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Mechanical Property Research for CSIP Thin-Wall Box-Beams

Lei Li [1,*], Nasim Uddin [2], Xianxian Zhao [1] and Limin Tian [3]

[1] School of Civil Engineering, Zhengzhou University of Aeronautics, Zhengzhou 450015, China
[2] Department of Civil Construction and Environmental Engineering, University of Alabama at Birmingham, Birmingham, AL 35294, USA
[3] Shaanxi Key Lab of Structure and Earthquake Resistance, School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China
* Correspondence: lilei@zua.edu.cn

Abstract: Composite structural insulated panels (CSIPs) are eco-friendly, high-performance materials, which not only good have mechanical properties, but also good waterproof, moisture-proof, fire-proof, and anti-corrosion characteristics, so they have been used to build envelope structures in recent years. However, how to improve stiffness of CSIPs remains unsolved. The poor stiffness is one of the biggest obstacles for the application of CSIPs in the load-bearing members of civil engineering. In this study, the layout of glass–polypropylene (PP) laminate layers is designed to enhance its stiffness, and this study applies CSIPs as load-bearing members of civil engineering for the first time. Thus, the bend model of CSIP thin-wall box-beams under uniform loading is built, based on Timochenko's theory. The deflection curve equation is presented, considering shearing deformation. The expressions for the bending of normal strain flanges of the beam and the equation considering principal shearing strain at the beam's web are obtained, respectively. Finally, mechanical properties of the thin-wall box-beam under uniformly distributed loads were performed by FE. FE results are entirely consistent with the theoretical results, thereby making the theoretical method applicable for the design of thin-wall box-beams, which are made of composite materials. Different from other beams, the shearing deformation is a critical factor that influences the deformation of thin-walled box-beams.

Keywords: thin-wall box-beam; CSIPs; mechanical property; shearing deformation

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1. Introduction

Conventional building materials encounter challenges, such as high self-weight, poor corrosion, poor fireproofing, poor waterproofing, poor moisture-proofing, and high maintenance costs. Nowadays, more and more researchers are committed to investigating innovative new material substitutes. Thus, extensive research on CSIPs has been conducted at the University of Alabama at Birmingham. Professor Uddin's research team presented composite structural insulated panels (CSIPs). The designs for the section of the CSIPs were proposed by Vaidva et al. [1]. (Figure 1), such as the thickness of the glass–polypropylene (PP) face sheets (3.04 mm) and EPS core (140 mm). The face sheets of CSIPs exhibit high impact-resistance and strength, good waterproofing, moisture-proofing, fire-proofing, anti-corrosion, and eco-friendly characteristics, whereas the EPS middle sheets bear the shearing stress, and two outer PP faces resist buckling and improve its stiffness. Thus, as the structural layout of CSIPs, the use of glass–polypropylene (PP) sheets is appropriate because it provides a high ratio of strength to weight, fine impact resistance, and good durability. Meanwhile, EPS foam is so light weight that it is used for the CSIP core. Thus, it has an excellent performance in things such as heat insulation, excellent impact-resistance, anti-bending, fire-proofing, and keeping warm [1]. Therefore, it is important that CSIPs' mechanical properties are studied.

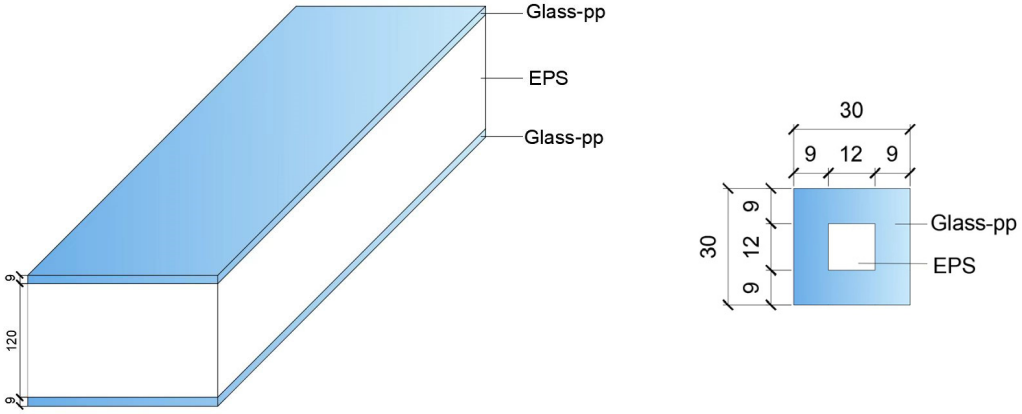


Figure 1. CSIP Sketch (unit: mm).

In recent years, considerable research has been devoted to developing sandwich composite materials. Wang et al. discussed the shearing of beams and panels with higher order hypotheses [2]. Liu et al. proposed layer-wise shear deformation theory of composite laminated plates by DQFEM [3]. Pawlus solved the stability of asymmetrical three-layered annular plates under loads in a plane [4]. The influence of a thin middle sheet of bending on the sandwich beams was presented the by Iaccarino et al. [5]. Grygorowicz and Lewiński presented a three-point bending of an I-beam considering the transverse shear effect [6]. Under the higher-order zigzag principle, static FE analyses of sandwich beams in both outer sheets and soft cores were presented by Chakrabarti et al. [7]. Wittenbeck et al. studied the three-point bending of sandwich beams with corrugated cores [8]. Roque et al. presented the bending of simply supported laminated composite beams subjected to transverse loads by a modified couple stress theory and a meshless method [9]. Batra and Xiao gave finite transient deformations of a curved laminated beam composed of a St. Venant–Kirchhoff material [10]. De Santis et al. obtained the behavior effects of composite glulam beams with circular holes [11]. Rocha et al. presented the structural concept of post-tensioned Fe-SMAs glass systems [12]. Bui et al. investigated transient responses and natural frequencies of sandwich beams with inhomogeneous functionally graded (FG) cores [13]. Marczak and Jędrysiak built a model of sandwich structures with inert cores [14,15]. Matuszewska and Strek studied a vibration analysis of a beam by an auxetic cross-section [16]. Grygorowicz and Magucka-Blandzi gave static and dynamic stabilities of a simply supported three-layered beam with a metal foam core [17]. Jopek and Strek presented the torsion of a two-phased composite bar with helical distribution of constituents by the FEM method [18]. Teter showed that simply supported columns are subjected to in-plane pulse loading at the loaded end by the analytical–numerical method (ANM), using Koiter's perturbations method [19]. The study of the failure mechanisms of sandwich beams with horizontal loads was performed by Steeves et al. and Qin et al. [20,21]. Tian et al. proposed the instability of structural members under axial compression causes [22] The bending problems of sandwich beams made of a metal foam core were presented by Magnucka-Blandzi et al. [23,24]. The connections between foam sheets was gained considering cracks in the connections of the fibers and foam sheets by Zenkert. [25]. The effect of the fiber transverse dimension of the binding layer under the deformation of beam bending was presented by Magnucki et al. [26]. Mori et al. gained insight into the mechanisms of deformation and the mechanics of sandwich structures subjected to underwater shock loading [27]. A formal engineering method of the mechanics of thin-walled laminated beams was obtained under kinematic assumptions by Barbero et al.; it has a good agreement with Timoshenko's beam theory [28]. Yuan et al. proposed the bending influence of shear deflection on laminated sandwich box cantilever beams [29]. Pawar demonstrated that the thin-walled composite box beams by 3D Finite Element Modeling were a feasible solution [30].

Uddin et al. investigated the behavior of the whole bending of CSIP wall panels (CSIPs) under concentric and eccentric load in a plane [31,32]. Du and Uddin presented concepts of the new CSIP thin-walled laminated shell, which it is different from the traditional concrete thin shell [33]. Due to the advantages of CSIP plates and shells, such as a high strength–weight ratio, excellent impact resistance, and high durableness, they are used as enclosure members in civil engineering. However, previous research did not focus on the stress, strain, and deflection in each laminated layer of the sandwich plates and beams.

With an excellent strength–weight ratio and good anti-impact properties, civil engineering will apply CSIPs to load-bearing structures. The stiffness of CSIPs is so small that the load-bearing members made of CSIP composite materials have a great challenge, which is the large deflection. Consequently, focusing research on enhancing CSIPs' stiffness is essential. In the present study, the new innovative CSIPs improved the stiffness of the materials, which are made of E-glass (PP) layers as the surface, and a polystyrene (EPS) foam core. Innovative CSIPs are derived from sandwich panels, which have a foam core with a thickness of 120 mm and a surface with thickness of 9 mm. On the other hand, the box-beams are used because of their excellent mechanical properties—a larger rigidity and strong torsion resistance. These innovations can be developed to enhance efficiency through special designs. In this study, stress, strain, and deflection of each of the face sheets of the CSIP thin-wall box-beam will be carried out by theoretical analysis. The FE model of the CSIP thin-wall box-beam was constructed using the ANSYS Workbench. Finally, by comparing the theoretical results with the FE results, the feasibility of the theoretical model is evaluated.

2. Design of the CSIP Thin-Wall Box-Beam

2.1. Cross Sectional Shapes of CSIP Box-Beams

The section design of the girder is important in building design. The section format of girders is mainly things such as box-beams, T-beams, and I-beams. In this study, the box-beam is formed (Figure 2), because it has a much greater torsional stiffness and strength than an open section. The closed cell is made of EPS foam, its web and flange are made of 12 mm and 9 mm glass PP, respectively.

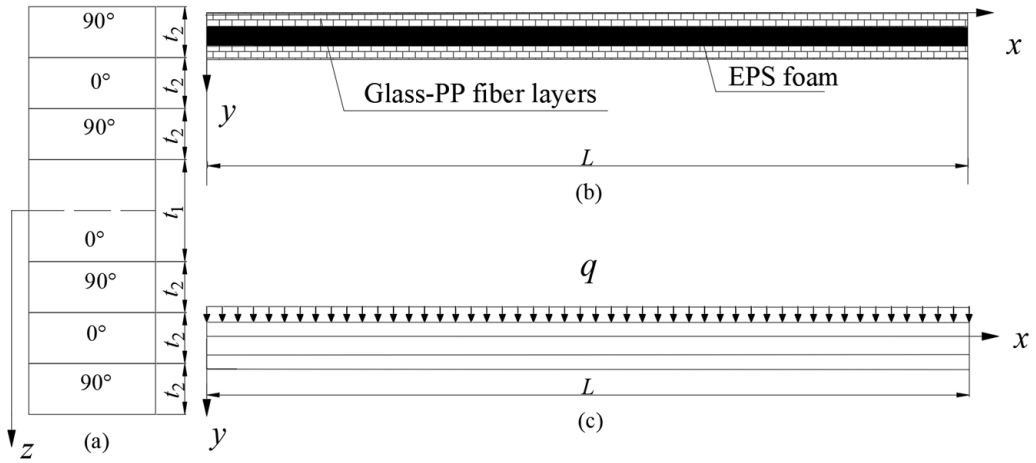


Figure 2. CSIP thin-wall box-beam. (**a**) Cross-section of the laminated composites. (**b**) The configuration vertical section. (**c**) A simply supported beam with a uniform load diagram.

2.2. Design of CSIPs

A cheap orthotropic thermoplastic (TP) glass PP surface and EPS foam core sheets are the CSIP composite materials. Bending stresses are borne by face sheets. The foam core has an important function, the shear load is resisted by the foam core. On the other hand, it improves bending performance of the CSIP girder [34]. A CSIP was developed, which was made of low-cost TP glass PP laminate as a face sheet and EPS as a core (Figure 1).

The PP resin impregnated E-glass fibers, then the glass PP surface was made of 70%, bidirectionally. The TP polymers have some advantages, such as high-temperature, short-time processing, good durability, being inexpensive, good toughness, excellent impact ability, good plasticity, and high recyclability and reusability for the thermosetting wastes. A direct reinforcement fabrication technology (DRIFT) process is used to turn out glass PP surfaces [35]. The manufacturer (Crane Composites, Inc., Channahon, IL, USA) can produce glass PP laminated layers (3.04 mm thickness). In this study, the glass PP mechanical performance was as described in Table 1. At the same time, due to the low price and low weight of EPS foam, a structure made of CSIPs has low weight, high thermal resistivity, and good impact ability, and is very good thermal insulation material. Due to its low cost, the core sheet comprised 140 mm EPS foam (Table 1). The manufacturer (Universal Packaging, Inc., Lutherville, MD, USA) supplied the EPS foam materials, its performance is as described in Table 2. Above all, CSIPs are high performance materials [36]. In this research, the new design method for CSIPs has been presented to improve its stiffness.

Table 1. Properties of the glass PP face sheets [36].

Items	Value
Nominal thickness (t)	3.04 mm
Density (ρ_f)	980 kg/m^3
Weight percentage of glass fiber	70%
Longitudinal modulus (Ex)	15,169 MPa
Transverse modulus (Ey)	15,169 MPa
Thickness direction modulus (Ez)	1050 MPa
Poisson's ratio (ν_{xy}, ν_{yz}, ν_{xz})	0.11, 0.22, 0.22
Shear modulus (G_{xy}, G_{yz}, G_{xz})	1800 MPa, 1800 MPa, 750 MPa
Tensile strength	690 MPa
Compression strength	317 MPa

Table 2. Properties of EPS foam core [36].

Items	Value
Nominal thickness (t)	140 mm
Density (ρ_f)	16 kg/m^3
Elastic modulus (Ec)	1.2–1.5 MPa
Poisson's ratio (ν)	0.25
Shear modulus (G)	1.9–2.2 MPa
Tensile strength	0.11–0.14 MPa
Compression strength	0.07–0.1 MPa

The CSIPs are made of laminate surfaces where glass fiber is 70% of the weight, and the EPS foam core the remainder. The new innovative composite structure for insulated panels (Figure 1), which is derived from the sandwich composite structure of a lightweight thick core (120 mm) and two stronger and thinner surfaces (9 mm), improves the stiffness of the materials. The box-beams are used because of their excellent mechanical properties, such as large rigidity and strong torsion resistance.

2.3. CSIP Thin-Wall Box-Beam Geometry

The mechanical behavior of a beam depends on its span–height ratio. Generally, the span–height ratio of a simply supported beam is from 10 to 20. The a span –height ratio is 20 in this study. The span of the box-beam is 600 mm, the cross section is a box-beam that is a square of about 30 mm on a side (Figure 2). To improve the stiffness of the CSIP thin-wall box-beams, the thickness of the flange is the same as in a beam web, 9 mm. The E-glass/PP layup orientation of the webs is consistent with those of the flanges.

3. Static Analysis of a CSIP Thin-Wall Box-Beams

3.1. Strain Stress of a CSIP Thin-Wall Box-Beams

Based on the hypothesis of the plain section, CSIP thin-wall box-beams with simple support will be studied under uniform loads. Regardless of the shear strain, the strain of a CSIP thin-wall box-beam can be calculated using Equation (1):

$$\varepsilon_k = \frac{M(x)}{D_{11}} y_k \tag{1}$$

where $M(x)$ is the bending moment of the cross-section at x point, D_{11} is the bending stiffness of the cross-section of the beam, and y_k is the distance from the neutral layer to the k^{th} layer of box-beam.

The bending stress at any point of its cross-section is presented using Equation (2):

$$\sigma_x^k = \frac{M(x)}{D_{11}} \overline{Q}_{11}^k y_k \tag{2}$$

where σ_x^k is the bending stress at the k^{th} glass–PP layers of the cross section, $\overline{Q}_{11}^k$ is the stiffness coefficient at the k^{th} glass-PP layers of the cross-section, the flexural rigidity of the cross-section is $D_{12} = \frac{E_c {b_c} {t_c}^3}{12(1-\mu_c{}^2)}$, where E_c is the elasticity modulus of the EPS foam, and μ_c is the Poisson's ratio of EPS foam.

The flexural rigidity of the web (D_{13}) is given as $D_{13} = 2\sum_{i=1}^{12} \overline{Q}_{11}^i \frac{t_{fi} {b_{fi}}^3}{12}$, where t_{fi} is web thickness at i^{th} layer, and ${b_{fi}}^3$ is the web height at the i^{th} layer. The flexural rigidity of the upper or lower flanges of the box-beam cross-section is obtained by $D_{14} = 2\sum_{i=1}^{12} \overline{Q}_{11}^i t_{yi} b_{yi} {z_{yi}}^2$, where b_{yi} is the flange width at the i^{th} layer, t_{yi} is flange thickness at i^{th} layer, and z_{yi} is distance from the middle surface of the i^{th} layer flange to the neutral axis.

The plane stress constitutive equation for orthotropic material is given as:

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{pmatrix} = \begin{bmatrix} s_{11} & s_{12} & 0 \\ s_{21} & s_{22} & 0 \\ 0 & 0 & s_{GG} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{Bmatrix} = [s]\{\sigma\} \tag{3}$$

where S_{ij} is the flexibility coefficient, and readily calculated by

$$s_{11} = \frac{1}{E} \tag{4}$$

$$s_{12} = -\frac{\mu}{E} \tag{5}$$

$$s_{GG} = \frac{1}{G} = \frac{2(1-\mu)}{E} \tag{6}$$

The other constitutive equation is obtained from Equation (3)

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{1G} \\ \overline{Q}_{21} & \overline{Q}_{22} & \overline{Q}_{2G} \\ \overline{Q}_{1G} & \overline{Q}_{2G} & Q_{GG} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \left[\overline{Q}\right]\{\varepsilon\} \tag{7}$$

where $\left[\overline{Q}_{ij}\right]$ is the stiffness matrix, given as:

$$\overline{Q}_{11} = Q_{11}\cos^4\theta + 2(Q_{12} + 2Q_{GG})\sin^2\theta\cos^2\theta + Q_{22}\sin^4\theta \tag{8}$$

$$\overline{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{GG})\sin^2\theta\cos^2\theta + Q_{12}(\sin^4\theta + \cos^4\theta) \quad (9)$$

$$\overline{Q}_{22} = Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{GG})\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta \quad (10)$$

$$\overline{Q}_{1G} = (Q_{11} - Q_{12} - 2Q_{GG})\sin\theta\cos^3\theta + (Q_{12} - Q_{22} + 2Q_{GG})\sin^3\theta\cos\theta \quad (11)$$

$$\overline{Q}_{2G} = (Q_{21} - Q_{12} - 2Q_{1G})\sin^3\theta\cos\theta + (Q_{12} - Q_{22} + 2Q_{GG})\sin\theta\cos^3\theta \quad (12)$$

$$\overline{Q}_{GG} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{GG})\sin^2\theta\cos^2\theta + Q_{GG}(\sin^3\theta + \cos^4\theta) \quad (13)$$

where "θ" is ply orientation angle, and Q_{ij} is the stiffness coefficient, which is calculated using the following formulae:

$$Q_{11} = \frac{E_1}{1 - \mu_{12}\mu_{21}} \quad (14)$$

$$Q_{22} = \frac{E_1}{1 - \mu_{12}\mu_{22}} \quad (15)$$

$$Q_{12} = \frac{E_1\mu_{21}}{1 - \mu_{12}\mu_{21}} = \frac{E_1\mu_{12}}{1 - \mu_{12}\mu_{21}} \quad (16)$$

$$Q_{GG} = G_{12} \quad (17)$$

3.2. Deflection Curve of CSIP Thin-Wall Box-Beams

On the basis of the plane-section hypothesis of the girder theory, the bending problem is studied in a simply supported CSIP thin-wall box-beam under a uniformly distributed of load magnitude q. When the system is in equilibrium, the flexural rigidity of the CSIP thin-wall box-beam is calculated using Equation (18):

$$EI_y = \int E_x Z^2 dA \quad (18)$$

The CSIP thin-wall box-girder is made of an EPS foam core and glass–PP fiber sheets. Because the ply orientation angle and thickness of the glass–PP fiber layers are the same above and below the EPS foam, the laminate is called the symmetric laminate (Figure 2). And the flexural rigidity of the cross-section of the beam is obtained by

$$\overline{EI_y} = (E_x I_y)_1 + (E_x I_y)_2 \quad (19)$$

where $(E_x I_y)_1$ is the flexural rigidity of the girder flange, which is obtained by $(E_x I_y)_1 = \sum_{i=1}^{n} E_x^i I_x^i$ and $(E_x I_y)_2$ is the flexural rigidity of the beam web that is given as $(E_x I_y)_2 = \sum_{j=1}^{n} E_x^j I_x^j$.

For the CSIP thin-wall box-girder, its shearing modulus is very small; that is, from 1.9 Mpa to 2.2 Mpa. Therefore, effect of the shearing deformation should be considered in the thin-wall box beam design. The shearing modulus of the girder is obtained by

$$\overline{GA} = (GA)_1 + (GA)_2 \quad (20)$$

When a Timoshenko beam is subject to bending moment, owing to shear stress, the additional deflections y_1 and y_2 occur to the beam. Thus, the deformation curvature is given by

$$\frac{d^2y}{dx^2} = -\frac{1}{EI}(M + \frac{KEI}{AG})w \tag{21}$$

where K is the shear correction factor, A is the cross-section area, and G is the shear modulus.

In this study, the simply supported CSIP box-beam carried the uniformly distributed of load magnitude q (Figure 2), where L is the box-girder span. Thus, the shearing and moment of the cross-section of the beam are given as

$$w(x) = \frac{q}{2}(1 - 2x) \tag{22}$$

$$M(x) = \frac{qx}{2}(1 - x) \tag{23}$$

Substituting Equations (22) and (23) into Equation (21), the deflection curvature of the thin-wall box-beam is obtained by

$$W = \frac{q}{EI}(-\frac{Lx^3}{12} + \frac{x^4}{24} + \frac{L^3x}{24}) + \frac{kq}{2AG}(Lx - x^2) \tag{24}$$

where the mid-span deflection is maximum deflection ($W_{\max}$), which is obtained by

$$W_{\max} = \frac{5qL^4}{384EI} + \frac{3kqL^2}{8AG} \tag{25}$$

Because the shear rigidity of the EPS foam is very small, the effect of the EPS foam on shear resistance ability is not considered.

4. Comparison between the Result of the Theoretical and FE Analyses

4.1. FE Model

In this study, the FE model of the simply supported CSIP thin-wall box-beam is based on theory-deduced calculations. Thus, the FE analysis is studied in the CSIP thin-wall box-beam subjected to uniform load. The FE analysis was performed with the FE commercial package ANSYS 18.0. Table 3 describes the element types for the research.

Table 3. Element Type Model.

Material Type Element	ANSYS
Glass–PP fiber sheet faces, EPS foam core	Solide186
Contact	Conta174

In this study, a CSIP thin-wall beam is a laminated sandwich thin shell structure, so element type selects the shell181, which it behaves as a four-node element, one node has six degrees of freedom, and is applied to laminated modeling structures. On the other hand, the CSIP thin-wall beam is made of the glass–PP surfaces and the EPS foam cores, where the cores use the solider45 element as its element type, which behaves as an element with an 8 nodes, a node has three degrees of freedom. It is applied to plastic deformation and cracking. At the same time, the adhesive between glass–PP laminated layers and EPS foam core is glued together for the CSIP box-beam models. In this study, Tables 1 and 2 show separately the performance of the CSIP materials.

The CSIP thin-wall box girder was built by FE (Figure 3). The span of the girder is 600 mm, and its cross-section is a square of about 30 mm on a side. When the aspect ratio of the rectangular unit is close to 1, it is high-precision. In this study, the rectangular unit is taken as finite element model mesh. The FE beam model is describe in Figure 3.

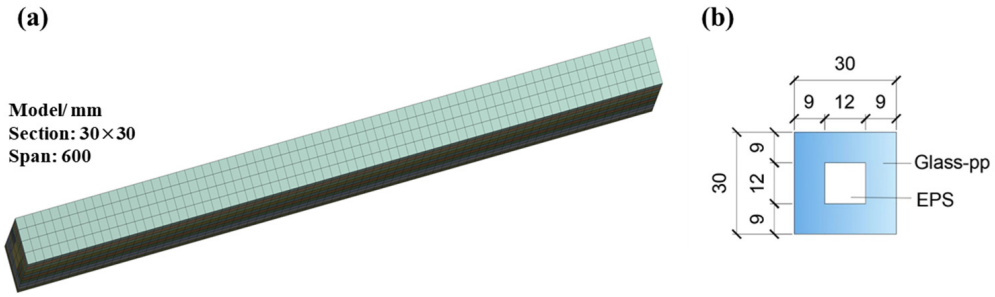


Figure 3. Diagram of the CSIP thin-wall box-beam (mm). (**a**) FE model. (**b**) Section of the beam.

4.2. FE Analysis

The CSIP thin-wall box-beam was subjected to the dead weight that is the uniform load, with a load intensity of 2.581 kN/m^2. In this study, the CSIP thin-wall box-beam is a simple supported beam. The boundary conditions of nodal points are as follows: where X = 0, all its deflections of nodal points are zero; where X = L, its X and Y deflections of nodal points are 0; and Z deflections of nodal points are free.

The stress distribution of each layer of the cross-section of CSIP thin-wall box-girder is shown in Figure 3. The maximum bending stress 6.76 MPa occurs in the outermost layer in a section of the middle of the span of the CSIP thin-wall box-girder. Further, the minimum bending stress exists at the neutral axis of ship section of the girder (Figure 4 and Table 4).

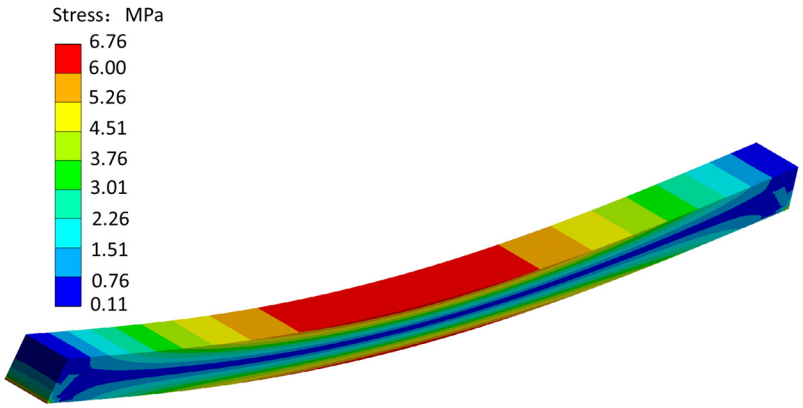


Figure 4. Stress of the CSIP thin-walled box-beam.

Figure 5 shows the total deformation of the CSIP thin-wall box-beam. The maximum deformation occurs at the mid-span of the CSIP thin-wall box-beam section, and its value is 0.83 mm. The FE results meet the requirements of the steel structure design code.

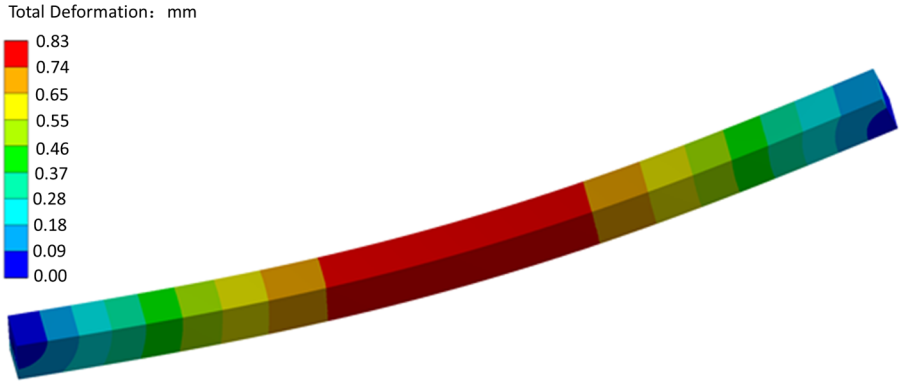


Figure 5. Total deformation of the CSIP thin-wall box-girder.

Table 4. Comparison of theoretical and FE results for the CSIP thin-wall box-beam.

E-Glass Sheets Stress of Mid-Span of Beam (Mpa)				
Section	**Fibrous Layer**	**Ansys**	**Theory**	**Error (%)**
$Flange_{top}$	first	−6.38	−5.93	7.50
	second	−5.53	−4.81	7.20
	third	−4.59	−4.29	7.00
	fourth	−4.14	−3.91	5.88
Web_{left}	first	3.59	−3.45	4.06
	second	−2.21	−2.35	5.60
	third	−1.59	−1.65	4.75
	fourth	−1.34	−0.91	3.64
	fifth	−0.20	−0.19	5.26
	sixth	1.34	0.91	3.64
	seventh	1.59	1.65	4.75
	eighth	2.21	2.35	5.60
	ninth	3.59	3.45	4.06
$Flange_{bottom}$	first	4.14	3.91	5.88
	second	4.59	4.29	7.00
	third	5.53	4.81	7.20
	fourth	6.38	5.93	7.50

A layer strain of the CSIP thin-wall box-girder is described in Figure 6. The maximum bending strain of 0.33 millimetres occurs the outermost layer in a section of the middle of span of the CSIP thin-wall box-girder. Meanwhile, the minimum bending strain exists at the neutral axis of that section of the girder. The strain values of each layer on the CSIP thin-wall box-beam are obtained (Figure 6 and Table 5).

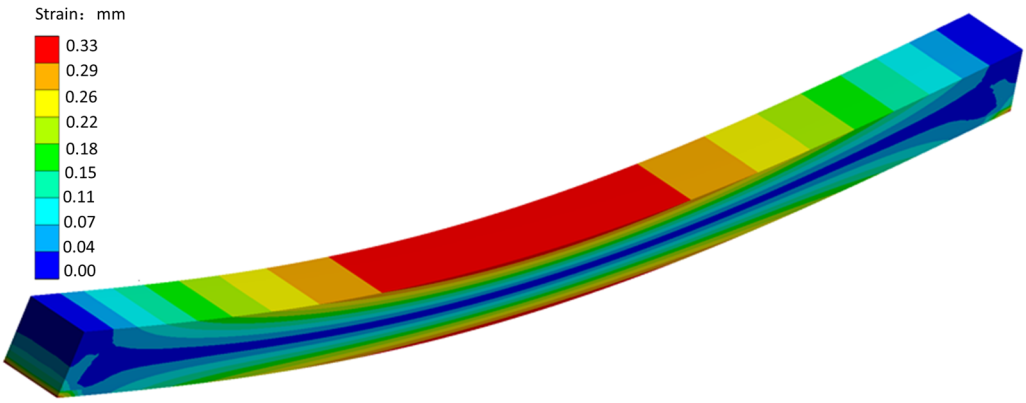


Figure 6. Strain of the CSIP thin-wall box-beam.

Table 5. Comparison of theoretical and FE solution for the CSIP thin-wall box-beam.

Deflection Mid-Span of Beam			
Deflection (mm)	**Ansys**	**Theory**	**Error (%)**
	0.83	0.836	0.7

4.3. Comparison of Theoretical and FE Results for the CSIP Thin-Wall Box-Beam

4.3.1. Comparison of Stress Theoretical and FE Results for the CSIP Beam

Table 4 shows the FE and theoretical stress values in the mid-span section of a simply supported CSIP thin-wall box-beam under uniform load. Table 4 shows that the FE results are generally consistent with the theoretical values. The error between the FE and the theoretical results is within 10%, where the maximum error is 7.5%. Thus, the theory results

are verified in terms of feasibility and reliability. The theory results meet the requirements of practical engineering.

4.3.2. Comparison of Theoretical and FE Results for the CSIP Beam

Based on Timoshenko's beam theory, the CSIP thin-wall box-beam is concerned with the bending problem. However, the influence on the shear deformation is ignored in the bending problem of the CSIP thin-wall box-beam. Its theoretical deformation model was presented on the basis of shearing deformation [Equation (24)]. The related theoretical results are compared with the FE solution, the maximum deflection is at the middle of the CSIP thin-wall box-gird span. Therefore, the mid-span deflection is the object of research. Table 5 shows the theoretical and FE mid-span deformation results.

The error of the total deformation between theoretical analysis and FE results is 0.7% (Table 5), thus the theory results of the total deformation are verified in terms of feasibility and reliability.

Meanwhile, the study results show that shearing deformation greatly affects the total deformation of the CSIP thin-walled box-beam. Therefore, shearing deformation should be considered in the engineering applications of the CSIP thin-walled box-beam. In addition, different strains of each E-glass layer are shown in Table 6, which contains the FE strain results and theory strain results.

Table 6. Comparison of theoretical and FE results for CSIP thin-wall box-beam.

E-Glass Sheets Strain of Mid-Span of Beam (mm)				
Section	**Fibrous Layer**	**Ansys**	**Theory**	**Error (%)**
$Flange_{top}$	first	−0.31	−0.322	3.72
	second	−0.28	−0.293	4.44
	third	−0.25	−0.263	4.94
	fourth	−0.20	−0.212	3.73
Web_{left}	first	−0.17	−0.181	5.56
	second	−0.13	−0.135	3.70
	third	−0.09	−0.089	1.12
	fourth	−0.06	−0.065	7.69
	fifth	−0.02	−0.021	4.76
	sixth	0.06	0.065	7.69
	seventh	0.09	0.089	1.12
	eighth	0.13	0.135	3.70
	ninth	0.17	0.181	5.56
$Flange_{bottom}$	first	0.20	0.212	3.73
	second	0.25	0.263	4.94
	third	0.28	0.293	4.44
	fourth	0.31	0.322	3.72

The errors between the theoretical and FE results are within 7.69%. The theory results meet requirements of the finite-element analysis values. Thus, the theory results for a CSIP thin-wall box-beam are feasible.

5. Conclusions

This study presents the theory model of a CSIP thin-wall box-beam, and the theory results are verified by the finite element method. The research findings are as follows:

1. The shear deformation is not ignorable in the CSIP thin-wall box-beam on bend problem. In this study, the deformation equations of the CSIP thin-wall box-beam considering the effects of the shear deformation are developed, and this model is verified by the numerical analysis. In addition, the effectiveness of the theorical method is certified.

2. The strain and stress expressions of the CSIP thin-wall box-beam for each E-glass layer are proposed based on Timoshenko's beam theory, and numerical simulations confirm the validity and correctness of the presented theory.
3. The bend theory of the CSIP thin-wall box-beam is presented for the first time. This theoretical model is built to improve the mechanical properties of the CSIP thin-wall box-beam by changing the value of the web width–thickness ratio.

In summary, the results of this study are very useful for the static and dynamic study of the CSIP thin-wall box-beam, and the theoretical deformation model of the CSIP thin-wall box-beam presented in this study may push the applications of CSIP as the main bearing members of civil engineering. Future research is required into nonlinear dynamic characteristics of the CSIP thin-wall box-beam.

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