the construction of rail passenger cars was a departure from traditional materials (e.g. stainless steel and steel) due to its strength to weight ratio and aesthetics. Various transit authorities adopted the aluminum rail vehicles for widespread use. These early designed aluminum rail cars are now more than 30 years old and are slowly approaching the end of their predicted useful life. The purpose of the use of aluminum was in the rail vehicles according to Zangani, D., M. Robinson, and G. Kotsikos, Improving the crashworthiness of aluminum rail vehicles The use of aluminum alloys in rail vehicle manufacture has introduced a number of advantages, namely good corrosion resistance, lightweight and superior surface finish.[6, 7]. Ladbroke Grove in his paper addresses the issues of weld unzipping and looks at alternatives to fusion welding. Existing joints have been characterized to determine the effects of the weld filler material, the type of aluminum and the heat affected[8]. Jaime L, et al, design of new structural elements for rail vehicles, (e.g. car body and bogie frame), usually seeks a useful life of 30 years [9].

The materials used during this period from 1964 to 2006 metallic materials (steel, aluminum). And from 2007 till now which used composite materials due to many disadvantages of using metallic materials such as very heavy weight of train body structure the speed of train was not increase more than 210 km/h, and also increase of fuel efficiency.

Used composite instead of traditional materials that design and manufacturing for the body panel of mass transit vehicle. Weight savings in vehicles enhances fuel efficiency and decreases maintenance costs, especially in mass transit systems. Lightweight composite materials, such as glass fiber reinforced polymers, have been used to replace traditional steel and aluminum components. In this paper, a mass transit bus side body panel was designed, analyzed, and manufactured using thermoplastic composite materials [10, 11].

Uses of composite materials in the design of the train cars body structural to Reduce weight that according to Belingardi, G., M. Cavatorta, and R. Duella, Material characterization of a composite–foam sandwich for the front structure of a high-speed train. Static and dynamic tests were then run on the sandwich structure, for all materials tested, no significant strain-rate effects were observed over the range of test conditions investigated in the study. Results show that the structural response of the sandwich depends primarily on the strength properties of the foam core material. The dynamic impact resistance of the sandwich structure was then substantially improved by adding a net of resin walls within the foam[12]. Schubel P.M, J-J. Luo, and I.M. Daniel. Stated Composite sandwich structures are susceptible to low velocity impact damage and thorough characterization of the loading and damage process during impact was important. The objective of this work is to study experimentally the low velocity impact behavior of sandwich panels consisting of woven carbon/epoxy factsheets and a PVC foam core. Results were compared with those of an equivalent static loading and showed that low velocity impact was generally quasi-static in nature except for localized damage, gave good agreement with experimental results [13]. Aloes used composite materials to improve fire resistance that by study by Kim, J.-S., et al. Fire resistance tests of a train car body made of composite materials. In this study, fire performance tests using specimens and a large-scale mock-up were performed to evaluate the fire safety of the composite train car body. From the specimen tests, it was seen that the interior panels met the fire safety for the flame propagation, toxicity and smoke density performance [14]. On author hand used composite materials to reduce weight according to Seo, S., J. Kim, and S. Cho, Development of a hybrid composite body shell for tilting trains. A concept of a hybrid body shell for a tilting train is proposed and a prototype model has been developed. The composite honeycomb panel was composed of carbon fiber reinforced skins and an aluminum honeycomb core. The hybrid structure made it possible to reduce the car body weight by almost 30 per cent [15].

2. MATERIALS AND METHODS

Mechanical characterizations of the selected composite material have been assessed in order to define the basic material properties that can be used as input in structural design in this study.

2.1 E-glass Fabric

The E-glass fabric is used as the skin of the sandwich structures. Specification of fabric was shown in the below table given by suppler: Changzhou Xingao insulation materials co. Ltd.

Table1: Specification of fabric

Quality index			Value
1	Fabric weave		Plain weave
2	Warp number * strand number		133
3	Weft number * strand number		131
4	Width (CM)		100
5	Thickness (CM)		0.235
6	Mass per unit area (g/m^2)		195
7	Density (cm)	Warp	8
		Weft	7
8	Tensile breaking strength N/50*200mm	Warp	2865
		Weft	2559
9	Moisture content %		0.09
10	Oil content %		0.71
11	Combustible content %		0.6

2.2 Epoxy resins

Epoxy resins were a family of thermoset plastic materials which do not give off reaction products when they cure and so have low cure shrinkage. They also have good adhesion to other materials, good chemical and environmental resistance, good chemical properties and good insulating properties, specification in table [2] given by suppler: Linhai Xinxiangrong Decoration Material Co. Ltd

Table 1: Specification of Matrix thermoset epoxy

Quality index		Value	
		Epoxy resin	**Hardener**
1	Mixing proportion	3	1
2	Specific gravity	1.14±0.1	1.02±0.1
3	Color	Colorless	Brown
4	Viscosity (Maps)	550±50	
5	Pot life (min)	30±10 at 23C0	
6	Hardening time (h)	24-36 at 23 C0	

2.3 Poly Vinyl Chloride (PVC) foam

USED POLY VINYL CHLORIDE (PVC) AS THE SANDWICH (CORE) IN THIS ARTICLES THE PVC FOAM

Code : 02310111- Name: 20mm foam board H45- with thickness (6mm and 3mm). Specifications: H45, Characteristics : Excellent heat resistance, Light material Easy installation. Excellent mechanical properties, good resilience and high impact energy absorption, good chemical corrosion resistance and good resistance to cracking under stress.

2.4 Fabrication Processing

Manufacturing sheet of glass fabric laminate structure quasi-isotropic flat configuration face (for the upper and lower face sheet) (-45^0 / $90^0/45^0/0^0$), in core Sandwich structure poly vinyl chloride (PVC).

Materials are Selection and prepared the mold prepared. The woven glass cloths were cut according to the angle sequence (0o/45o/-45o/90o). The woven fabric is laminated over the core material with the epoxy resin and hardener are employed to begin the polymerization process, giving a gel time of about 45 min. This is hand lay-up method which is designed specifically for transport application. In order to ensure good bonding between the overall layers of the composite and for uniform distribution of the resin, the sample was being subjected to vacuum. Vacuum system of 1 bar was applied and the machine was left running for 4 h, so that the panel will cure under vacuum on the oven (120 c^o). Once the panel had cured, it was left for 12 h with the vacuum pump disconnected. The overall panel sizes, which will be later cut into the required testing specimen sizes, are (80*40cm with8.7 mm thickness and 60*40cm with 5.5mm thickness).

2.5 Flexural tests

Flexural Properties of Sandwich Constructions tests were performed according to ASTM C393-00 standard[16]. This test method covers determination of the properties of flat sandwich constructions subjected to flatwise flexure in such a manner that the applied moments produce curvature of the sandwich facing planes, used machine Zwick / Roell tester with zwick z010 load cell 10 KN with single arm extensometer at pre-load (0.1 MPa) and speed 1mm / min.

3. RESULTS AND DISCUSSION

3.1 Flexural Properties of Sandwich Constructions

This test method evaluates the properties of flat sandwich constructions under flatwise flexure, where the applied moments induce curvature in the facing planes of the sandwich structure. The primary outcomes are force and displacement values, which are subsequently analyzed to generate force–displacement curves.

Fig 1: Zwick / Roell tester machine for 3 point bending teats.

The load–displacement curves represent the relationship between the applied load on the specimen and the displacement of the testing machine's loading head, which is taken as the mid-span deflection of the upper face where the load is applied. As shown in Figure 2 the curves can be divided into three distinct regions.

In the first region, the response corresponds to the compressive behavior of the skin laminates, characterized initially by a reversible, linear elastic relationship. The second region reflects the compressive behavior of the core due to bending of the top skin, producing a nonlinear response that is largely governed by the mechanical properties of the foam core. In the third region, further load application leads to the initiation and propagation of delamination between the skin and core, ultimately causing fracture of the skin. This fracture is associated with an abrupt load drop of approximately 40% of the maximum load. After skin failure, the load is redistributed to the core, resulting in local crushing under the concentrated force.

The PVC foam core in the central region of the specimen experiences compressive stresses, manifested as a plateau in the load–displacement curve. At the end of this plateau, multiple failure mechanisms interact, leading to the complete collapse of the sandwich structure.

For the tested face-sheet materials (woven E-glass fibers with a thermoset epoxy matrix), it was observed that specimens with a 6 mm core exhibited higher flexural stiffness (≈180 N) and greater maximum load compared to specimens with a 3 mm core (≈160 N). Additionally, failure involved the initiation, progression, and development of transverse cracking in the 90° plies of the skin.

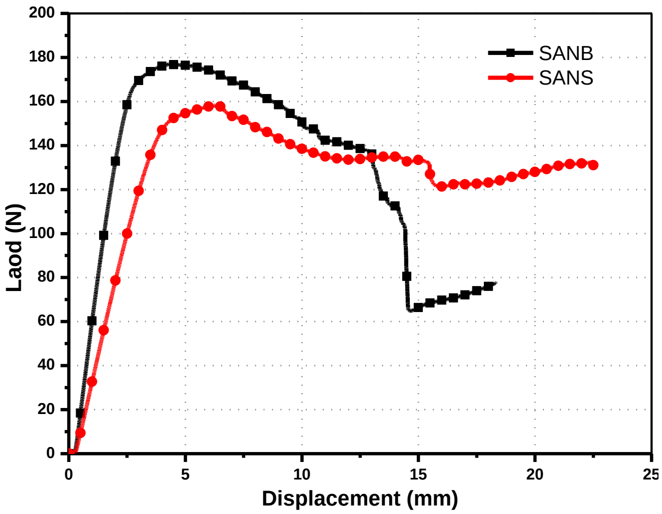

Fig 2: The Load - Displacement curve of sandwich composite with 6mm (B) and 3mm (S) core thickness.

For the specimen with a 3 mm core thickness, the peak load was reached at approximately 160 N, with a relatively short linear region before transitioning into the nonlinear stage and subsequent failure. In contrast, the specimen with a 6 mm core thickness reached a higher peak load of about 180 N, with a longer linear region prior to the onset of nonlinearity and failure. The 6 mm core specimen demonstrated a greater capacity to sustain higher energy levels compared to the 3 mm core specimen. Energy absorption analysis showed that the 3 mm core specimen exhibited a larger displacement of approximately 7 mm, whereas the 6 mm core specimen showed a lower displacement of around 3 mm. These results indicate that the 6 mm core thickness provides superior mechanical performance, with higher load-bearing capacity and improved energy absorption efficiency compared to the 3 mm core thickness.

3.2 Failure modes

Figures 3, and 4 illustrate the failure modes observed in static tests of sandwich composites with 3 mm and 6 mm core thicknesses. The load–displacement curves initially exhibit a linear response, followed by a pronounced nonlinear region. This nonlinear behavior is primarily attributed to plastic deformation of the core cell walls under extensional and bending stresses. The overall response indicates ductile material behavior.

The results show that the static strength of the sandwich composites is strongly influenced by the properties of the core, particularly its thickness. Specimens with higher core thickness demonstrated greater static strength, where displacement continued to increase after reaching the maximum load until failure occurred. The failure was characterized by the formation of an almost vertical crack that initiated on the tension side of the beam and rapidly propagated to the compression side. The observed cracks were similar in shape for both the 3 mm and 6 mm core specimens, suggesting that both thicknesses share the same fundamental failure mechanism.

Fig 3: Shows surfaces of specimen with 3and 6 mm core thickness pending test.

Fig 4: Shows cross-sectional view of specimen with 3and 6 mm core thickness pending test.

3.2 Calculation of bending stress

Table 3 presents the calculated of bending stresses for specimens with 3 mm and 6 mm core thicknesses. As shown in Figure 2 load–displacement curves illustrate the variation in mechanical response. The results indicate that face bending stress increases as the core thickness decreases, due to the shorter distance between the top and bottom face sheets. In this configuration, the two face sheets act together more effectively to resist the applied load. Consequently, the specimen with a 3 mm core thickness exhibited higher face bending stress compared to the specimen with a 6 mm core thickness.

$$\sigma = \frac{PL}{2t(d+c)b} \quad (1)$$

Where: σ = facing bending stress, MPa; P= load, N; L= span length, mm; t= facing thickness, mm; d= sandwich thickness mm; c= core thickness mm (in.); and b= sandwich width mm.

Specimen	Load(N)	Stress (MPa)
3mm core thickness (S)	160	21.08
6mm core thickness (B)	180	19.86

4. Conclusions

Sandwich composites made of woven E-glass fibers with a thermoset epoxy matrix and PVC foam cores demonstrated suitable mechanical performance for railway vehicle body applications, combining lightweight design with good strength characteristics.

- Increasing the core thickness from 3 mm to 6 mm significantly improved flexural stiffness, maximum load capacity, and energy absorption, as confirmed by three-point bending and drop-weight impact tests.
- The 6 mm core specimens exhibited longer linear elastic regions and higher load-bearing capacity, while the 3 mm core specimens showed greater face bending stresses due to the shorter distance between the face sheets.
- Failure mechanisms in both thicknesses followed similar patterns, involving delamination, transverse cracking in 90° plies, and eventual crushing of the core under concentrated loading. The cracks were of similar type for both core thicknesses, indicating comparable failure modes.
- While the 3 mm core specimens achieved higher face bending stress, the 6 mm core specimens provided superior overall mechanical performance, particularly in terms of stiffness, impact resistance, and energy absorption.

Overall, a thicker core (6 mm) enhances the structural efficiency capacity of sandwich composites, making them more suitable for lightweight, high-performance railway vehicle body applications.

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