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Influence of foam densities and span to depth ratios on the Flexural properties of rigid polyisocyanurate foam-glass fabric/epoxy Sandwich Composites

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Abstract **- The experimental investigation here focuses on the study of flexural and shear properties of sandwich composites. Rigid unfilled thermoset Polyisocyanurate (PIR) foam is used as the core material and glass fabric reinforced epoxy based laminates are used as the outer skin layers of the sandwich. PIR foams with densities of 125kg/m^3 and 250kg/m^3 are used for the study. Skin to core weight ratios of 3:1 and 4:1 were maintained for the panels fabricated separately with the vacuum bagging technique. Specimens with varying span to depth ratios of 16:1, 12:1 and 6:1 were tested using an Instron UTM machine. The investigation follows a three-point bending test method carried out for finding bending strength, flexure rigidity, shear deflection, shear stress, shear strain etc. The test results were compared and analyzed in depth to find the influence of the core density and span to depth ratios on the flexural and shear properties of the sandwich composite. Useful conclusions have been drawn based on the fracture behaviour of these sandwich composites.**

Keywords: Rigid polyisocyanurate foam, Flexural properties, Sandwich composites, Foam Density, Span to depth ratios.

I. Introduction

Composite materials are combination of two or more materials, which has mechanical properties superior to its inherent materials. The constituent materials in composites are referred to as matrix and reinforcements. Reinforcement materials are of different forms such as fibres, flakes, fragments etc. which are surrounded and bound together by the matrix material. Sandwich composites are formed by sandwiching a core material in between two laminate skin layers[1]. They exhibit excellent mechanical properties such as high strength to weight ratios and find wide applications which requires high flexural rigidity and bending strength. Thin Aluminium sheets, fibre reinforced epoxy of glass, carbon, natural fibres are commonly used facing materials. Rigid unfilled thermoset polymer foams such as Polyisocyanurate, Polyurethane, Polystyrene, Polyethylene etc. are used as core materials[1,2]. The aim of this study is to find the flexural behaviour of sandwich composite with PIR foam as core and glass fabric reinforced epoxy laminate as face sheet with varying densities of the core and the span to depth ratio of the sandwich [3]. PIR foams are rigid unfilled thermoset plastics having good thermal insulation property and machinability. Sandwich panels with core densities of 125 kg/m^3 and 250 kg/m^3 are considered for the testing. For each densities of cores used, panels with skin to core weight ratio 3:1 and 4:1 are also tested for the flexural properties. Specimens with span to depth ratios of 6:1, 12:1 and 16:1 are tested using three-point bending test method in Instron UTM machine and load versus deflection graphs were plotted. The flexural properties such as flexural rigidity, bending stress, bending stiffness, maximum shear stress in core, shear strain etc., were determined[3,4]. Relevant graphs were plotted to reach a thorough conclusion about the trend in the behaviour of the failure of the specimens on flexure. Composites find wide applications in aerospace, marine, defence, construction etc[5].

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II. Experiment

A. Fabrication

Sandwich panels with core densities 125kg/m^3 and 250kg/m^3 were prepared. Separate panels were prepared for skin to core weight ratios of 3:1 and 4:1.

Figure 1 Vacuum-bagging

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Vacuum bagging method was used for the fabrication of each panels. The number of layers of 280GSM and 100GSM glass fabrics required were determined and the amount of resin and hardener was calculated for maintaining the exact weight ratios. A volume fraction of 0.3 was taken between the resin and glass fabric to maintain a continuation from previous study[6]. Also, Theulen [7] has given details on stiffness optimization of sandwich panels. Hand lay-up of the glass fabrics were carried out and after completion of laying up process, entire assembly was sealed manually in a vacuum bag connected to a vacuum pump. Vacuum was applied using the pump for about half an hour and the panels were kept for curing for 24 hours. After curing, specimens with the span to depth ratios of 6:1, 12:1 and 16:1 with suitable overhang were cut from the panels. Each specimens were labelled and numbered for the tests to be performed.

TABLE I. MECHANICAL PROPERTIES OF FOAM CORES.

Foam Density	PIR-125 kg/m^3	PIR-250 kg/m^3
Elastic Modulus (MPa)	24	28.38
Poisson's Ratio	0.28	0.345

TABLE II. MECHANICAL PROPERTIES OF SKIN

Material	Glass Fabric	Epoxy	Skin
Elastic Modulus (MPa)	35000	1850	11550
Poisson's Ratio	0.25	0.35	0.32

Figure 2. PIR 125kg/m^3 weight ratio 3:1 and span to depth ratio 6:1 specimens

B. Testing

The test method used for this study is a Three-point bending test method which gives the flexural rigidity, shear deflection, bending strength, shear stress, shear strain etc[8,9,10]. The test was carried out in an Instron UTM machine. The apparatus for flexure test was fixed on the machine which consists of two supporting cylindrical steel rollers and a loading roller, each roller having a diameter of 25mm. Five specimens for each span to depth ratios were tested in order to determine precise mode of failure for each span. Each specimen is kept on the two cylindrical supporting steel rollers at equal distance and load is applied using another roller at the mid span at a rate of 2mm/min until failure occurs in the specimen. The failure modes were observed and a real time graph of load versus deflection was obtained from the machine simultaneously. Raw data file containing the load and corresponding deflection data was obtained and copied for detailed investigations. An overhang length of 35mm was maintained on both sides of all specimens. Width of the specimens were taken as two times the thickness of the panel. Failure occurs mainly by face yielding, face wrinkling, core shear, core tensile yield, core compressive yield, core indentation, de-bonding. Yielding occurs at faces and core due to shear, tension or compression.

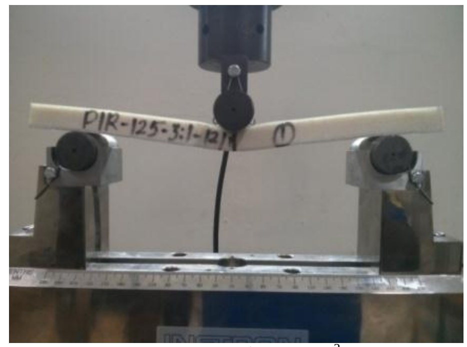

Figure 3. Three-Point bending testing of 125kg/m^3 12:1 specimen on Instron machine

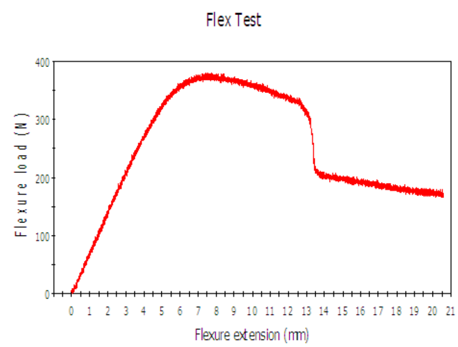

Figure 4. Load v/s deflection plot

C. Evaluations

Various Flexural properties are evaluated from the experimental values obtained from the three-point bending test. Generally shear stresses are mainly taken up by the core whereas faces carry almost all the normal stresses. Following are the different important flexural properties of sandwich composite that can be evaluated from the flexural test :

Flexural Rigidity, D, Nmm^2

$$D = hbt^3 + E_f(2tb)\left[\frac{d+t}{2}\right]^2 + \frac{E_c b c^3}{12} \qquad \text{\_\_\_\_\_\_ (1)}$$

Flexural Rigidity per unit width, Nmm^2/mm = D/b (2)

Bending Stiffness, N/mm = $\frac{W}{\delta}$ __________(3)

Bending Stiffness per unit width, N/mm^2 = $\frac{W}{\delta.b}$ ___ (4)

Bending strength, B, Nmm

$$B = \frac{Wa}{8} \quad \text{\_\_\_\_\_\_\_\_(5)}$$

Bending strength per unit width, Nmm/mm = $\frac{W.a}{8.b}$ __ (6)

Bending stress, σ, N/mm^2

$$\sigma = \frac{M.h}{b.t.d^2} \quad \text{\_\_\_\_\_\_ (7)}$$

Maximum Shear stress in core, τ_c, N/mm^2

$$\tau_c = \left(\frac{Q}{D}\right)\left[\left(\frac{E_f t d}{2}\right) + \left(\frac{E_c}{2}\right)\left(\frac{c^2}{4} - y^2\right)\right] \quad \text{\_\_\_\_\_\_\_ (8)}$$

where,

h = Total height of sandwich, mm
b = width of the specimen, mm
t = thickness of the skin, mm
E_f = Elastic modulus of the fabric, N/mm^2
E_c = Elastic modulus of the core, N/mm^2
d = Centroidal height of the specimen, mm
c = Core thickness, mm
W = maximum load, N
δ = deflection corresponding to maximum load, mm
a = span of the specimen, mm
M = Bending moment, Nmm
y = distance from the neutral axis, mm

III. *Results and discussions*

The mode of failure of each specimens were observed in detail and their behaviour on applying bending loads at a uniform rate was recorded for thorough investigation on the flexural behaviour. The load versus deflection plots were directly obtained from the test machine and the maximum load, the specimen can withstand, was directly noted down. From the load deflection plot, it is understood that the load increases with deflection almost linearly up to a certain limit and the slope reduces and tends to show constant load until failure occurs. When failure occurs, the plots show sudden fall in the load value. Further application of the load does not make any significant affect on the specimen. On further application of flexure extension, the specimen started showing slippage from the rollers and the load deflection shows sudden and frequent zigzag variations in the plot. From the obtained values, flexural properties such as Flexural rigidity, Shear deflection, bending stress, bending moment, bending strength, bending stiffness, maximum shear stress in core, shear strain etc., were calculated and graphs were plotted against density and span to depth ratios and the trend in the variations are thoroughly interpreted and understood. Testing five specimens for each span to depth ratios for corresponding densities and weight ratios gives a clear idea of the behaviour of the composite. Average of the five specimens were taken for comparing the values with different densities and weight ratios. Attempts at design optimization for maximum strength and stiffness have been discussed earlier by some investigators[1,2,5,6]. This paper covers a part of the investigations that lead towards design optimization of sandwich composites.

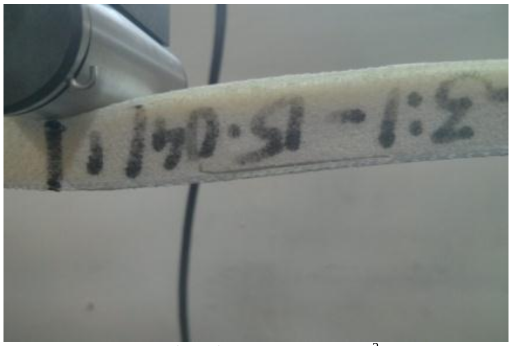

Figure 5. Laminate Core interface failure in 125kg/m^3, 3:1 specimen, with span to depth ratio 15.04:1

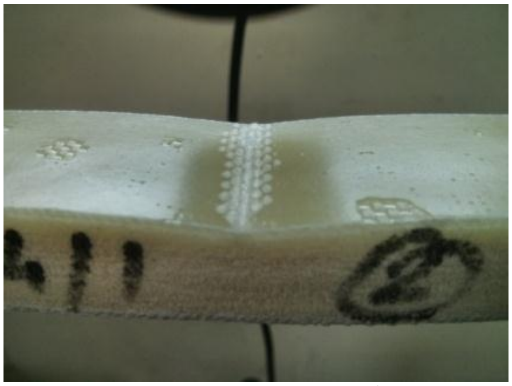

Figure 6. Laminate compression and core compression failure in 125kg/m^3 3:1 specimen

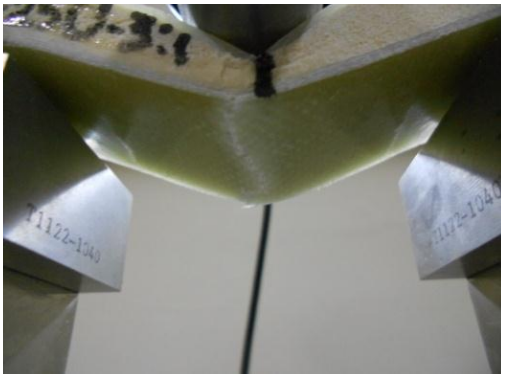

Figure 7 Tensile failure in 250kg/m^3 specimen with skin to core weight ratio 3:1

TABLE III. FLEXURAL PROPERTIES OF 125kg/m^3 DENSITY PIR SANDWICH FOR VARYING SPAN TO DEPTH RATIOS

Skin/ Core Wt. Ratio	Flexure Properties	15.04:1	12:1	6:1
3:1	Flexural Rigidity per unit width Range, (Nmm^2/mm) x10^6, (Average)	4.75 - 5.28 (5.06)	4.36 - 4.93 (4.63)	5.34 - 6.83 (6.03)
	Bending Stiffness per unit width Range, (N/mm^2) (Average)	0.96 - 1.11 (1.03)	1.26 - 1.52 (1.39)	1.81 - 3.39 (2.15)
	Bending Strength per unit width Range, (N-mm/mm) (Average)	264.18 - 319.19 (297.67)	272.34 - 292.11 (278.17)	183.14 - 254.00 (202.36)
	Bending stress Range, (N/mm^2) (Average)	15.97 - 18.46 (17.29)	16.71 - 17.07 (17.10)	9.64 - 12.31 (10.57)
	Maximum Shear stress in core (N/mm^2), Range (Average)	0.21 - 0.24 (0.2324)	0.27 - 0.28 (0.2791)	0.34 - 0.45 (0.3741)

TABLE IV. FLEXURAL PROPERTIES OF 125kg/m^3 DENSITY PIR SANDWICH FOR VARYING SPAN TO DEPTH RATIOS

Skin/ Core Wt. Ratio	Flexure Properties	14.7:1	12:1	6:1
4:1	Flexural Rigidity per unit width Range (Nmm^2/mm) x10^6 (Average)	4.97 - 5.99 (5.54)	5.00 - 5.54 (5.14)	5.72 - 6.21 (5.93)
	Bending Stiffness per unit width Range (N/mm^2), (Average)	1.12 - 1.25 (1.17)	1.20 - 2.27 (1.50)	1.76 - 3.69 (2.76)
	Bending Strength per unit width Range (N-mm/mm) (Average)	344.77 - 391.99 (376.57)	276.51 - 393.29 (310.70)	219.61 - 267.42 (234.06)
	Bending stress Range (N/mm^2), (Average)	18.26 - 22.53 (20.80)	15.21 - 22.67 (17.90)	11.73 - 13.85 (12.34)
	Maximum Shear stress in core Range (N/mm^2), (Average)	0.25 - 0.30 (0.2867)	0.25 - 0.37 (0.2962)	0.40 - 0.48 (0.4268)

TABLE V. FLEXURAL PROPERTIES OF 250kg/m^3 DENSITY PIR SANDWICH FOR VARYING SPAN TO DEPTH RATIOS

Skin/ Core Wt. Ratio	Flexure Properties	14.92:1	12:1	6:1
3:1	Flexural Rigidity per unit width Range (Nmm^2/mm) x10^6, (Average)	5.29 - 5.75 (5.45)	5.14 - 5.87 (5.55)	4.81- 5.49 (5.23)
	Bending Stiffness per unit width Range (N/mm^2), (Average)	2.83 - 4.10 (3.20)	3.67 - 5.59 (4.18)	6.62 - 7.28 (6.90)
	Bending Strength per unit width Range (N-mm/mm) (Average)	926.72 - 1319.90 (1057.54)	884.97 - 1067.85 (929.19)	574.17 - 615.96 (590.51)
	Bending stress Range (N/mm^2), (Average)	51.87 - 71.00 (58.71)	48.53 - 56.75 (51.06)	32.76 - 34.48 (33.65)
	Maximum Shear stress in core Range (N/mm^2), (Average)	0.71 - 0.99 (0.8074)	0.83 - 0.99 (0.8778)	1.11 - 1.17 (1.1363)

TABLE VI. FLEXURAL PROPERTIES OF 250kg/m^3 DENSITY PIR SANDWICH FOR VARYING SPAN TO DEPTH RATIOS

Skin/ Core Wt. Ratio	Flexure Properties	13.92:1	12:1	6:1
4:1	Flexural Rigidity per unit width Range (Nmm^2/mm) x10^6, (Average)	6.89 - 9.11 (7.73)	6.68 - 7.44 (6.85)	5.48 - 6.96 (6.15)
	Bending Stiffness per unit width Range (N/mm^2), (Average)	5.25 - 10.10 (6.67)	4.10 - 6.03 (4.97)	7.28 - 8.63 (7.85)
	Bending Strength per unit width Range (N-mm/mm) (Average)	1899.18 - 2539.85 (2128.31)	1548.06 - 1674.66 (1624.53)	677.49 - 754.81 (726.53)
	Bending stress Range (N/mm^2), (Average)	91.30 - 103.75 (95.69)	75.87 - 82.25 (78.66)	34.39 - 41.34 (37.644)
	Maximum Shear stress in core Range (N/mm^2), (Average)	1.34 - 1.64 (1.4546)	1.31 - 1.42 (1.3760)	1.17 - 1.35 (1.2745)

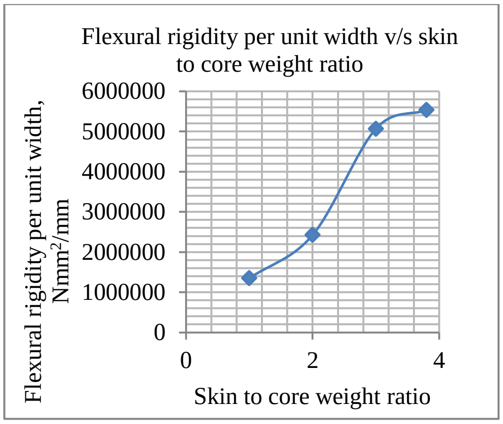

Figure 8. Flexural rigidity per unit width v/s Skin to core weight ratio plot for a span to depth ratio of 16:1

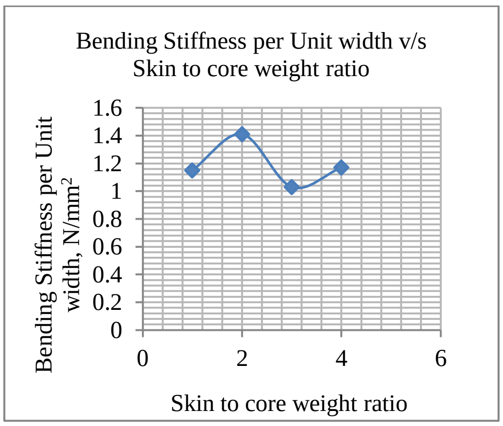

Figure 9. Bending Stiffness per unit width v/s Skin to core weight ratio plot for a span to depth ratio of 16:1

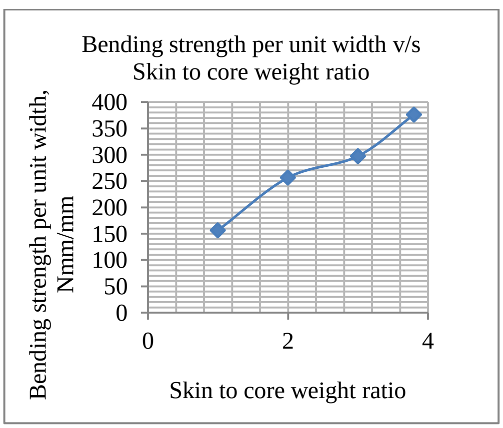

Figure 10. Bending strength per unit width v/s Skin to core weight ratio plot for a span to depth ratio of 16:1

IV. *Conclusions*

Three-point bending test on PIR foam glass/epoxy sandwich composites were carried out for varying spans and plotted the relevant graphs for determining the flexural behaviour. Specimens were expected to be failed by laminate shear failure, compressive core crushing, laminate core interface failure, tensile and compressive yielding. Majority of specimens failed by laminate shear, while only a few number of specimens undergone failure by laminate-core interface shear failure which can be due to desired failure mode for optimization. The laminate-core shear interface failure was found only in two specimens of 125kg/m^3 density 3:1 skin to core weight ratio, with span to depth ratios 15.04:1 and single specimen in 12:1. From the plots, flexural rigidity of specimens with span to depth ratio 12:1 is lower than 6:1. This could be due to the variation in the Elastic modulus for shorter span specimens. The bending strength increases with increase in span almost linearly. With increase in skin to core weight ratio flexural rigidity and bending strength increases but variation is not exactly linear. There is no particular trend in the variation of bending stiffness with weight ratio as it gives a zigzag plot. This may be due to the increase in the sandwich panel thickness, which increases the distance from neutral axis giving more normal stress bearing capacity to the specimen and thereby increasing the flexural rigidity and bending strength.

V. *Acknowledgements*

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