



Methodology Article

# Influence of Core Compressibility, Flexibility and Transverse Shear Effects on the Response of Sandwich Structures

Koovapparambil Ramunny Pradeep<sup>1</sup>, Boggarappu Nageswara Rao<sup>2,\*</sup>,  
Sivakumar Madras Srinivasan<sup>3</sup>, Krishnan Balasubramaniam<sup>4</sup>, Sirajudeen Ahamed<sup>5</sup>

<sup>1</sup>Operational Launch Vehicle Team, Vikram Sarabhai Space Centre, Trivandrum, India

<sup>2</sup>Department of Mechanical Engineering, Koneru Lakshmaiah University, Green Fields, Vaddeswaram, Guntur, India

<sup>3</sup>Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai, India

<sup>4</sup>Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai, India

<sup>5</sup>Structural Design and Engineering Group, Vikram Sarabhai Space Centre, Trivandrum, India

## Email address:

kr\_pradeep@vssc.gov.in (K. R. Pradeep), bnrao52@rediffmail.com (B. N. Rao), mssiva@iitm.ac.in (S. M. Srinivasan),  
balas@iitm.ac.in (K. Balasubramaniam), s\_sirajudeen@vssc.gov.in (S. Ahamed)

\*Corresponding author

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**Abstract:** This paper examines the adequacy of first order shear deformation theory (FSDT) based layered shell finite element by comparing with 2D and 3D models without imposing any constraint on the deformation behaviour of core. The effect of core compressibility and transverse flexibility in the behaviour of sandwich beams are studied. Plane and 3D models are able to capture the higher order shear stress variation across the thickness of core, whereas classical models and layered models results in constant shear stress across the thickness of the core. Results of the finite element models indicate the necessity of shear correction factor for rigid core considering shear strain energy criteria or average shear strain criteria, whereas for soft core, the shear correction factor is unity ( $=1$ ).

**Keywords:** Sandwich Structures, Honeycomb Core, Skin, Finite Element Method, Zigzag Theory

## 1. Introduction

Sandwich structures composed of two thin, strong and stiff facing sheets (skin sheet) separated by a thick, lightweight core (Figure 1), are extensively used in aerospace industry due to their low density and high specific stiffness and strength. They are mainly designed for secondary structures such as payload adaptors; deck plates; heat shield; flight control surfaces include flaps, spoilers, ailerons, horizontal stabilisers, elevators, rudders, and winglets. The materials choice for skin sheet ranges from metallic isotropic to orthotropic composites with same or different thickness for top and bottom skins. The material choice for core ranges from transversely stiff metallic

honeycomb to flexible poly-urethane foam.

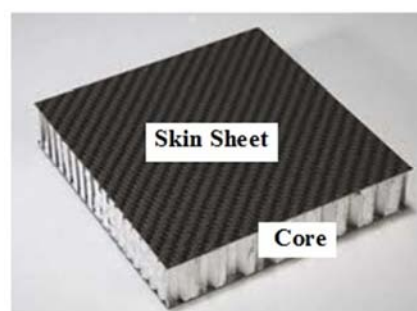


Figure 1. Sandwich Panel.

Finite element method (FEM) has been widely employed for analyzing sandwich structures. In early stages, sandwich structures are modelled using equivalent stiffness concept. Later on, they are modelled using 3D models and layered finite elements. Generic first order shear deformation theory (FSDT) based layered shell elements are widely used. Higher order effects such as core compressibility and transverse shear stress variation can be captured using planar or 3D models. Plantema [1], Allen [2], Zenkert [3] and Vinson [4] have made studies on the incompressible metallic honeycomb core. A quadratic transverse displacement field is required to capture the behaviour of sandwich with compressible core [5]. Finite elements with higher order transverse displacement formulations are proposed Bekuita [6] and Etemadi [7]. Schwarts-Givli *et al.* [8] have suggested a formulation for a delaminated unidirectional sandwich panels with soft-core accounting the transverse flexibility resulting in high-order displacement, acceleration, and velocity fields within the core. On the basis of core mechanical behavior, one has to adopt a suitable finite element model for sandwich construction [9].

Cook *et al.* [10] and Mathews [11] have provided generalised finite element formulation to carry out static and dynamic analyses of structures. Noor *et al.* [12] have made a review on the first order and higher order computational models of sandwich structures. Majority of sandwich finite elements use refinements of the classical lamination theory (CLT) with FSDT, whereas the higher order shear deformation models are based on ESL approach. Carrera and Brischetto [13] have made a comparison of sandwich structural analysis results of zig-zag and layer-wise models with those of equivalent single layer (ESL) model. A very few researchers have examined layer-wise theory accounting the transverse compressibility. Rikards [14] has carried out vibration and damping analysis of a sandwich composite beam and plate considering each layer as a simple Timoshenko beam or a Mindlin-Reissner plate element. Shell91 is a layered shell finite element based on CLT and FSDT, of ANSYS<sup>TM</sup> finite element analysis software, which has six degrees of freedom (3 translations and 3 rotations at each node).

### 1.1. Higher-Order Models

Higher-order shear deformation theories are introduced to capture the realistic variation of shear stress across the thickness [15, 16]. The finite element formulation of Liu [17] takes into account the parabolic distribution of the transverse shear deformation through the thickness of the plate.

### 1.2. Zigzag Theory Based Models

Kapurja and Kulkarni [18] have presented a four node quadrilateral element based on third-order zigzag theory. Singh *et al.* [19] have followed the refined higher order zigzag theory and presented a C0 continuous eight node isoparametric element with seven degrees of freedom without accounting the transverse compressibility of core. This element ensures shear free conditions at the top and bottom of the plate, cubic variation of the in-plane displacements and

interlaminar shear stress continuity at the layer interfaces.

### 1.3. Models with Core Compressibility

Very few finite element models can handle the analysis of the sandwich plate considering the effect of transverse normal deformation for the core. Noor and Burton [20, 21] have proposed a predictor-corrector approach for analysis of composite and sandwich plates. In the predictor phase, FSDT will be adopted for the in-plane stresses and initial estimates of the gross response characteristics of the plate (vibration frequencies, average through-the-thickness displacements and rotations). Later on, three-dimensional equilibrium equations and constitutive relations are used for evaluation of transverse shear and transverse normal stresses and strains; through-the-thickness strain energy density distributions; and posteriori estimates for the composite shear correction factors by equating the transverse shear strain energies (per unit area) from two- and three-dimensional models.

Leger and Chan [22] have developed a quasi-three-dimensional eight node isoparametric quadrilateral element having three degrees of freedom to evaluate interlaminar stresses in a composite laminate under combined loadings. Tanov and Tabiei [23] have suggested a method to evaluate transverse normal stress adopting a displacement based shear deformation shell theory. The in-plane stresses are evaluated using the constitutive relations of FSDT. The transverse normal stresses are evaluated from the three-dimensional equilibrium equations, which are found to be cubic in thickness ordinate.

Prandtl *et al.* [24] have developed a C0 finite element following the higher order zigzag theory and considering the effect of the transverse normal deformation of the core to carry out the analysis of laminated sandwich plate. The in-plane displacement field assumes a combination of the linear zigzag model with different slopes in each layer and a cubically varying function over the entire thickness. The out-of-plane displacement is quadratic within the core and constant throughout the faces. Normal and shear stresses of the core obtained are reasonably in agreement with 3D elasticity theory of Pagano *et al.* [25]. The C0 continuous 9 node isoparametric quadratic plate element of Chalak *et al.* [5] is developed based on zigzag theory having 11 field variables at each node accounting the in-plane rigidity and transverse compressibility of the core. Hua *et al.* [26] have presented a 1D finite element to carry out the global and local instability failure analysis of sandwich beam accounting transverse flexibility of core. Face sheets are modeled using classical laminate theory (CLT) ignoring the shear effects in the skins, whereas high order model for longitudinal and transverse displacement fields in the core.

### 1.4. Models with Standard Elements

Generic planar, shell and solid finite elements in commercial software packages are being used to model the sandwich structures and to validate the newly developed theoretical models. Rothschild *et al.* [27] have utilized a

four-node quadrilateral plane stress element to simulate four-point bending of sandwich beam having foam core. Their analysis results show good agreement for the central displacements with test results in the linear regime. Shiyang and Yao [28] have utilized 8 node planar elements and validated their solution with the exact solution of four-point bend sandwich beam. Kim and Swanson [29] have carried out the finite element analysis using 4-node quadrilateral plane stress elements for sandwich structures under concentrated loading. Their analysis results are found to be in good agreement with experimental results and recommended higher order theory for many practical problems.

Chamis et al. [30, 31] and, Elspass and Flemming [32] have carried out three-dimensional finite element analysis of sandwich panels with metallic honeycomb core and laminated composite face sheets. Pradeep and Rajagopal [33] have generated a three-dimensional finite element model for analyzing the sandwich panel with metallic skin under differential heating conditions. Pradeep et al. [34] have used 3D shell element for modelling and solved the problem of three-point sandwich beam under bending. Xu and Qiao [35] have proposed a constitutive modeling of honeycomb sandwich considering skin effect by applying homogenization theory to periodic plates using transverse shear deformation

theory. They have used 2-D unit cell homogenization procedure and employed a geometry-to-material transformation following Ashby and Gibson [36]. Flexural and stretch stiffness of honeycomb are evaluated and verified from the FE analysis of regular honeycomb cell using general shell elements.

Kardomateasa et al. [37] have used 8 node brick element of ABACUS and DYNA 3D and predicted buckling load of a sandwich cantilever column. Ramtekkar et al. [38] have developed an eighteen node solid finite element and evaluated transverse shear stresses in sandwich composites. Rezaeifard et al. [39] demonstrated elastic-plastic behaviour of the core by a bilinear constitutive relation of the shear stress. Khandelwal et al. [40] have evaluated transverse stresses in soft-core sandwich laminates using a displacement-based  $C^0$  continuous 2D FE model derived from refined higher-order shear deformation theory (RHSST) and a least square error (LSE) method. Various theories and modeling techniques for the analysis of sandwich structures are focused on two elastic responses of core, viz., core compressibility and higher order transverse shear variation. Table 1 presents a summary of various finite element modeling techniques of sandwich structures.

**Table 1.** Summary of techniques on finite element modeling of sandwich structures.

S. No.	Finite element modeling techniques	Remarks
1	Homogenous shell element [23, 28]	Simple efficient for general analysis. Transverse compressibility is neglected.
2	Layered shell element with shear deflection [15, 16, 24]	Layer-wise computationally efficient. Transverse compressibility is ignored.
3	Plane stress/plane strain modeling of sandwich cross section [27, 29]	Applicable to plane strain and axi-symmetric problems.
4	Plane element for the core and beam element for skin [9]	Skin is idealized by Bernoulli beam element.
5	Solid-brick (core) and shell (skin) elements [41, 42]	Limited to small size problems.
6	Solid-brick (core) and solid-brick (skin) [23, 37]	Computationally expensive.
7	3D model with general shell elements [34, 35].	No restriction on core kinematics.
8	Layer-wise models [39,40, 43, 44]	Core compressibility is accounted.

Sandwich composites are process dependent bonded structures, which are prone to skin- core detachment due to manufacturing defects or due to in-service loads. The influence of such debonds is examined through modelling, detection and fracture analysis of sandwich structures by several researchers as indicated in [45-50]. It is noted that computationally efficient models as well as the interface fracture parameters are required for simulation of debonded structures.

### 1.5. Objective of the Present Study

Motivated by the work of the above researchers, studies are made to examine the effect of core compressibility and transverse flexibility in the sandwich beam. The adequacy of FSDT based layered shell element is examined through comparison of results from 2D and 3D models without imposing any constraint on the core deformation.

## 2. Response of Sandwich Structures

Layer-wise and higher order ESL based models are currently unavailable in commercial finite element software packages. Two case studies are made on sandwich three- point bend beam (Beam with a point/line load within the span and span supporting points close to the ends of the beam-Figure-2). First is to examine the influence of the core compressibility in global response such as displacements and stresses. The second case study is to capture the variation of transverse shear stress within the core.  $u_y$  and  $u_z$  displacements are zero at supports and a line load of 1kN is applied at the center of the span. In the first case, core modulus ( $E_c$ ) is varied from 10 to 400MPa, whereas in the second case, core thickness ( $t_c$ ) is varied from 2.75 to 30.25mm keeping modulus of core  $E_c=400$ MPa.

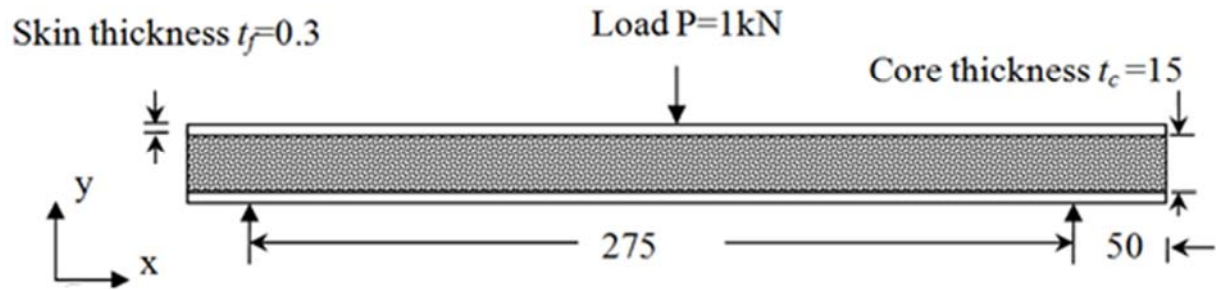


Figure 2. Configuration of the simply supported beam (Beam width=50mm) with a line load at the centre of span (Units in mm).

Five models (three finite element models and two theoretical models) are described in Table 2 having varying capability in capturing of core compressibility and transverse shear variations.

Table 2. Five models for evaluation of the core compressibility.

Model No	Description	Core model	Details
I	2D Plane finite element	Compressible (2D elastic medium)	2D model with a plane strain assumption along the width (see Figure-3). Nodes-3470, Elements- 882.
II	Solid finite element	Compressible (3D elastic medium)	3D geometry of the beam is simulated (see Figure-4). Nodes-51170, Elements-8820.
III	Layered shell finite element based on CLT and FSDT	Incompressible	2D model using layered shell element considering the mid-surface of the beam Figure-5). Nodes-2453, Element-760.
IV	Classical sandwich theory (rigid).	Incompressible, rigid.	Full expression of bending stiffness is considered.
V	Classical sandwich theory (flexible)	Incompressible, flexible	In-plane modulus of core $E_{cx, y}=0$

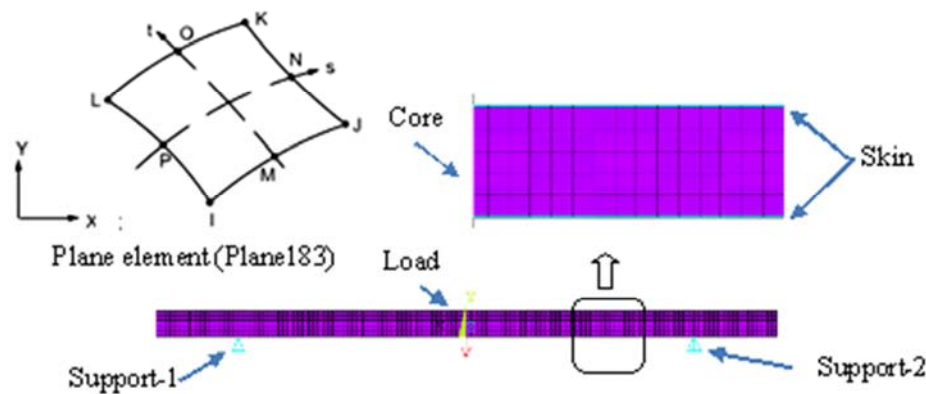


Figure 3. Planar finite element model of sandwich beam using quadratic 8 node plane element (plane 183, ANSYS) having two dof ( $u_x$  and  $u_y$ ).

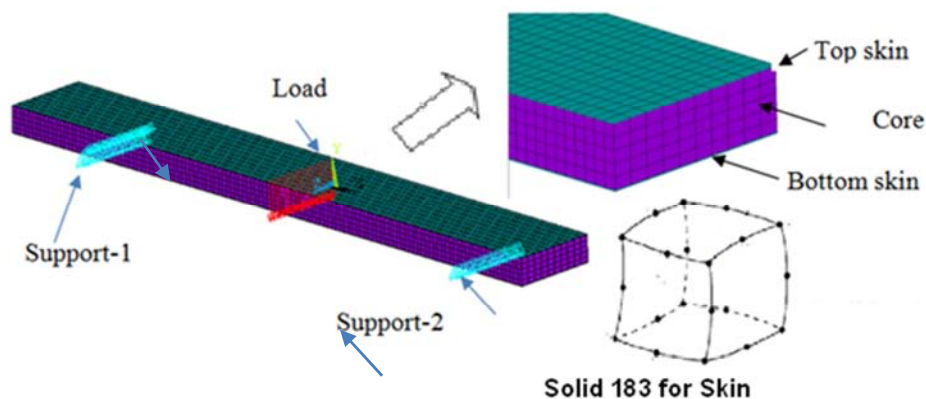
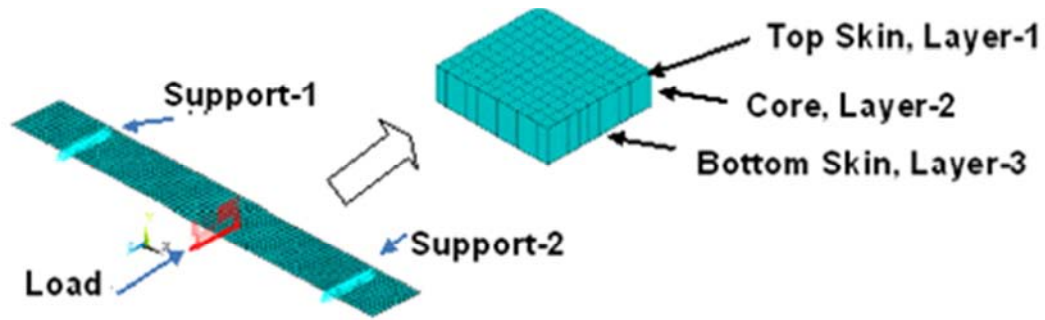


Figure 4. Model of the sandwich beam with quadratic 20node solid finite element (Solid 183, ANSYS) having three dof. Core and skin layer are defined with different material properties.



**Figure 5.** Equivalent single layered model using CLT-FSDT based quadratic 8 node layered shell element (shell91, ANSYS) having six dof.

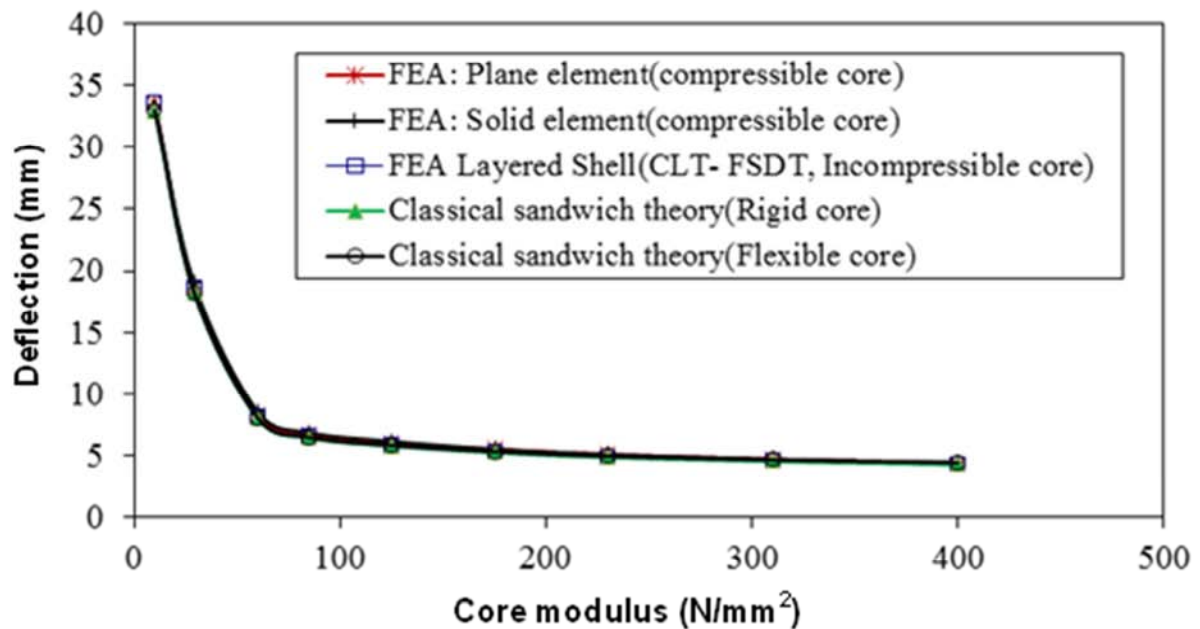
The influence of core compressibility is examined by analyzing 9 different soft cores whose properties are given in Table 3, whereas Table 4 gives properties of Aluminium AA2014-T6 skin having thickness of 0.3mm.

**Table 3.** Properties of core materials [3] used for the modeling and analysis of sandwich beam for the case study-1 (Influence of core material in deformation and stresses). Case study -2 uses material property case no.9 of this table with thickness ranging from 2.75mm to 30.25mm.

Case No.	Type of Core	Core elastic modulus $E_c$ (N/mm <sup>2</sup> )	Shear Modulus $G_c$ (N/mm <sup>2</sup> )	Density $\rho_c$ (kg/m <sup>3</sup> )
1	PUR foam Core	10	3	30
2	Extruded PS foam	29	6	45
3		60	20	60
4		85	31	80
5	PVC foam	125	40	100
6		175	52	130
7		230	66	160
8		310	85	200
9		400	108	250

**Table 4.** Properties of AA2014 skin sheet for a sandwich beam.

Young's Modulus $E_f$ (N/mm <sup>2</sup> )	Poisson's ratio $\nu$	Density $\rho_f$ (kg/m <sup>3</sup> )
68670	0.3	2800



**Figure 6.** Central deflection of the beam with core elastic modulus.

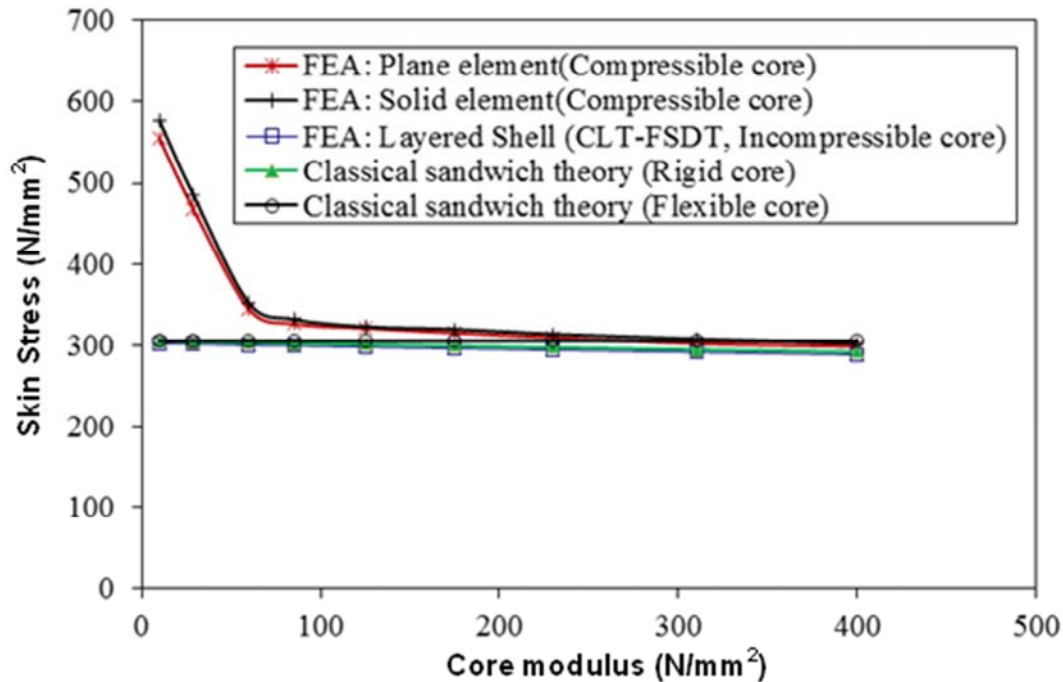


Figure 7. In-plane tensile stress with core elastic modulus in bottom skin at the middle span of the beam.

### 2.1. Influence of Core Compressibility

The central deflection of the beam obtained from classical sandwich theory and different finite element models are in close agreement (Figure 6). The in-plane stress at the bottom skin evaluated at mid-span is shown in Figure 7. In the case of very soft core with elastic modulus below 100MPa,

substantial increase in the skin stress is observed. This shows a local bending of bottom skin due to the soft core. For high core modulus, negligible difference is noticed in the central deflection computed using the classical theory and the finite element models.

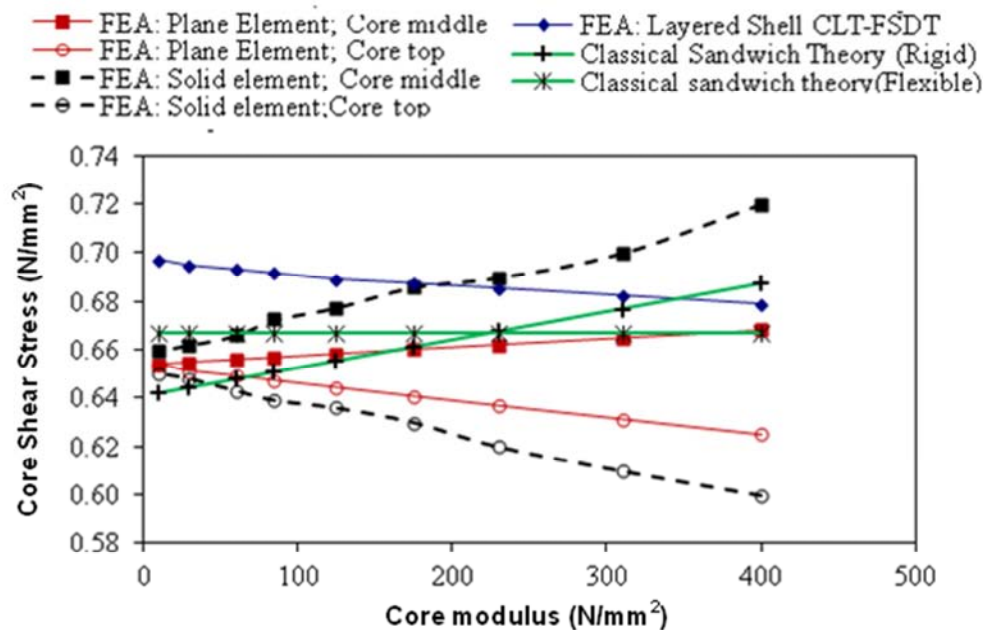


Figure 8. Core shear stress with core modulus at quarter span of the beam.

Core shear stress evaluated from classical models and finite element models are shown in Figure 8. Plane model and 3D model are able to capture the higher order shear stress

variation across the thickness of core, whereas classical models consider a constant shear stress in the core. As the core modulus reduces, the difference between the shear stress in



core top and middle reduces. This justifies the assumption of constant shear stress across the depth for anti-plane/flexible core. For the stiff core (towards  $E_c=400\text{MPa}$ ) shear stress shows a maximum variation between centre and top side of the core. This indicates that the core with higher in-plane stiffness need to be analysed with higher order shear deformation theories. It is to be noted that the shear stress obtained from simplified models are within an acceptable limit compared to the complex 3D models from designer's point of view. For the case of low modulus core/soft core, the shear stress is constant throughout the core depth. The plane model and solid element models are efficient in capturing the transverse shear stress

variation across the depth. The shear stress variation observed with stiff core sandwich may be significant for the case of high core thickness.

## 2.2. Variation of Transverse Shear Stress

To examine the influence of the core depth in the core shear stress distribution, the stiff core having  $E_c = 400\text{MPa}$  is considered by varying the core depth from 2.75 to 30.25mm without changing other parameters. All models show close agreement in the central deflection of the beam in (see Figure 9).

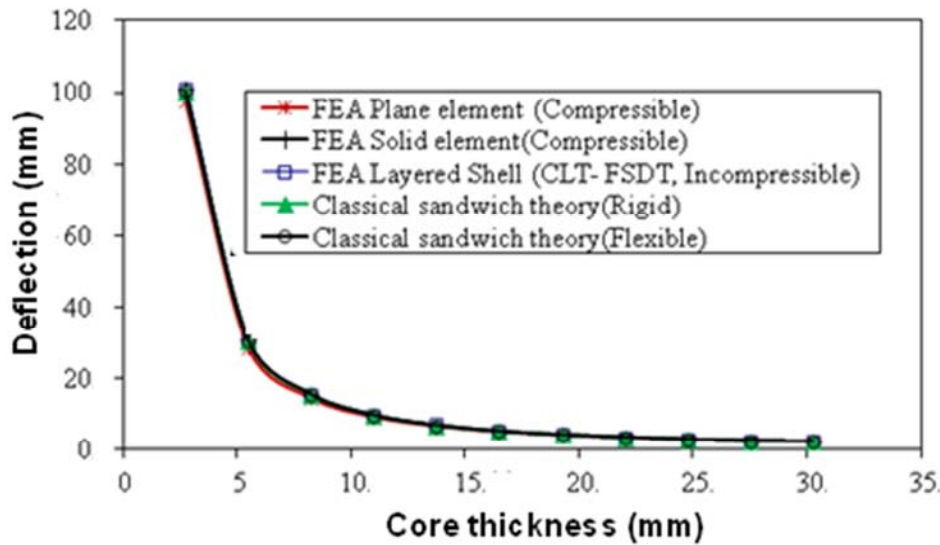


Figure 9. Central deflection of the beam with core thicknesses.

In-plane stress in the skin and transverse shear stress in the core are shown in Figures 10 and 11 respectively. Transverse shear stress distribution obtained from planar finite element analysis is shown in Figure 12. The model clearly captures the

higher order distribution of transverse shear stress. 3D model of the beam shows that transverse shear stress is slightly higher towards edge than the middle of the beam (See Figure 13), whereas the planar model unable to capture the trend.

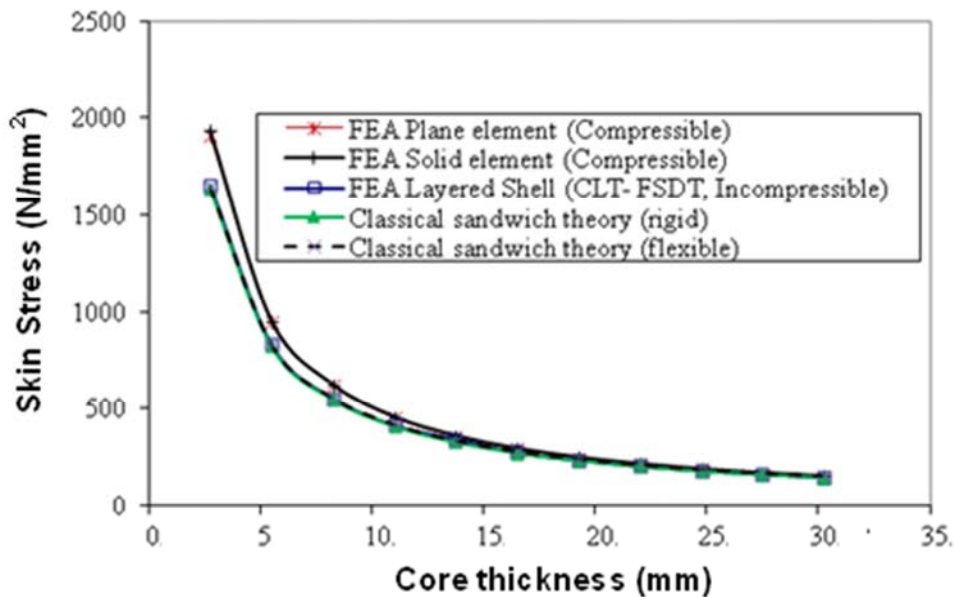


Figure 10. In-plane skin stress with core depth in bottom skin at middle span of the beam.

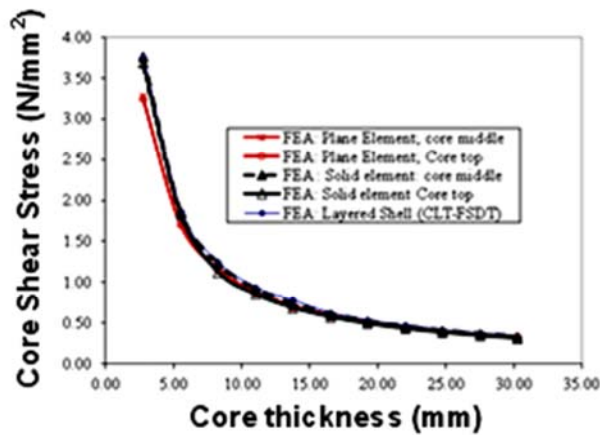


Figure 11. Core shear stress with core depth at quarter span of the beam.

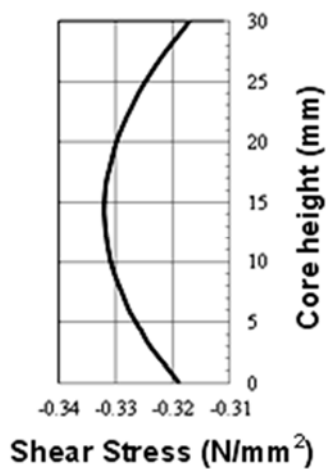


Figure 12. Transverse shear stress in the core.

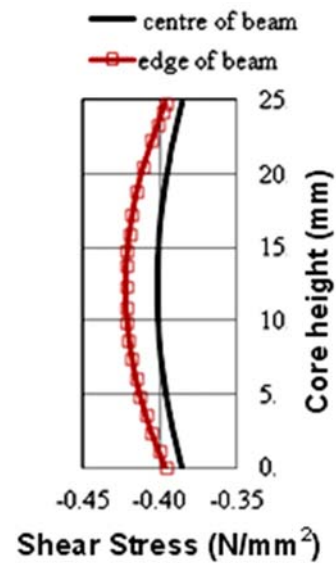


Figure 13. Transverse shear stress in the 24.75mm thick core indicating high stress at the core edges when compared to the interior portion.

It is noted from the above studies that 2D layered shell model is efficient in capturing the global deformation and stresses except for very soft core having  $E_c$  below 100MPa. Soft core with lower thickness shows deviation from the classical theories for the skin stresses. This is due to the interaction of top and bottom skins at loading location for the lower core thickness.

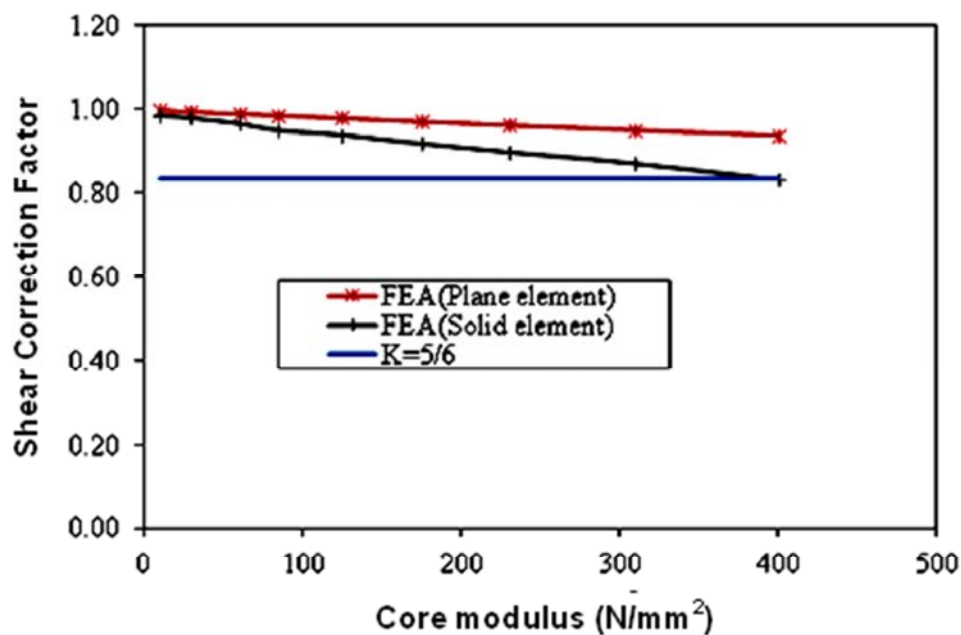


Figure 14. Shear correction factor with core modulus.



Shear correction factor evaluation is carried out from the finite element analysis results by considering the ratio of shear stress at top and middle of the sandwich core. Figure 14 shows the variation of shear correction factor with core Young's modulus. Solid model provides the shear correction factor ( $k$ ) close to  $5/6$  for a rigid core having Young's modulus  $E=400\text{MPa}$ . In the case of soft core symmetric sandwich structure,  $k$  value reaches unity.

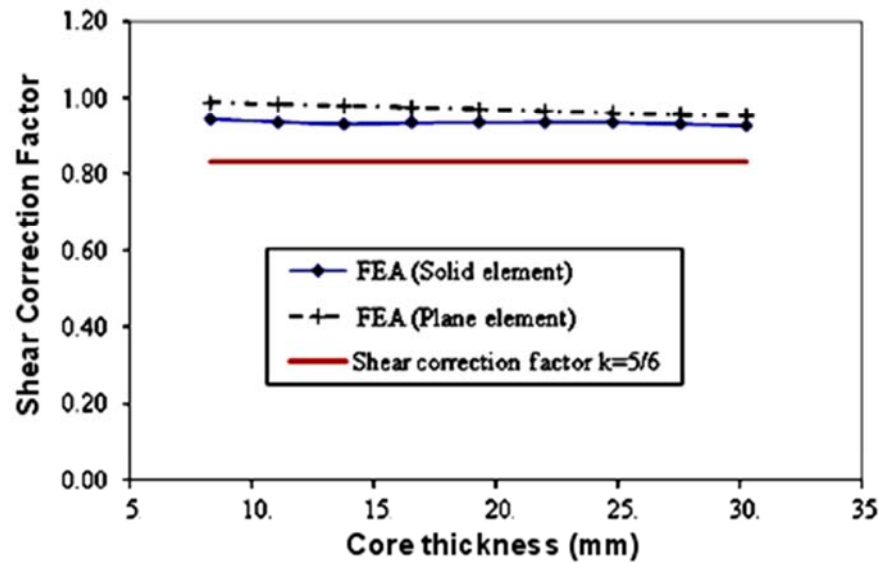


Figure 15. Shear correction factor with core thickness.

Figure 15 shows the variation of shear correction factor with core thickness. As expected shear correction factor reduces with increasing core thickness. Results indicate that  $k$  is equal to unity for soft core, whereas for the case of rigid core, it should be evaluated considering shear strain energy criteria or average shear strain criteria.

### 3. Concluding Remarks

Finite element analysis has been carried out on three-point sandwich beam to examine the influence of core compressibility, flexibility and transverses shear by varying core modulus and thickness. Global deformation and stress levels obtained from layered element analysis and classical sandwich theory are in good agreement with higher order models except for the case of a very soft core. In terms of modeling and computational complexity, solid element and plane element models are prohibitive, whereas layered element is superior.

FSDT based layered element fails to give the distribution of shear stress across the thickness as the formulation assumes that the shear stress within the layer is constant. But plane and 3D models captures local stress concentration at loading point/supports; local deformation of skin sheet; transverse shear distribution across the thickness of core; and transverse normal stresses in the core. Plane and 3D models have no such limitation with respect to the local stresses, deformation and transverse shear stress as observed FSDT based models. For a sandwich with aluminium skin and the low modulus core ( $E_c < 80\text{MPa}$ ), it is fairly accurate to assume constant shear stress across the depth. For stiff core ( $E_c > 100\text{MPa}$ ), deformation and stresses have a close agreement between the layered

models and 3D solid or planar models. Aerospace industry prefers honeycomb type core having low modulus in the in-plane direction and transversely stiff with core modulus above  $1000\text{MPa}$ . For such cores, layered models are recommended.

Sandwich panels of aerospace industry have support locations/loading points, which are made rigid by using special solid inserts. Thus the effects due to concentrated load on soft core can be reduced to a greater extent. Shear stress variation across the thickness for the stiff core is insignificant. From the designers of point of view, detailed 3D or planar finite analysis may not provide any added advantage. In the design and analysis of sandwich structures, global response can be obtained using layered shell element and local analysis can be carried out using three-dimensional or planar models.

Global responses from the classical sandwich models and FSDT based layered element models are in good agreement with those of 3D and planar models. For the case of soft core/flexible core, it is fairly accurate to assume constant shear across the thickness, whereas for the case of rigid core, higher order distribution is to be considered. Thus, it is concluded that the computational model for sandwich structure shall be selected based on the kinematic behaviour of core and skin. For health monitoring of aerospace structures, computationally efficient models are required for simulation of de-bonded sandwich structures to extract the global response signature and interface fracture parameters.

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