WEB CORE SANDWICH BRIDGE DECKS HAVING DIFFERENT CONFIGURATIONS

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Abstract

This paper has proposed three different core configurations of web core sandwich bridge decks made of lightweight composite materials and investigated their performances. A simple but efficient technique is developed for the homogenization of the core layer consists of equispaced vertical web plates oriented in two, three or four directions having equal internal angles. The homogenization of the complex core configuration has helped to model the entire sandwich deck system as a simple laminated plate which is analysed using the finite element technique. This simple plate finite element model is based on Reissner-Mindlin's hypothesis for considering the effect of shear deformation of the plate. The performance of the proposed technique is tested with the detailed finite element analysis of the deck system where plate elements are used to model the face sheets as well as individual web plates.

1 Introduction

The use of sandwich bridge decks made of fibre reinforced polymer (FRP) composites with laminated configuration is becoming popular in new and existing bridges [1-4]. The traffic load of many existing bridges has been exceeded their design load with population growth where the replacement of the heavy concrete decks with these lightweight deck systems can accommodate the extra traffic load. Moreover the replacement process of these lightweight decks takes relatively less time which has the benefit of having shorter duration of traffic interruption. As the concrete desks are the major contributors of the deal load in a bridge structure, the use of lightweight sandwich decks can help to achieve more economical design of new bridges. The foam core sandwich construction is quite popular in many structures but this is not preferred in bridge decks as delaminations at the interfaces between the core and face sheets can be produced easily by the impact of wheels. In order to address this problem, different types of core configurations have been investigated by the different researchers [1-4]. The web core sandwich construction appears to be one of the most promising alternatives from these investigations.

The proposed bridge deck system consists of FRP web core sandwiched between two FRP face sheets as shown in Figure 1 where the core is constructed with equispaced vertical web plates which may be oriented in two, three or four directions having equal internal angles as shown in Figure 2. The web plates give a cellular type of construction of the core having different configurations and they also form a grid type of structure of the core which may be defined as ortho-grid, iso-grid and bi-grid when the web plates are provided in two, three and four directions respectively (Figure 2). The core will have a number of identical cells with a regular pattern where the specific shape of these cells will be rectangle, equilateral triangle and right angle triangle for ortho-grid, iso-grid and bi-grid configurations respectively (Figure 2). The space within these cells may be filled with polymer foam or it may be kept empty.

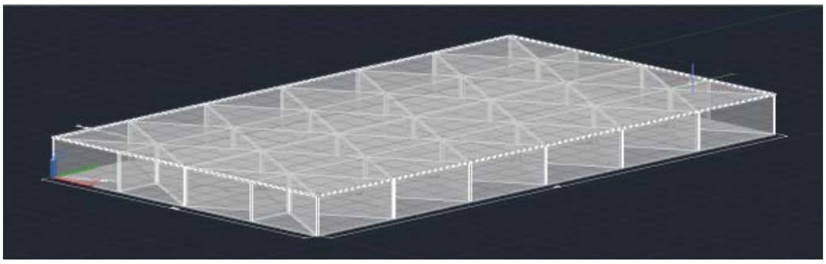
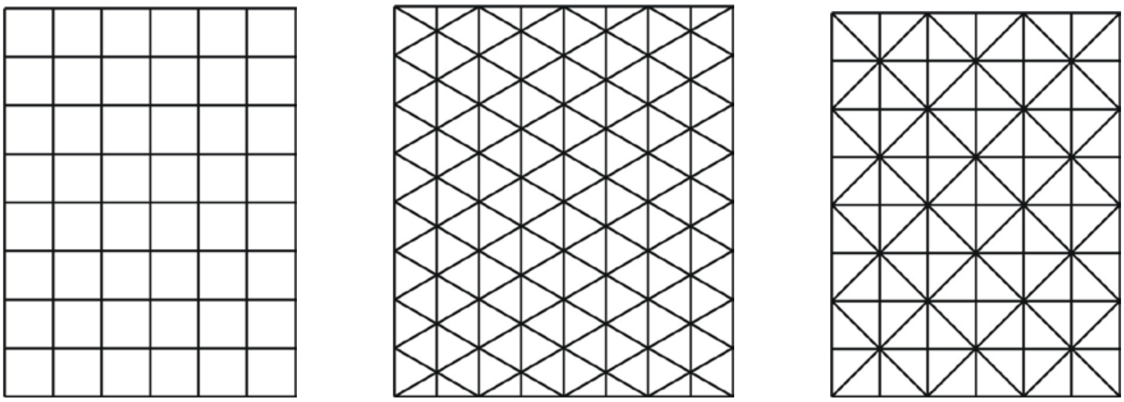


Figure 1. Sandwich bridge deck



(a) (b) (c)

Figure 2. a) Ortho-grid, b) Iso-grid, c) Bi-grid core configurations (top view)

The structural response of these bridge decks can be predicted accurately by modelling all the vertical web plates and horizontal face sheets (Figure 1) with laminated plate/shell elements which can accommodate multiple layers having different fibre orientations. These elements are commonly found in commercially available finite element codes such as ANSYS which can be used to analyse these structure satisfactorily but it needs significant efforts to model all these components in details. The modelling will be much more tedious when the cells formed by these webs are filled with foam which can be modelled using solid elements. In order to avoid the abovementioned modelling complexities, which is primarily due to the complex core configurations, an efficient technique is developed in this study for the homogenisation of the core utilising the regularity of its structure. This will help to model the entire bridge deck as a single laminated plate where the core will be one of its layers. This elegant modelling strategy is accomplished through an eight node isoparametric element based on Reissner-Mindlin's pate theory where a computer program is written in FORTRAN to implement the entire process. The performance of the proposed model is assessed by comparing the results obtained from the analysis of a number of structures by this model with those obtained from a detailed finite element analysis of these structures using ANSYS.

2 Mathematical formulations

The simplified finite element model proposed in this paper has followed the basic principles outlined by Haldar, Sheikh and Sarkar [5] for a finite modelling of laminated composite plates. However, it needs homogenised material properties of the core layer so that it can be treated as any other layer of the laminated plate. So the homogenisation of the core is a significant aspect of this study which is presented below.

For the homogenisation of the web core having any configuration (Figure 2), consider a representative set of equispaced parallel web plates as shown in Figure 3. The in-plane stiffness of these web plates can be homogenised conveniently in their local axis system by smearing the actual stiffness contributions of a discrete web plate (E_1, G_{12}) over a span of s (spacing of web plates) and this may be expressed in the form of stress-strain relationship as

$$\begin{Bmatrix} \sigma_1 \\ \tau_{12} \end{Bmatrix} = \frac{b}{s} \begin{bmatrix} E_1 & 0 \\ 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \gamma_{12} \end{Bmatrix} \text{ or } \{\sigma\}_L = [Q_i]_L \{\varepsilon\}_L \tag{1}$$

where the notations are having their usual meanings [6]. It should be noted that the normal stress in the thickness direction of the web plate (σ_2) is assumed to be zero. Moreover, the above equation is written based on the assumption that the fibres are oriented along the length of the web plate. If the fibres are having different orientations in the plane of the web plate, an additional transformation [7] will be required to get the stiffness contributions of a web plate used in the above equation.

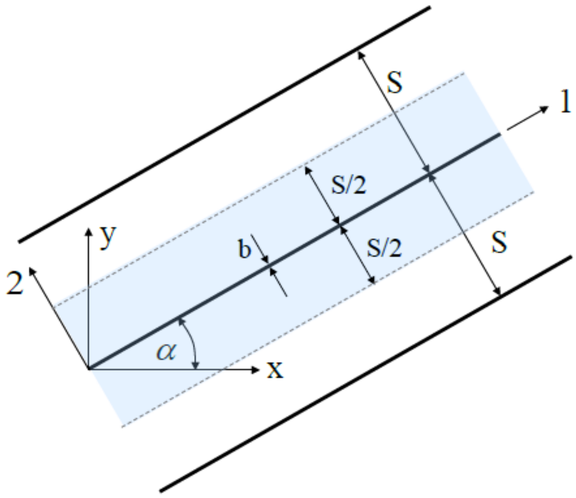


Figure 3. A set of parallel vertical web plates of a web core sandwich bridge deck (top view)

The in-plane stress transformation [6] considering all stress components may be expressed as

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & -2\cos\alpha\sin\alpha \\ \sin^2\alpha & \cos^2\alpha & 2\cos\alpha\sin\alpha \\ \cos\alpha\sin\alpha & -\cos\alpha\sin\alpha & \cos^2\alpha-\sin^2\alpha \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix}. \tag{2}$$

The above equation is reduced to the following form by dropping the stress component σ_2 as

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \cos^2\alpha & -2\cos\alpha\sin\alpha \\ \sin^2\alpha & 2\cos\alpha\sin\alpha \\ \cos\alpha\sin\alpha & \cos^2\alpha - \sin^2\alpha \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \tau_{12} \end{Bmatrix} \text{ or } \{\sigma\} = [T_{1i}]\{\sigma\}_L . \tag{3}$$

The in-plane strain transformation [6] considering all strain components may be expressed as

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & \cos\alpha\sin\alpha \\ \sin^2\alpha & \cos^2\alpha & -\cos\alpha\sin\alpha \\ -2\cos\alpha\sin\alpha & 2\cos\alpha\sin\alpha & \cos^2\alpha - \sin^2\alpha \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} . \tag{4}$$

The above equation is reduced to the following form by dropping a strain component ε_2 as

$$\begin{Bmatrix} \varepsilon_1 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & \cos\alpha\sin\alpha \\ -2\cos\alpha\sin\alpha & 2\cos\alpha\sin\alpha & \cos^2\alpha - \sin^2\alpha \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \text{ or } \{\varepsilon\}_L = [T_{2i}]\{\varepsilon\} . \tag{5}$$

With the help of Equations (1), (3) and 5), the stress-strain relationship (in-plane) in the laminate axis system (*x*-*y*) can be expressed as

$$\{\sigma\} = [T_{1i}][Q_i]_L [T_{2i}]\{\varepsilon\} \text{ or } \{\sigma\} = [Q_i]\{\varepsilon\} \tag{6}$$

where $[Q_i]$ gives the homogenised in-plane stiffness of the web plates (Figure 3) in the laminate axis system. Similarly, the transverse shear stiffness of these web plates (Figure 3) can be homogenised in their local axis system by smearing the actual stiffness contribution of a discrete web plate (G_{13}) over a span of *s* and it may be expressed as

$$\tau_{13} = \frac{b}{s} G_{13}\, \gamma_{13} \text{ or } \{\tau\}_L = [Q_s]_L \{\gamma\}_L . \tag{7}$$

The shear stress transformation [6] considering all stress components may be expressed as

$$\begin{Bmatrix} \tau_{xz} \\ \tau_{yz} \end{Bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{Bmatrix} \tau_{13} \\ \tau_{23} \end{Bmatrix} . \tag{8}$$

The above equation is reduced to the following form by dropping the stress component τ_{23} which is assumed to be zero.

$$\begin{Bmatrix} \tau_{xz} \\ \tau_{yz} \end{Bmatrix} = \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} \tau_{13} \text{ or } \{\tau\} = [T_{1s}]\{\tau\}_L \tag{9}$$

The shear strain transformation [6] considering all strain components may be expressed as

$$\begin{Bmatrix} \gamma_{13} \\ \gamma_{23} \end{Bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{Bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} . \tag{10}$$

The above equation is reduced to the following form by dropping the strain component γ_{23} as

$$\gamma_{13} = \begin{bmatrix}\cos\alpha & \sin\alpha\end{bmatrix}\begin{Bmatrix}\gamma_{xz} \\ \gamma_{yz}\end{Bmatrix} \text{ or } \{\gamma\}_L = [T_{2s}]\{\gamma\}. \quad (11)$$

With the help of Equations (7), (9) and (11), the stress-strain relationship (transverse shear) in the laminate axis system (*x*-*y*-*z*) can be expressed as

$$\{\tau\} = [T_{1s}][Q_s]_L[T_{2s}]\{\gamma\} \text{ or } \{\tau\} = [Q_s]\{\gamma\} \quad (12)$$

where $[Q_s]$ gives the homogenised transverse shear stiffness of the web plates (Figure 3) in the laminate axis system.

For a specific core configuration e.g. orth-grid web core (Figure 2a), the in-plane stiffness matrix $[Q_i]$ and the shear stiffness matrix $[Q_s]$ are computer twice ($\alpha = 0^0$ and $\alpha = 90^0$) and these are combined together to get the homogenised stiffness of the core layer. This is similarly applicable for iso-grid web core and bi-grid web core (Figure 2) where this process is repeated thrice ($\alpha = 30^0$, $\alpha = 90^0$ and $\alpha = 150^0$) and four times ($\alpha = 0^0$, $\alpha = 45^0$, $\alpha = 90^0$ and $\alpha = 135^0$) respectively. If the cells formed by the vertical web plates are filled with any polymer foam, the stiffness of the foam will be just added to the homogenised stiffness of the web plates as derived in the above section.

3 Results and discussions

In this section the proposed simplified finite element approach is used to analyse a number of web core sandwich panels having different core configurations. A detailed finite element analysis of these structures has also been carried out using ANSYS and the results obtained by these two approached are compared to assess the performance of the proposed technique.

3.1 Ortho-grid web core sandwich panel

An example of a vertical dock gate investigated by the author with a different idealization of the structure in an earlier study [8] is considered here. The rectangular dock gate panel has a length of 48.768 m (160 ft), breadth (or height) of 15.24 m (50 ft) and overall thickness of 3.048 m (10 ft) which is made with 11 longitudinal web plates having a spacing of 1.524 m (5 ft) and 17 transverse web plates having a spacing of 3.048 m (10ft) that formed the core of the sandwich panel having a ortho-grid construction. The thickness of all the web plates as well as the face sheets is 0.0127 m (0.5 in). The gate is subjected to a hydrostatic pressure due to water on one side of the gate at its full height while there is no water pressure on the other side of the gate. The top edge of the gate has no support (i.e. free edge) but its other three edges are having simply supported conditions. The results in the form of deflections at some impotent sample points obtained by the proposed model and the detailed finite element model (ANSYS) are presented in Table 1. It shows a good agreement between the results which ensures the performance of the proposed model. As the structure is symmetrical along its length, half of structure is analysed by the proposed simplified finite element approach with different mesh sizes (4x4, 6x6, 8x8) and the results obtained for all these mesh sizes are presented in Table 1 which shows a rapid convergence of the results with mesh refinements. The author analysed this structure with a different approach in an earlier study [8] where the gate was idealised as a stiffened plate structure. Based on that approach [8] the deflection obtained at the mid-span of the top edge of the gate is also reported in Table 1. It is not agreement well with the result obtained from the detailed finite element analysis which indicates that the idealisation technique proposed in the present investigation is better than that of earlier study [8].

Point	Present (4x4)	Present (6x6)	Present (8x8)	ANSYS	Reference 9
1	58.186	58.217	58.217	59.436	72.146
2	31.425	31.791	31.791	30.785	
3	42.215	42.215	42.215	41.605	
4	23.433	23.430	23.430	24.006	

Table 1. Deflection (mm) at four points (1: mid-span at the top edge, 2: quarter-span at the top edge, 3: mid-span at mid-height, 4: quarter-span at mid-height) of the dock gate sandwich panel.

3.2 Iso-grid web core sandwich panel

An example of a sandwich panel having the core configuration shown in Figure 2b is studied in this section. The length of the sides a representative equilateral triangular cell is taken as 200 mm. The overall thickness of the of the panel is taken as 233.4 mm whereas its length and breadth are varied in order to see the effect of panel size/cell size ratio on the homogenisation scheme used for the core. The face sheets are 6 mm thick consists of 6 layers whereas the web plates are 3 mm thick consists of 3 layers. The other details are available in reference 9. The panel is clamped at its four edges and subjected to uniformly distributed load. The structure is analysed with the proposed finite element approach using a higher mesh size (12x12) in order to get a converged solution taking full geometry of all panels. The deflections at the centre of the panels obtained in the present analysis are presented in Table 2 with those obtained from the detailed finite element analysis using ANSYS (Figure 4) of the panels. The table shows that the performance of the proposed homogenisation technique is quite encouraging as the deflection predicted by the simplified finite element model based on this technique approached to that predicted by the detailed finite model (ANSYS) when the panel possesses a feasible number of triangular cells.

Panel size (m x m)	Present model	ANSYS
0.3464 x 0.6	1.188	2.002
0.6928 x 0.6	4.697	6.719
1.5588 x 0.6	9.381	10.321
1.5588 x 1.4	10.210	10.756

Table 2. Deflection (mm) at the centre of the iso-grid sandwich panel having different sizes.

3.3 Bi-grid web core sandwich panel

Similar to the iso-grid web core sandwich panels, an example of a bi-grid web core sandwich panel (Figure 2c) is studied in this section. The panel has a length of 8 m, breadth of 8 m and overall thickness of 1 m whereas the size of a right angle triangular cell (Figure 2c) is 1m x 1 m. The thickness of the face sheets and the web plates is 5 mm. The panel is simply supported at its four edges and subjected to uniformly distributed load. The other details are available in reference 9. The structure is analysed with the proposed simplified finite element technique using three different mesh sizes (4x4, 6x6, 8x8). The variation of deflection along one of the centre lines of the panel obtained in the present analysis is presented in Table 3 along with that obtained from the detailed finite element analysis of the panel using ANSYS. The table shows that the proposed homogenisation technique performed well and it is comparative better than the previous case which is expected as the number web plates is more in the present core configuration.

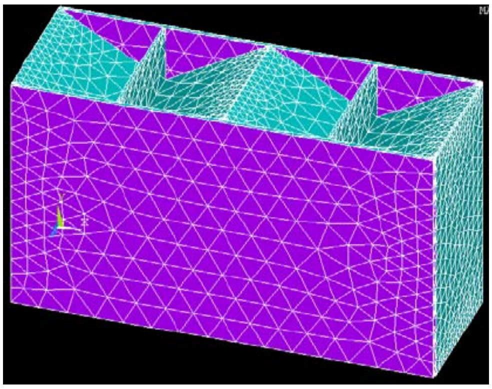


Figure 4. A detailed finite element model the 0.6928 m x 0.6 m sandwich panel (iso-grid core)

Distance from edge	Present (4x4)	Present (6x6)	Present (8x8)	ANSYS
1 m	10.610	10.626	10.630	10.742
2 m	18.882	18.883	18.883	18.979
3 m	23.910	23.910	23.910	24.153
4 m	25.610	25.625	25.630	25.871

Table 3. Variation of deflection (mm) along one of the centre lines of the bi-grid web core sandwich panel.

2 Conclusions

This paper has introduced three types of core configurations for web core sandwich bridge decks entirely made of FRP laminated plates. As the web plates create a grid type of structure of the core, it is defined as ortho-grid, iso-grid or bi-grid core depending on the number of directions the web plates are provided. The geometries of these cores are quite complex but they have a regular pattern which is utilised to develop a simple but efficient technique for the homogenisation of the core layer. This has helped to simplify the analysis of the structure significantly because the entire deck panel can now be modelled as a single laminated plate where the core can be treated as any other layers. The homogenisation technique for the core is implemented within a finite element framework for laminated composite plates where a quadratic isoparametric element based on first order shear deformation is used. The entire process is achieved through a computer program (FORTRAN) developed for this study. This simplified finite element is used to solve a number of examples of sandwich bridge decks having the abovementioned core configurations. A detailed finite element analysis of these structures is also carried out using ANSYS and the results from these two approaches are compared. The results show a very good performance of the proposed simplified technique which can be used to analyse the sandwich bridge decks elegantly.

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