Static Flexure of Soft Core Sandwich Beams using Trigonometric Shear Deformation Theory

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ABSTRACT

This study deals with the applications of a trigonometric shear deformation theory considering the effect of the transverse shear deformation on the static flexural analysis of the soft core sandwich beams. The theory gives realistic variation of the transverse shear stress through the thickness, and satisfies the transverse shear stress free conditions at the top and bottom surfaces of the beam. The theory does not require a problem-dependent shear correction factor. The governing differential equations and the associated boundary conditions of the present theory are obtained using the principle of the virtual work. The closed-form solutions for the beams with simply supported boundary conditions are obtained using Navier solution technique. Several types of sandwich beams are considered for the detailed numerical study. The axial displacement, transverse displacement, normal and transverse shear stresses are presented in a non-dimensional form and are compared with the previously published results. The transverse shear stress continuity is maintained at the layer interface, using the equilibrium equations of elasticity theory.

1. Introduction

Sandwich beam is a special form of laminated composite beam which has stiff face sheets and light weight but thick core. The modulus of the core material is significantly lower than that of the face sheets. The main benefit of using the sandwich concept in the structural components is its high bending stiffness and high strength to weight ratio. In addition, the sandwich constructions are much preferred to conventional materials because of their superior mechanical and durability properties. Due to these properties the composite sandwich structures have been widely used in the automotive, aerospace, marine and other industrial applications. Therefore, the analytical study of the sandwich beams becomes increasingly important.

Since the Classical Beam Theory (CBT) neglects the effect of the shear deformation and the First-order Shear Deformation Theory (FSDT) of Timoshenko [1] requires a shear correction factor, these theories are not suitable for the analysis of the laminated composite and the sandwich beams. These limitations of CBT and FSDT have led to the development of the Higher-order Shear Deformation theories (HSDTs) taking into account the effect of the transverse shear deformation, obviating the need of a shear correction factor.

The beam theories can be developed by expanding the displacements in power series of the coordinate normal to the neutral axis. In principle, the theories developed by this means can be made as accurate as desired simply by including the sufficient number of terms in the series. These higher-order theories are cumbersome and computationally more
demanding, because with an additional power of the thickness coordinate, an additional dependent variable is introduced into the theory. It has been noted by Lo et al. [2, 3] that due to the higher-order terms included in their theory, it has become inconvenient to use. This observation is more or less true for many other higher-order theories as well. Thus, there is a wide scope to develop a simple to use higher-order beam or plate theory.

Several theories have been proposed by researchers in the last two decades. Among many theories, some of the well-known theories are the parabolic shear deformation theories [4-5], the trigonometric shear deformation theory [6], the hyperbolic shear deformation theory [7] and the exponential shear deformation theory [8]. Recently, these theories are accounted into a unified shear deformation theory developed by Sayyad [9] and Sayyad et al. [10]. In accordance with Reddy’s third-order shear deformation theory, Sayyad [11] has developed the refined theories and applied them for the static and vibration analysis of the isotropic beams.


In the class of Trigonometric Shear Deformation Theories (TSDTs), the shear deformation is assumed to be trigonometric with respect to the thickness coordinate. These theories are accounted cosine distribution of transverse shear stress. The TSDTs are taking into account the kinematics of higher-order theories more effectively without loss of the physics of the problem. Some of the well-known articles on trigonometric theories are published by Touratier [6], Shimpi and Ghugal [20], Ghugal and Shinde [21], Arya et al. [22], Sayyad and Ghugal [23], Mantari et al. [24], Ferreira et al. [25], Zenkour [26] and Sayyad et al. [27]. Recently, Dahake and Ghugal [28, 29] and Ghugal and Dahake [30] have applied the trigonometric shear deformation theory for the bending analysis of the single-layer isotropic beams with various boundary conditions using general solution technique.

In the current study, a trigonometric shear deformation theory is applied for the bending analysis of the laminated composite and the soft core sandwich beams. The theory involves three unknowns. The theory satisfies the transverse shear stress free conditions at the top and bottom surfaces of the beam and does not require shear correction factor. The governing equations are obtained using the principle of the virtual work. The closed-form solutions for the beam with simply supported boundary conditions are obtained using Navier solution technique. The displacements and stresses of three different types of lamina scheme are obtained.

The exact elasticity solution for the three-layered (0⁰/90⁰/0⁰) laminated composite developed by Pagano [31] is used as a basis for the comparison of the present results. However, the exact elasticity solutions for the three-layered (0⁰/core/0⁰) and five-layered (0⁰/90⁰/core/90⁰/0⁰) sandwich beams are not available in the literature. Authors have generated the numerical results using FSDT of Timoshenko [1], HSDT of Reddy [5] and CBT being not available. It is found that the present results are in excellent agreement with those of HSDT, FSDT, CBT and exact elasticity solution.

2. Sandwich Beam under Consideration

Consider a beam of length ‘L’ along x direction, width ‘b’ along y direction and thickness ‘h’ along z direction. The coordinate system and geometry of the beam under consideration are shown in Fig. 1. The beam consists of the face sheets at the top and bottom surfaces and the middle portion is made up of a soft core.

The beam is bounded in the region 0 ≤ x ≤ L, -b/2 ≤ y ≤ b/2, -h/2 ≤ z ≤ h/2 in Cartesian coordinate system. u and w are the displacements in x and z directions, respectively.

![Figure 1. The beam geometry and the coordinate system](image-url)
2.1. The Assumptions made in the Theoretical Formulation

In the present equivalent single-layer trigonometric shear deformation theory, the theoretical formulation is based on the six following assumptions:

1) The axial displacement $u$ in $x$ direction consists of two parts including (a) a displacement component analogous to the displacement in the classical beam theory and (b) a displacement component due to the shear deformation which is assumed to be sinusoidal in nature with respect to the thickness coordinate.

2) The transverse displacement $w$ in the $z$ direction is assumed to be a function of the $x$ coordinate only.

3) The beam is made up of 'N' number of layers which are perfectly bonded together.

4) One dimensional Hook’s law is used.

5) The beam is subjected to the lateral load only.

6) The body forces are ignored.

2.2. The Kinematics of the Present Theory

Based on the above mentioned assumptions, the displacement field of the present trigonometric shear deformation theory is written as:

$$u(x, z) = u_0(x) - z w_0 + (h/\pi)(\sin \pi z) \phi(x)$$

$$w(x) = w_0(x)$$

where $u$ and $w$ are the displacements in $x$ and $z$ directions, respectively and $\pi z = z / h$ is the thickness coordinate. $u_0, \ w_0$ and $\phi$ are the unknown functions to be determined. The normal and shear strains obtained within the framework of the linear theory of elasticity are as follows:

$$\varepsilon_x = u_x = u_{0,x} - z w_{0,x} + f(z) \phi_x$$

$$\gamma_{xz} = w_z = g(\pi z) \phi$$

where

$$f(z) = (h/\pi) \sin(\pi z)$$

and $g(\pi z) = \cos(\pi z)$

$' , z$ represents the derivative with respect to $x$.

2.3. The constitutive relations

The normal and transverse shear stresses are obtained using one-dimensional constitutive relations. These relations for the $k$th layer of the beam are given by the following equations:

$$\sigma_x^k = Q_{11}^k \varepsilon_x + Q_{12}^k [u_{0,x} - z w_{0,x} + (h/\pi)(\sin \pi z) \phi_x]$$

$$\tau_{xz}^k = Q_{51}^k \gamma_{xz} = Q_{55}^k g(\pi z) \phi$$

where $Q_{11}^k$ and $Q_{55}^k$ are the stiffness coefficients of the $k$th layer of the beam and are defined as follows:

$$Q_{11}^k = E_{11}^k \quad \text{and} \quad Q_{55}^k = G_{13}^k$$

where $E_{11}^k$ is the Young’s modulus and $G_{13}^k$ is the shear modulus of $k$th layer of the beam.

3. Governing Equations and Boundary Conditions

In order to derive the governing equations, the principle of the virtual work is used.

$$b \int_0^{L/2} \left[ (\sigma_x \delta z + \tau_{xz} \delta \phi_x) dz dx - \int_0^L q(x) \delta w dx \right] = 0 \tag{5}$$

Using the expressions for strains from Eq. (2) and stresses from Eq. (4), the Eq. (5) can be written as:

$$b \int_0^{L/2} \left[ (u_{0,x} \delta u_{0,x} - z w_{0,x} \delta w_{0,x} + f(z) u_{0,x} \delta \phi_x)ight.$$ 

$$- z w_{0,x} \delta u_{0,x} + (h/\pi)(\sin \pi z) \phi_x \delta \phi_x +$$

$$f(z) \phi_x \delta u_{0,x} - z f(z) \phi_x \delta w_{0,x} + f(z) \phi_x \delta \phi_x \right] \delta z dx$$

$$+ b \int_0^{L/2} \left[ \int_0^L g(z) \phi \delta \phi dx dz - \int_0^L q \delta w dx \right] = 0 \tag{6}$$

Integrating Eq. (6) with respect to the $z$-direction, Eq. (6) can be simplified as:

$$\int_0^{L/2} \left[ \sum_{l=1}^{N} A_{ik} u_{ik,0} - B_{ik} u_{0,ik} + C_{ik} u_{0,ik} \delta \phi_x \right.$$ 

$$- B_{ik} w_{0,ik} + D_{ik} w_{0,ik} \delta w_{0,ik} - E_{ik} w_{0,ik} \delta \phi_x$$

$$+ C_{ik} \phi_x \delta u_{0,ik} - E_{ik} \phi_x \delta w_{0,ik} + F_{ik} \phi_x \delta \phi_x$$

$$+ G_{55} \phi \delta \phi - q \delta w \right] dx = 0$$

where $A_{ik}, B_{ik}$ etc. are the beam stiffnesses as defined below:

$$(A_{ik}, B_{ik}, C_{ik}) = b \sum_{l=1}^{N} \left[ \int_0^L (1, z, f(z)) dz, \right.$$

$$(D_{ik}, E_{ik}, F_{ik}) = b \sum_{l=1}^{N} \left[ \int_0^L (z^2, z f(z), f(z)^2) dz, \right.$$

$$G_{55} = b \sum_{l=1}^{N} \int_0^L g(z)^2 dz$$

Integrating Eq. (8) by the parts and setting the coefficients of $\delta u_{ik}, \delta w_{ik}$ and $\delta \phi$ equal to zero, we obtain the coupled Euler-Lagrange equations which are the governing differential equations and associated boundary conditions of the beam. The governing equations of the beam are as follow:

$$-A_{ik} u_{ik,0} + B_{ik} u_{0,ik} - C_{ik} \phi_x = 0 \tag{10}$$

$$-B_{ik} w_{0,ik} + D_{ik} w_{0,ik} \delta w_{0,ik} - E_{ik} w_{0,ik} \delta \phi_x = q(x) \tag{11}$$

$$-C_{ik} \phi_x \delta u_{0,ik} - E_{ik} \phi_x \delta w_{0,ik} + F_{ik} \phi_x \delta \phi_x + G_{55} \phi = 0 \tag{12}$$

The associated consistent natural boundary conditions at the ends $x = 0$ and $x = L$ are as follows:

$$N_x = 0 \quad \text{or} \quad u_0 \text{ is prescribed} \tag{13}$$

$$dM_x^t / dx = 0 \quad \text{or} \quad w_0 \text{ is prescribed} \tag{14}$$

$$M_x^t = 0 \quad \text{or} \quad w_{0,1} \text{ is prescribed} \tag{15}$$

$$M_x' = 0 \quad \text{or} \quad \phi \text{ is prescribed} \tag{16}$$

where the resultants $N_x, M_x', M_x^t$ are defined using the following equations:
\[ N_x = \int_{-h/2}^{+h/2} \sigma_x \, dz = A_0 u_{0,x} - B_{11} w_{0,xx} + C_1 \phi_x \]  
\[ M_x = \int_{-h/2}^{+h/2} \sigma_x z \, dz = B_{11} u_{0,x} - D_{11} w_{0,xx} + E_{11} \phi_x \]  
\[ M_x' = \int_{-h/2}^{+h/2} \sigma_x f(x) \, dz = C_1 u_{0,x} - E_{11} w_{0,xx} + F_{11} \phi_x \]  

Thus, the variationally consistent governing differential equations and boundary conditions are obtained.

4. A static Flexure of Sandwich Beam

The Navier solution satisfies the governing differential equation and boundary conditions when the beam is simply supported at the ends. Therefore, a static flexural analysis of the simply supported laminated composite and the soft core sandwich beams subjected to transverse distributed load has been carried out using Navier solution technique. According to this technique, the following solution form for unknown functions \( u_0 \), \( w_0 \) and \( \phi \) is assumed.

\[ u_0(x) = \sum_{n=1,3,5}^\infty u_m \cos \alpha x, \]
\[ w_0(x) = \sum_{n=1,3,5}^\infty w_m \sin \alpha x, \]  
\[ \phi(x) = \sum_{m=1,3,5}^\infty \phi_m \cos \alpha x \]

where \( \alpha = \pi \sqrt{m} / L \) and \( u_m \), \( w_m \) and \( \phi_m \) are the unknown Fourier coefficients to be determined for each \( m \) value. A beam of length \( L \) and thickness \( h \) is considered. The transverse load acting on the top surface of the beam is expanded in the following form:

\[ q(x) = \sum_{n=1,3,5}^\infty q_n \sin \alpha x: \text{Sinusoidal Load} \]  
\[ q(x) = \sum_{n=1,3,5}^\infty 4q_n \sin \alpha x: \text{Uniform Load} \]

where \( q_n \) is the maximum intensity of the load. Substituting the solution form from Eq. (20) and transverse load from Eqs. (21) and (22) into the three governing Eqs. (10)-(12), leads to the following set of simultaneous equations:

\[ (A_0 \alpha^2) u_m - (B_{11} \alpha^4) w_m + (C_1 \alpha^2) \phi_m = 0 \]  
\[ -(B_{11} \alpha^2) u_m + (D_{11} \alpha^4) w_m - (E_{11} \alpha^2) \phi_m = q_m \]  
\[ (C_1 \alpha^2) u_m - (E_{11} \alpha^2) w_m + (F_{11} \alpha^2 + G_{55}) \phi_m = 0 \]  

Eq. (23) can be solved to obtain the Fourier coefficients \( u_m \), \( w_m \) and \( \phi_m \). Further, the final expressions for displacements and stresses are obtained using Eqs. (1)-(4).

5. Illustrative Examples and Numerical Results

To prove the efficacy of the present theory, it is applied to the flexural analysis of the following examples on the laminated composite and soft core sandwich beams.

Example 1:

A static flexure of the three-layered (0°/90°/0°) laminated composite beams, as shown in Fig. 2 (a).

Example 2:

A static flexure of the three-layered (0°/core/0°) soft core sandwich beams, as shown in Fig. 2 (b).

Example 3:

A static flexure of the five-layered (0°/90°/core/90°/0°) soft core sandwich beams, as shown in Fig. 2 (c).

The following material properties are used in the above examples:

Example 1:

0° layer: \( Q_{11} = 25 \times 10^6 \) psi, \( Q_{55} = 0.5 \times 10^6 \) psi
90° layer: \( Q_{11} = 1.0 \times 10^6 \) psi, \( Q_{55} = 0.2 \times 10^6 \) psi

Examples 2 and 3:

Face sheets (0°): \( Q_{11} = 25 \times 10^6 \) psi, \( Q_{55} = 0.5 \times 10^6 \) psi
Face sheets (90°): \( Q_{11} = 1.0 \times 10^6 \) psi, \( Q_{55} = 0.2 \times 10^6 \) psi
Core: \( Q_{11} = 0.04 \times 10^6 \) psi, \( Q_{55} = 0.06 \times 10^6 \) psi.

The numerical results obtained for the displacements and stresses at the critical points are presented in the following non-dimensional form (Take \( E_3 = 1 \)).

\[ \bar{u}(0,-h/2) = \frac{u b E_3}{q_0 h}, \quad \bar{w}(L/2,0) = \frac{w 100 h^3 E_3}{q_0 a^2}, \]  
\[ \bar{\sigma}_{x}(0,-h/2) = \frac{\sigma_{x} b}{q_0}, \quad \bar{\tau}_{x}(0,0) = \frac{\tau_{x} b}{q_0}. \]

Example 1:

In this example, the bending response of the simply supported three-layered (0°/90°/0°) laminated composite beam is investigated as shown in Fig. 2 (a).
The detailed procedure to obtain this stress using equilibrium equation is given by Sayyad et al. [27]. The through thickness distributions of axial displacement, normal stress and transverse shear stress are shown in Figs. 3-5.

**Example 2:**

This example investigates the bending response of the three-layered (0°/core/0°) soft core sandwich beams as shown in Fig. 2 (b). The beam has thin top and bottom face sheets of thickness $0.1h$ each and thick core of thickness $0.8h$. The comparison of results for the beam subjected to the sinusoidal load is shown in Table 3.

**Table 3:** The comparison of the axial displacement ($u$), the transverse displacement ($w$), the normal stress ($\sigma_z$), and the transverse shear stress ($\tau_{xz}$), for the three-layered (0°/90°/0°) laminated composite beam subjected to the sinusoidal load

<table>
<thead>
<tr>
<th>$L/h$</th>
<th>Theory</th>
<th>$u$</th>
<th>$w$</th>
<th>$\sigma_z$</th>
<th>$\tau_{xz}$</th>
</tr>
</thead>
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<tr>
<td>10</td>
<td>Present</td>
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<td>0.6528</td>
<td>7786.5</td>
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<td></td>
<td>HSDT [5]</td>
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<td></td>
<td>FSDT [1]</td>
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</tr>
<tr>
<td></td>
<td>CBT</td>
<td>10368.6</td>
<td>0.6480</td>
<td>7776.7</td>
<td>68.387</td>
</tr>
<tr>
<td>4</td>
<td>Present</td>
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<td>1.108</td>
<td>85.68</td>
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<tr>
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<td>85.03</td>
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<td></td>
<td>FSDT [1]</td>
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<td>6.838</td>
</tr>
<tr>
<td></td>
<td>CBT</td>
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<td>0.648</td>
<td>77.76</td>
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</tr>
<tr>
<td>20</td>
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<td>3.143</td>
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<tr>
<td></td>
<td>FSDT [1]</td>
<td>0.663</td>
<td>2.991</td>
<td>12.44</td>
<td>2.735</td>
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<tr>
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<td>CBT</td>
<td>0.663</td>
<td>0.648</td>
<td>12.44</td>
<td>2.735</td>
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The detailed procedure to obtain this stress using equilibrium equation is given by Sayyad et al. [27]. The through thickness distributions of axial displacement, normal stress and transverse shear stress are shown in Figs. 3-5.
It is observed from the results that the present theory is in excellent agreement with HSDT to predict the bending response of soft core sandwich beams. The through thickness distributions of displacement and stresses are shown in Figs. 6-8.

**Example 3:**

In this example, the bending response of the five-layered (0°/90°/core/90°/0°) soft core sandwich beams is investigated as shown in Fig. 2 (c). The beam has two face sheets at the top and bottom and transversely flexible core at the center. The thickness of each face sheet is 0.05h each and thickness of core is 0.8h. The comparison of displacements and stresses for the beam subjected to the sinusoidal load is shown in Table 4 for various aspect ratios (L/h).

**Figure 3.** The through thickness variation of the axial displacement for the three-layered (0°/90°/0°) laminated composite beam subjected to the sinusoidal load

**Figure 4.** The through thickness variation of the normal stress for the three-layered (0°/90°/0°) laminated composite beam subjected to the sinusoidal load

**Figure 5.** The through thickness variation of the transverse shear stress for the three-layered (0°/90°/0°) laminated composite beam subjected to the sinusoidal load

**Figure 6.** The through thickness variation of the axial displacement for the three-layered (0°/core/0°) soft core sandwich beam subjected to the sinusoidal load

**Figure 7.** The through thickness variation of the normal stress for the three-layered (0°/core/0°) soft core sandwich beam subjected to the sinusoidal load
the normal stress (σ), for five-layered (0°/90°/core/90°/0°) soft core sandwich beam subjected to the sinusoidal load. The comparison of the axial displacement (u), the transverse displacement (w), the normal stress (σ), and the transverse shear stress (τz), for five-layered (0°/90°/core/90°/0°) soft core sandwich beam subjected to the sinusoidal load.

![Figure 8](image1.png)

**Figure 8.** The through thickness variation of the transverse shear stress for the three-layered (0°/core/0°) soft core sandwich beam subjected to the sinusoidal load.

**Table 4:** The comparison of the axial displacement (u), the transverse displacement (w), the normal stress (σ), and the transverse shear stress (τz), for five-layered (0°/90°/core/90°/0°) soft core sandwich beam subjected to the sinusoidal load.

<table>
<thead>
<tr>
<th>L/h</th>
<th>Theory</th>
<th>u</th>
<th>w</th>
<th>σ</th>
<th>τz</th>
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<tr>
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<tr>
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<tr>
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</table>

The results show that the axial displacement and stresses are increased with an increase in the aspect ratio, while the transverse displacement is decreased. Since an exact solution for this example is not available in the literature, the results of the present theory are compared with other theories and are found to agree well with each other. Table 5 shows the displacements and stresses for the five-layered soft core sandwich beams subjected to the uniform load. The through thickness distributions of the axial displacement, the normal stress and the transverse shear stress via equilibrium equation are shown in Figs. 9-11.

**6. Conclusions**

In this study, a trigonometric shear deformation theory has been presented for the bending analysis of the soft core sandwich beams. The theory is a displacement-based theory which includes the transverse shear deformation effect. The number of unknown variables is the same as that of the first-order shear deformation theory. The theory satisfies zero shear stress conditions on the top and bottom surfaces of the beam perfectly. Hence, the theory obviates the need for the shear correction factor.
From the numerical study and discussion it is concluded that the present theory is in an excellent agreement with other theories, while predicting the bending response of the laminated composite and soft core sandwich beams with transversely flexible core.

References


