Numerical analysis on flexural behaviour of GFRP sandwich roof panel with multilayer core material

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Abstract. In this study, the flexural performance of Glass Fibre Reinforced Polymer (GFRP) sandwich roof panel with multilayer polyurethane foam core was investigated using commercial FEM software ANSYS WORKBENCH. The GFRP sandwich panel is composed of thin GFRP face sheets at top and bottom infilled with Polyurethane (PU) foam core of two different densities. GFRP sandwich panels with different stacking sequences of the multilayer core was considered to determine the best sequence in which the different layers of core material can be laid on top of each other. The optimum panel size was obtained from parametric study conducted with number of GFRP plies and thickness of core as parameters. Alternatively, the flexural behaviour of GFRP sandwich panel with three different web core configurations were also studied, which includes trapezoidal shaped GFRP webs infilled with PU foam (Type 1), rhombus shaped GFRP webs infilled with PU foam (Type 2), and wave shaped GFRP webs infilled with PU foam (Type 3). Based on the finite element analysis, GFRP sandwich panel with Type 3 core configuration (wave shaped GFRP webs infilled with PU foam) with lesser deformation represented a feasible model to be used as a roofing panel for small residential buildings and prefabricated modular constructions.

Keywords: GFRP sandwich roof panel; Multilayer Polyurethane foam core; Core configurations; Finite Element Analysis.

1. Introduction
Fibre-reinforced polymer (FRP) sandwich panel systems are laminated FRP composite structures attached to thick lightweight foam core. The facesheets typically provide the high bending strength and stiffness, whereas the core material provides the shear rigidity and strength to the sandwich panel system. Normally, a low density core could have excellent thermal insulation characteristics whereas a high density core has better structural performance [1]. The fibre orientation of each lamina, the stacking sequence of the laminae of different orientations and the bond between the skin and core interface influences the mechanical properties of the laminate and the core material. FRP had proven its wide range applications related to flexural and shear strengthening of RC structures, prestressed concrete structures and also some other special strengthening techniques which include prestressing of composite strips, automated wrapping and curing of columns or other vertical elements, prefabricated shapes bonded to structures, FRP fasteners and so on [2]. FRP composites are gaining interest in civil infrastructure due to its increased durability and corrosion resistance, leading to significant reduction in life cycle cost when compared to conventional materials.
Many numerical as well as experimental investigations were carried out to investigate the feasibility of fabrication, structural performance and utilisation of FRP sandwich panels for structural application such as GFRP sandwich wall cladding panels, light weight FRP highway bridge decks and for repairing and retrofitting of existing bridge structures. Sharaf et al. [3] conducted a study on the flexural behaviour of GFRP sandwich wall cladding panels with two different densities of polyurethane foam. Sharaf and Fam [4] studied the structural performance of GFRP sandwich panel proposed for large scale cladding of buildings under out of plane bending by applying uniform air pressure and simulated mechanical loads. The static behaviour of GFRP composite deck panels tested under AASHTO HS20/IRC Class A wheeled vehicle loading indicated that the deck panels have achieved the performance within the deflection limits of span/800 as specified by Ohio Department of Transportation (ODOT), USA [5]. Osei-Antwi et al. [6] constructed multilayer FRP sandwich bridge deck panels using both high and low density balsa wood core to improve the impact and wrinkling strength as well as the thermal insulation performance simultaneously. FRP bridge decks have a larger service life about three times more than that of RC bridge decks [7]. The feasibility of design of multifunctional integration of self-luminous GFRP composites for structural applications was explored by Bai et al. [8]. Keller et al. [9] constructed a lightweight GFRP roof structure in Switzerland, which facilitated function integration as well as easy transportation to the site, rapid construction and installation on site.

As of now, limited studies are available which focuses on the flexural behaviour of GFRP sandwich roof panel. The necessity of this study is to provide construction industry with a lightweight, more durable and highly energy efficient roof panel with an optimum configuration, incorporating both soft and rigid cores so that strength, stiffness as well as thermal insulation characteristics are enhanced simultaneously. This paper presents a detailed numerical study on the flexural behaviour of Glass Fibre-Reinforced Polymer (GFRP) sandwich roof panel with multilayer polyurethane foam core having two different densities. In addition, the flexural behaviour of GFRP sandwich roof panel with different web core configurations, one existing and other two newly proposed, was also studied. This study also compares the flexural behaviour of GFRP panels comprising multilayer core with and without web configurations. The three different web core configurations include:

- trapezoidal shaped GFRP webs infilled with multilayer PU foam (Type 1),
- rhombus shaped GFRP webs infilled with multilayer PU foam (Type 2), and
- wave shaped GFRP webs infilled with multilayer PU foam (Type 3).

2. Preliminary study on GFRP panels with different stacking sequences of multi layer core

Preliminary study involves analysing the flexural behaviour of GFRP sandwich panels with total deformation at the midspan as the main criterion since it is the governing factor for the design of FRP sandwich panels as revealed in previous studies. GFRP sandwich panels with different stacking sequence of the multilayer core was analysed to determine the best sequence of arrangement of the core. The selected panels were 3000 mm x 1000 mm x 74 mm, each comprised 35 mm thick rigid PU foam of density 192 kg/m³ and 35 mm thick flexible PU foam of density 31.9 kg/m³ along with 2 mm thick top and bottom GFRP facesheets. The facesheet consists of 5 numbers of plies, with each ply of thickness 0.4 mm. The different stacking sequence in which each panels with multilayer core arranged (depicted in figure 1) are as shown below.

- Case 1: Facesheet – High density PU – Low density PU – Facesheet
- Case 2: Facesheet – Low density PU – High density PU – Facesheet
- Case 3: Facesheet – High density PU – Low density PU – High density PU – Facesheet
- Case 4: Facesheet – Low density PU – High density PU – Low density PU – Facesheet
2.1. Material properties

Epoxy E-glass fibres were used to define the facesheets because of its high tensile strength and relatively lower cost. The core material preferred was high and low density polyurethane foam. The high density PU foam can contribute to high strength and stiffness to the panel, whereas low density PU foam can contribute to better insulation effectiveness and low weight to the panel. Low density PU foam is less costly than denser ones. The material properties of Polyurethane Foam and Epoxy E-glass Woven Fabric were shown in Table 1 and 2. Isotropic material properties were used to define polyurethane foam and orthotropic properties to define epoxy E-glass woven fibres.

### Table 1. Material Properties of Polyurethane Foam.

| Material Property                  | High density PU foam | Low density PU foam |
|-----------------------------------|----------------------|---------------------|
| Density                           | 192 kg/m³            | 31.9 kg/m³          |
| Modulus of elasticity             | 66.1 MPa             | 2.1 MPa             |
| Shear modulus                     | 25.114 MPa           | 0.82 MPa            |
| Poisson’s ratio                   | 0.316                | 0.279               |

### Table 2. Material Properties of Epoxy E-glass Woven Fabric.

| Material Property                           | Value                  |
|---------------------------------------------|------------------------|
| Density                                     | 2000 kg/m³             |
| Longitudinal modulus of elasticity, E₁      | 45 GPa                 |
| Transverse in-plane modulus, E₂             | 10 GPa                 |
| Transverse out-of-plane modulus, E₃         | 10 GPa                 |
| In-plane shear modulus, G₁₂                 | 5 GPa                  |
| Out-of-plane shear modulus, G₂₃             | 3.846 GPa              |
| Out-of-plane shear modulus, G₁₃             | 5 GPa                  |
| Major in-plane Poisson’s ratio, µ₁₂         | 0.3                    |
| Out-of-plane Poisson’s ratio, µ₂₃           | 0.4                    |
2.2. Numerical modelling and analysis

Finite element models were developed for the different types of panels and were used to study the flexural behaviour of the proposed sandwich panels using ANSYS WORKBENCH 19. The low and high density foam cores were modelled using isotropic solid element ‘solid 186’ that had three translational degrees of freedom at each node whereas the GFRP facesheets were modelled by orthotropic shell element ‘shell 181’ which had six degrees of freedom at each node. Shell elements can be used for getting effective results, which are easier to mesh and allow modelling of thinner components with fewer mesh elements, further lead to huge computational savings.

Full contact behaviour was considered between the sandwich panel components in order to avoid any kind of delamination in the panels. Adequate mesh size was provided after conducting mesh convergence study to obtain the most realistic results. The sandwich panel was modelled as a simply supported roof panel by providing pinned support at one end and roller support at the other end. The sandwich panels were applied a uniformly distributed load of 0.75 kN/m², according to IS 875 Part II (Table 2), for the case of a flat roof or a slope roof with slope less than 10°, where access is not provided.

2.3. FEA results

The FEA results for maximum deflection obtained for the panels with different cases of stacking sequence, for an overall span of 3 m and an overall thickness of 74 mm were shown in Table 3. Panel with Case 2 configuration (Facesheet – Low density PU foam – High density PU foam – Facesheet) exhibited relatively lesser deformation when compared to the other panels, thus suggesting a suitable arrangement so that better results of total deformation can be achieved. Panel with Case 3 configuration was the next preferred one in which a minute percentage variation in total deformation was observed when compared to panel with Case 2 stacking configuration.

Table 3. FE results of total deformation.

| Configurations                                           | Total deformation (mm) |
|---------------------------------------------------------|------------------------|
| Case 1: Facesheet – High density PU – Low density PU –   | 11.802                 |
| Facesheet                                               |                        |
| Case 2: Facesheet – Low density PU – High density PU –   | 11.357                 |
| Facesheet                                               |                        |
| Case 3: Facesheet – High density PU – Low density PU –   | 11.510                 |
| High density PU – Facesheet                             |                        |
| Case 4: Facesheet – Low density PU – High density PU –   | 11.690                 |
| Low density PU – Facesheet                              |                        |

Thus GFRP sandwich roof panel with Case 2 design configuration (Facesheet-Low density PU foam-High density PU foam-Facesheet) has been selected for the further analysis and parametric study. From Table 3, it was clear that the values of total deformation were not within the limit of permissible deflection, for a panel of span 3 m. Thus parametric study was found to be essential to find out the required thickness of the core and the number of GFRP layers/plies so as to fix the optimum panel size achieving the deflection criteria.

3. Flexural behaviour of GFRP sandwich roof panels with different span

To confirm with the best stacking configuration obtained before and also to check the suitability of GFRP sandwich panels as roofs for small residential buildings and prefabricated modular buildings, study with different span was conducted. Based on the size of commercially available roofing panels,
panels with span 3 m, 3.3 m and 3.6 m with width 1 m and an overall thickness of 74 mm have been selected for further analysis.

3.1. FE modelling
The 3D FE model was developed to evaluate the flexural behaviour of GFRP sandwich panels with multilayer polyurethane foam core for different span of 3 m, 3.3 m and 3.6 m with width 1 m and thickness 74 mm for the four different cases of configuration. Figure 2 shows the FE model of GFRP sandwich panel. A 3D orthotropic shell element ‘SHELL181’ was used to model the GFRP facesheets, which is defined by eight nodes and has six degrees of freedom at each node, namely translations in the nodal x, y, and z directions, and rotations about the nodal x, y, and z axes. A 3D SOLID186 element was used to model the polyurethane foam core, defined by twenty nodes and having three translational DOFs at each node.

3.2. FE results
The maximum deflection obtained for the panels with different cases of stacking configuration, for varying span of 3 m, 3.3 m, 3.6 m with an overall thickness of 74 mm were shown in Table 4. The FEA results have confirmed that GFRP sandwich roof panel with Case 2 stacking configuration was the best design configuration with relatively smaller deformations when compared to the other three cases. For the different span considered, the values of total deformation were not attained within the deflection limit of span/360. Thus for the parametric study, different core thickness have been considered for each span while keeping the thickness of facesheet as 2 mm and another one was increasing the overall thickness of the panel by increasing the number of ply layers and keeping the core thickness constant.

| Span (m) | Case 1 | Case 2 | Case 3 | Case 4 |
|---------|--------|--------|--------|--------|
| 3.0     | 11.802 | 11.357 | 11.510 | 11.690 |
| 3.3     | 15.135 | 14.646 | 14.807 | 15.010 |
| 3.6     | 19.142 | 18.609 | 18.777 | 19.005 |

4. Parametric study
The parametric study involves analysing the results for total deformation of GFRP panels by varying certain parameters. The GFRP sandwich roof panel with Case 2 stacking configuration (Facesheet-Low density PU- High density PU- Facesheet) has been selected for parametric study to arrive at the
optimum panel size for varying span. The permissible deflection (i.e., span/360) is 8.33 mm for panel with span 3 m, 9.167 mm for panel with span 3.3 m and 10 mm for panel with span 3.6 m. Fibre orientation was not included in this scope as $0^\circ$ orientation was already proven to be the best one for good results rather than in the other directions. The expected outcome of this study is to obtain GFRP sandwich roof panel with optimum size confirming to the permissible deflection criteria. The parameters considered for the study include:

- Thickness of core
- Number of plies

### 4.1. Varying core thickness

The FE models of GFRP panels of different core thickness ranging from 80 mm to 120 mm for each span were modelled in ANSYS WORKBENCH 19 and the total deformation for panels with different span and varying core thickness were recorded as shown in Table 5, 6 and 7. The thickness of top and bottom GFRP facesheet was kept as 2 mm for all models. Figure 3, 4 and 5 shows the deflection v/s overall panel thickness graph for GFRP panel with span 3, 3.3 and 3.6 m.

#### Table 5. Total deformation for 3 m span.

| Core thickness (mm) | Overall panel thickness (mm) | Total deformation (mm) | Equivalent stress (MPa) | Shear stress (MPa) |
|---------------------|------------------------------|------------------------|-------------------------|-------------------|
| 80                  | 84                           | 9.558                  | 5.73                    | 0.033             |
| 90                  | 94                           | 8.2258                 | 5.09                    | 0.032             |
| 92                  | 96                           | 8.0011                 | 4.98                    | 0.032             |
| 94                  | 98                           | 7.7878                 | 4.88                    | 0.032             |
| 98                  | 102                          | 7.3926                 | 4.68                    | 0.031             |
| 100                 | 104                          | 7.2091                 | 4.60                    | 0.031             |

#### Table 6. Total deformation for 3.3 m span.

| Core thickness (mm) | Overall panel thickness (mm) | Total deformation (mm) | Equivalent stress (MPa) | Shear stress (MPa) |
|---------------------|-------------------------------|------------------------|-------------------------|-------------------|
| 90                  | 94                           | 10.5                   | 6.09                    | 0.035             |
| 100                 | 104                          | 9.1664                 | 5.48                    | 0.034             |
| 102                 | 106                          | 8.9387                 | 5.38                    | 0.040             |
| 104                 | 108                          | 8.7206                 | 5.28                    | 0.040             |
| 110                 | 114                          | 8.1234                 | 4.99                    | 0.039             |

#### Table 7. Total deformation for 3.6 m span.

| Core thickness (mm) | Overall panel thickness (mm) | Total deformation (mm) | Equivalent stress (MPa) | Shear stress (MPa) |
|---------------------|-------------------------------|------------------------|-------------------------|-------------------|
| 80                  | 84                           | 15.489                 | 8.08                    | 0.040             |
| 90                  | 94                           | 13.208                 | 7.18                    | 0.039             |
| 100                 | 104                          | 11.486                 | 6.46                    | 0.037             |
| 110                 | 114                          | 10.145                 | 5.88                    | 0.043             |
| 120                 | 124                          | 9.0718                 | 5.40                    | 0.042             |
Figure 3. Deflection-Overall thickness responses for panel with span 3 m.

Figure 4. Deflection-Overall thickness responses.

Figure 5. Deflection-Overall thickness responses.
4.2. Varying number of plies

The FE models of GFRP panels for different core thickness ranging from 80 mm to 120 mm were analysed in ANSYS WORKBENCH 19 by increasing the number of ply layers from 3 to 10 for each span considered. The number of ply layers was limited to 10 since it results in the increased cost of production even though it results in higher strength and stiffness. The total deformation of GFRP panels for different span with varying number of plies was recorded and shown in Table 8, 9 and 10. The thickness of each ply layer was kept as 0.4 mm. Figure 6, 7 and 8 shows the graph of deflection v/s number of plies for GFRP panel with different span.

Table 8. Total deformation for 3 m span.

| No. of plies | Total deformation (mm) for overall core thickness |
|--------------|--------------------------------------------------|
|              | 80 mm | 90 mm | 100 mm | 110 mm | 120 mm |
| 3            | -     | -     | 8.4197 | 7.4135 | 6.611  |
| 4            | -     | -     | 7.6657 | 6.7887 | 6.0845 |
| 5            | 9.558 | 8.2258| 7.2091 | 6.4101 | 5.7652 |
| 6            | 9.0812| 7.8479| -      | -      | -      |
| 7            | 8.7376| 7.5753| -      | -      | -      |
| 8            | 8.4769| -     | -      | -      | -      |

Table 9. Total deformation for 3.3 m span.

| No. of plies | Total deformation (mm) for overall core thickness |
|--------------|--------------------------------------------------|
|              | 90 mm | 100mm | 110 mm | 120 mm |
| 4            | -     | -     | 8.6721 | 7.7478 |
| 5            | 10.5  | 9.1664| 8.1234 | 7.2855 |
| 6            | 9.9525| 8.7215| -      | -      |
| 7            | 9.5582| 8.4011| -      | -      |
| 8            | 9.2599| -     | -      | -      |

Table 10. Total deformation for 3.6 m span.

| No. of plies | Total deformation (mm) for overall core thickness |
|--------------|--------------------------------------------------|
|              | 100 mm | 110 mm | 120 mm |
| 4            | -      | -      | 9.7211 |
| 5            | 11.486 | 10.145 | 9.0718 |
| 6            | 10.861 | 9.6268 | -      |
| 7            | 10.411 | 9.2543 | -      |
| 8            | 10.072 | -      | -      |
Figure 6. Deflection v/s No. of plies responses.

Figure 7. Deflection v/s No. of plies responses.
4.3. Results and discussions

The results have proved that as the core thickness increases, the total deformation decreases significantly with decrease in equivalent stress and no significant variation in the values of shear stress, for all cases with varying span. Nevertheless, increasing the number of plies also contributed to the significant reduction in total deformation. The equivalent stresses and shear stresses were found to be decreasing but without showing a considerable reduction in values. It was interpreted that 80 mm thick core cannot be provided for a 3 m panel, whereas the selected core thickness ranging from 90 mm to 100 mm would be adequate for achieving the deflection criteria. In the other case, it was required to provide at least 9, 5, and 4 numbers of plies for panels having core thickness 80 mm, 90 mm, and 100 mm respectively. For panels with core thickness 110 mm and 120 mm, a minimum of 3 numbers of plies satisfied the permissible deflection. Thus an overall panel thickness of 94 mm, 96 mm and 98 mm will be sufficient for a 3 m x 1 m panel to give the best configuration.

Similarly, for panels with 3.3 m span, core thickness ranging from 100 mm to 110 mm were found to be adequate for achieving the deflection criteria. It was found from the results that to keep the maximum deflection within the limits, it would be better to provide panels with core thickness 102 mm, 104 mm and up to 110 mm. Only least number of plies was found to be sufficient for 110 mm and 120 mm thick panels. The slope of the curve remains same for panels of different core thickness. The panel with 90 mm core thickness showed larger values of deflection whereas the panel with 120 mm core thickness showed least values of deflection.

As in the case of GFRP panel of 3.6 m span, a minimum of 120 mm core thickness was found to be required with an overall panel thickness of 124 mm to obtain a total deformation of 9.0718 mm, which offered the optimum panel size. For 100 mm thick panels, as the number of plies increased from 5 to 10, no considerable reduction in deformation was observed, but the permissible deflection was achieved when the number of plies was increased to 9. For 110 mm thick panels, 6 numbers of plies were found to be adequate to achieve the deflection within limit and for 120 mm thick panels, 4 numbers of plies were found to be sufficient to keep the panel within the deflection limit.

From parametric study, the following different sets of panel size were found to be optimum and Table 11 shows the optimum size of GFRP roof panel with permissible deflection.

- 90 mm thick core & 2 mm thick facesheet for 3 m x 1 m panel
- 100 mm thick core & 2 mm thick facesheet for 3.3 m x 1 m panel
- 120 mm thick core & 2 mm thick facesheet for 3.6 m x 1 m panel
Table 11. Total deformation for panels with optimum configuration.

| Size of GFRP panel | Total deformation (mm) |
|--------------------|------------------------|
| 3 m x 1 m x 94 mm  | 8.2258                 |
| 3.3 m x 1 m x104 mm| 9.1664                 |
| 3.6 m x 1 m x 124 mm| 9.0718                |

5. GFRP sandwich panels with different web core configurations

GFRP sandwich panels with three different web core configurations, one existing model and other two newly proposed, were developed to understand the extent of improvement in the flexural behaviour of the sandwich panels with multilayer polyurethane foam core. The different foam core configurations include trapezoidal shaped GFRP webs infilled with PU foam (Type 1), rhombus shaped GFRP webs infilled with PU foam (Type 2), and wave shaped GFRP webs infilled with PU foam (Type 3). In this scope of work, while incorporating shear layers/web layers in addition to the core, the panel thickness is reduced to 74 mm as considered in the preliminary study. From literatures it was understood that addition of shear layers/web layers can significantly improve the structural behaviour of the panels while reducing its size. The panels were modelled as simply supported roof panels and loaded with a uniformly distributed load of 0.75 kN/m², as per IS 875 Part II (Table 2). An overall thickness of 74 mm was considered for the panels in all the cases and it was then analysed for total deformation, equivalent von-mises stress and shear stress with varying span.

5.1. GFRP panel with type 1 configuration

GFRP panel with Type 1 configuration is characterised by trapezoidal shaped GFRP web layers infilled with polyurethane foam core. Figure 9 shows the FE model of Type 1 panel. GFRP panels were modelled by incorporating trapezoidal shaped GFRP web layers within the core, having a thickness of 1 mm with material properties same as that of GFRP facesheets. Figure 10 shows the FE model indicating the loading conditions. The FEM results obtained for panel with Type 1 configuration were shown in Table 12. The results have shown a significant reduction in the values of total deformation for Type 1 panel when compared to those panels without internal web layers. Figure 11 shows the FE model showing the results for total deformation. The total deformation was found to be decreased by 63% with respect to those panels considered in the preliminary study, without web layers and it was found to be obtained within the deflection limit of span/360. It is important to consider the deflection rather than strength as deflection is the governing criterion in the design of sandwich panels as reported by various literatures.

Table 12. FE Results for Type 1 panel.

| Span  | Total deformation (mm) | Equivalent stress (MPa) | Shear stress (MPa) |
|-------|------------------------|-------------------------|--------------------|
| 2000  | 1.02                   | 5.35                    | 1.90               |
| 3000  | 4.16                   | 8.65                    | 4.10               |
| 3300  | 5.92                   | 11.35                   | 2.82               |
| 3600  | 8.16                   | 9.63                    | 4.44               |
5.2. GFRP panel with type 2 configuration

GFRP panel with Type 2 configuration is characterised by rhombus shaped GFRP web layers infilled with polyurethane foam core (as shown in Figure12). GFRP panels were modelled by incorporating rhombus shaped GFRP web layers within the core, having a thickness of 1 mm. Figure13 shows the FE model of Type 2 panel with loading conditions. The FEM results obtained for Type 2 configuration were shown in table 13. A significant reduction in the values of total deformation, of about 68%, was observed for Type 2 panel when compared to those panels without internal web layers and it was found to be obtained within the deflection limit of span/360. Figure14 shows the FE model showing the results for total deformation. It was clear from Table 13 that total deformation, equivalent stress as well as shear stress increased with increasing the span of the panel.

Table 13. FE Results for Type 2 panel.

| Span | Total deformation (mm) | Equivalent stress (MPa) | Shear stress (MPa) |
|------|------------------------|-------------------------|-------------------|
| 2000 | 0.91                   | 4.64                    | 2.04              |
| 3000 | 3.62                   | 6.68                    | 2.93              |
| 3300 | 4.96                   | 7.24                    | 3.16              |
| 3600 | 6.71                   | 10.12                   | 3.42              |
5.3. GFRP panel with type 3 configuration

GFRP panel with Type 3 configuration is characterised by sinusoidal wave shaped GFRP web layers infilled with polyurethane foam core. Figure 15 shows the FE model of GFRP Panel with Type 3 Configuration. GFRP panels were modelled by incorporating wave shaped GFRP web layers within the core, having a thickness of 1 mm with material properties same as that of GFRP facesheets. Figure 16 and figure 17 shows the FE model indicating the loading conditions and the results for total deformation respectively.

Table 14 shows the results of FE analysis for Type 3 panel. The values of total deformation were found to be obtained within the deflection limit of span/360 and stresses were also found to be satisfactory. Since strength is not the factor governing the design of sandwich panels, the total deformation of the panels will be the factor which governs the design of sandwich panel and also allows us to determine the feasible model with optimum configuration. The values of total deformation were found to be too small for all the panels with different span and a 92% decrease in total deformation was observed with respect to those panels without any internal webs. When
compared to those panels with Type 1 and Type 2 configurations, Type 3 panel has the least deformation due to the presence of higher percentage volume of fibre content in the panel.

Table 14. Total deformation for 3.6 m span.

| Span  | Total deformation (mm) | Equivalent stress (MPa) | Shear stress (MPa) |
|-------|------------------------|-------------------------|--------------------|
| 2000  | 0.50                   | 27.60                   | 8.05               |
| 3000  | 0.53                   | 20.07                   | 5.93               |
| 3300  | 0.55                   | 21.72                   | 5.61               |
| 3600  | 0.56                   | 39.34                   | 5.37               |

Figure 15. FE model of GFRP Panel with Type 3 Configuration.

Figure 16. Loading Conditions of FE model.

Figure 17. FEM results for total deformation.

5.4. Comparison of flexural behaviour of GFRP sandwich panels with different configurations of core
GFRP sandwich panel with three different foam core configurations, namely trapezoidal shaped GFRP webs infilled with PU foam (Type 1), rhombus shaped GFRP webs infilled with PU foam (Type 2), and wave shaped GFRP webs infilled with PU foam (Type 3) were introduced to investigate the
flexural behaviour of the proposed sandwich panels and to compare with those panels having no web configurations. The panels comprised of GFRP facesheets of 2 mm thickness, high density polyurethane foam of thickness 35 mm placed on top of the bottom facesheet, low density polyurethane foam having thickness 35 mm placed over high density polyurethane foam and GFRP webs of 1 mm thickness. The 3D models of proposed sandwich panels with different span were modelled to analyse the flexural behaviour of the panels under uniformly distributed load.

GFRP sandwich panel with Type 3 configuration was found to exhibit lesser deformation and capable of carrying large stresses when compared to those panels with Type 1 and Type 2 configurations. The improved flexural behaviour of these panels was attributed to the presence of higher percentage volume of fibre content in the panel when compared to those panels without webs. The total deformation obtained for Type 2 panels were found to be lesser than and comparable with that of Type 1 panels. The percentage volume of fibre content in Type 1 and Type 2 panels were found to be almost equivalent, hence not much variation in the values of total deformation was observed. Also equivalent von-Mises stresses and shear stresses were almost comparable between Type 1 and Type 2 panels, whereas a relatively higher stresses were observed for panel with Type 3 configuration. The values of total deformation for panels with Type 1, Type 2 and Type 3 configurations were found to be decreased substantially by 63%, 68% and 92% respectively, when compared to those panels without any web core configurations.

6. Conclusions
Finite element analyses were carried out to investigate the flexural performance of Glass Fibre Reinforced Polymer (GFRP) sandwich roof panel using commercial FEM software ANSYS WORKBENCH 19. The GFRP sandwich panel was composed of thin GFRP facesheets at top and bottom infilled with Polyurethane (PU) foam core.

GFRP sandwich panel with multilayer polyurethane foam core having two different densities were developed and four different cases of design configuration with different stacking sequence of multilayer core were also studied. GFRP sandwich roof panel with Case 2 design configuration (Facesheet – Low density PU foam – High density PU foam – Facesheet) was found to be the best design configuration with total deformation lesser than that of the other cases and within the limit of deflection criteria. The best configurations with optimum size were finalised by conducting a parametric study with varying core thickness and number of GFRP plies for different span length. The total deformation was found to be decreased considerably as the core thickness and number of GFRP plies increased.

The flexural behaviour of three different models of GFRP sandwich panels incorporating different web core configurations, namely trapezoidal shaped GFRP webs infilled with PU foam (Type 1), rhombus shaped GFRP webs infilled with PU foam (Type 2), and wave shaped GFRP webs infilled with PU foam (Type 3) were evaluated. The panel with Type 3 configuration was found to exhibit lesser deformations when compared to those with Type 1 and Type 2 configurations and to those panels without any webs. The total deformations for Type 1, Type 2 and Type 3 panels were found to be decreased substantially by 63%, 68% and 92% respectively, with respect to panels without webs, depending on the different core configurations.

Based on the numerical analysis, it is suggested that GFRP sandwich panels with Type 3 core represent a feasible configuration to be used as a roofing panel for small residential buildings and prefabricated modular constructions. Further study can be conducted on GFRP roofing panel with Type 3 core for larger spans and higher loads, analysis of strength characteristics and development of large scale GFRP roofing panel for multipurpose buildings. Also, the numerical analyses of stress distribution in each ply layers using ANSYS Composite Prepost would be a further scope for this work.
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