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Research Article

Thermo-Mechanical Analysis of Laminated Composite Sandwich Plates Under Combined Thermal and Mechanical Loading

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finite element analysis

Abstract:

This work presents a set of refined shear deformation plate theories that also account for transverse normal deformation, aimed at performing thermo-mechanical analysis of laminated composite and sandwich plates. Conventional plate models (Kirchhoff, Mindlin) often fall short when the structure is multilayered and is subjected to thermal gradients together with mechanical loads, so a more detailed formulation is needed. To address this, a finite element model was built in ABAQUS and used to study bending behaviour, stress transfer through the thickness, and the overall response of sandwich plates with different stacking sequences and core types. The motivation behind the study is the use of such advanced modelling to support the design of climate-responsive, temporary housing panels intended for post-disaster situations. The analyses show that changing the core material—whether honeycomb, polymer foam or balsa—leads to clearly different stiffness and stress patterns, and that the plate aspect ratio plays a major role in the observed deflections. The numerical results were compared with well-known solutions from the literature to check their reliability.

1. Introduction

Laminated sandwich plates represent advanced structural elements characterized by their multi-layered configuration consisting of two stiff, thin face sheets separated by a lightweight core. This design achieves an excellent balance of mechanical performance and weight reduction, making them ideal for applications requiring high strength-to-weight ratios. The face sheets, typically made of high-strength materials such as metals or fiber-reinforced composites, resist tensile and compressive stresses caused by bending loads. Meanwhile, the core, often composed of low-density materials such as honeycomb, foam, or balsa wood, provides shear rigidity, thermal insulation, and energy absorption capabilities.

The application of sandwich structures spans diverse engineering fields including aerospace, marine, automotive, civil engineering, renewable energy, defence, and industrial applications. In civil engineering particularly, these structures offer promising solutions for rapid construction. Laminated sandwich plates are a class of high-performance structural members made up of two thin, stiff faces separated by a relatively thick, lightweight core. This layered arrangement allows the element to carry bending and in-plane loads through the face sheets, while the core maintains the spacing between them and carries most of the shear. Because of this division of functions, sandwich plates can provide very good stiffness and strength for a much lower weight than a solid plate made from the same material. In most cases, the faces are produced from metals or fibre-reinforced polymer (FRP) laminates so that they can resist the tensile and compressive stresses generated by bending. The core, on the other hand, is usually made from a low-density material—honeycomb, polymer foam, or even balsa—so that it can supply shear rigidity, thermal insulation, and a certain level of impact/energy absorption without adding much mass.

Owing to these characteristics, sandwich constructions are now found in many sectors: aircraft and marine panels, automotive body parts, wind turbine blades, building envelopes, defence equipment, and a wide range of industrial

components. For civil engineering in particular, they are attractive for fast-track or modular systems—temporary shelters, emergency housing for post-disaster rehabilitation, demountable building panels—where light weight, good thermal performance, and ease of erection are all required at once. Typical advantages reported for such plates include a high strength-to-weight ratio, good thermal behaviour, improved specific stiffness, resistance to corrosion (for FRP faces), geometric and material design flexibility, and relatively simple on-site assembly.

However, the same multi-layered nature that gives these benefits also introduces some difficulties. Manufacturing may be more involved than for monolithic plates; poor bonding can lead to face–core debonding or delamination; some cores have limited through-thickness strength; costs of high-quality core and FRP materials can be significant; and repairs after impact or local crushing are not always straightforward. Differences in thermal expansion between the faces and the core can also create additional stresses. As a result, an accurate prediction of their behaviour often requires higher-order analytical models or detailed numerical simulations rather than classical plate theory.

A substantial amount of research has therefore focused on modelling laminated and sandwich elements. Cheng (2011), for example, analysed elastic critical loads for plane frames using the transfer-matrix approach. Earlier, Reddy (1984) proposed a refined nonlinear shear deformation plate theory in which the in-plane displacements vary cubically through the thickness and the traction-free boundary conditions on the plate surfaces are satisfied. Kant and Pandya (1988) later introduced a straightforward isoparametric higher-order formulation applicable to unsymmetrically laminated composite plates, which was able to recover transverse shear and normal stresses directly from equilibrium. More recent survey papers by Ghugal and Shimpi (2001) and by Sayyad and Ghugal (2017) traced how plate and beam theories have evolved from classical (Kirchhoff/Mindlin-type) models to layer-wise and other refined shear deformation theories capable of reproducing the actual interlaminar stress distribution in anisotropic, multi-layer systems.

2. Theoretical Background and Literature Review

2.1 Overview of Plate Theories

2.1.1 Classical Plate Theory (CPT):

In CPT the plate is treated as very thin, so the effect of transverse shear is ignored. Following Kirchhoff's assumption, a line that is normal to the mid-surface before deformation is assumed to stay straight and exactly perpendicular to that surface afterward. This works well for slender plates and small deflections, but it becomes unreliable when the plate is relatively thick or when the material is layered, because in those cases shear strains through the thickness are no longer negligible.

2.1.2 First-Order Shear Deformation Theory (FSDT):

The Mindlin–Reissner formulation relaxes the strict Kirchhoff condition and allows the normal to the mid-surface to rotate, so transverse shear deformation is included. Because the actual shear stress varies through the thickness, the theory introduces shear correction factors to obtain realistic shear forces. FSDT is therefore more accurate than CPT for moderately thick plates, but the dependence on empirical correction factors is a limitation.

2.1.3 Higher-Order Shear Deformation Theory (HSDT):

Higher-order models extend the displacement field with additional terms so that the shear strain can vary in a nonlinear manner through the thickness. In this way, the correct zero-shear condition at the plate surfaces is satisfied automatically, and no shear correction factor is needed. Such theories are well suited to thick, layered, or sandwich plates and to problems involving strongly anisotropic laminates, where an accurate representation of the interlaminar stresses is essential.

2.2 Limitations of Classical Theories

2.2.1 Neglect of shear deformation:

Classical plate formulations omit transverse shear strains, which is acceptable for very thin plates but not for thick or sandwich-type elements. As a result, they tend to underestimate deflection, mispredict stress resultants, and give non-conservative natural frequency estimates when the thickness is not small.

2.2.2 Unsuitability for composite laminates:

The basic assumptions in classical theories were derived for isotropic, single-material plates. They do not reflect the strongly directional and layer-dependent behaviour of fibre-reinforced composites, where stiffness and thermal properties vary from ply to ply.

2.2.3 No layer-wise stress prediction:

Because the theory treats the plate as an equivalent single layer, it cannot resolve stresses and strains in

each individual lamina. This makes it inadequate for interlaminar stress evaluation, debonding studies, or failure analysis in laminated and sandwich constructions.

2.3 Recent Developments

Aydogdu (2009) proposed a new higher-order shear deformation theory constructed from three-dimensional elasticity bending solutions using an inverse method, exactly satisfying stress boundary conditions on plate surfaces. Soldatos and Watson (1997) developed a method for substantially improving stress analysis performance of higher-order plate theories for laminated composite elements.

Khdeir (1988) developed an exact mathematical tool based on generalized Levy-type solution with state space concept to analyze free vibration and buckling of symmetric cross-ply laminated plates. Srinivas and Rao (1970) presented a unified three-dimensional elasticity solution for bending, vibration, and buckling of simply supported thick orthotropic rectangular plates and laminates. Kumar et al. (2017) employed smoothed finite element technique with edge-based method (ES-FEM) for linear and nonlinear analyses of shear deformable quadrilateral plates. Thai and Choi (2013) proposed a simple first-order shear deformation theory containing only four unknowns with strong similarities to classical plate theory, achieving accuracy comparable to existing theories with greater computational efficiency. Di Sciuva (1992) developed a non-linear third-order shear deformation plate theory accounting for continuous interlaminar transverse shearing stresses, demonstrating excellent agreement with three-dimensional elasticity solutions.

Recent studies have applied advanced modeling techniques to address the bending, buckling, and vibration behavior of laminated and sandwich composite structures under combined thermal and mechanical loading, particularly in aerospace settings. Wang et al. (2024) applied a Nitsche-based isogeometric framework to study plates with openings subjected to thermal loading. Qian et al. (2023) examined the behaviour of carbon nanotube–reinforced sandwich plates exposed to combined mechanical and thermal actions. Nejati et al. (2022) investigated the coupled thermo-mechanical performance of shape memory alloy (SMA) hybrid sandwich beams. Zang et al. (2025) carried out a vibration study on laminated components with holes intended for use in electric aircraft structures, while Ahmed et al. (2024) leveraged machine learning models to forecast the buckling response of composite laminates.

3. Problem Statement

Classical plate formulations do not adequately describe the behaviour of laminated composite and sandwich panels when the problem involves:

- transverse normal deformation in multi-layer assemblies,
- temperature gradients combined with simultaneous in-plane and out-of-plane actions,
- buckling under uniform edge compression, and
- the need for analysis platforms that can embed refined shear deformation theories for coupled thermo-mechanical loading.

Because of these limitations, engineers still encounter difficulties when trying to design lightweight but dependable components for sectors such as aerospace, civil infrastructure, and marine structures. The present work tackles these issues by formulating advanced shear deformation models tailored for laminated and sandwich plates, implementing them in computational routines for detailed numerical studies, benchmarking the predictions against available exact or high-fidelity solutions, and finally demonstrating their practical use in the design of prefabricated, climate-responsive temporary shelters for post-disaster deployment.

4. Research Objectives

The main aims of this study are to:

1. Formulate refined shear deformation plate theories that also include transverse normal deformation, specifically for laminated composite and sandwich configurations.
2. Perform linear analyses of these plates under different combinations of thermal and mechanical loading.
3. Develop the necessary computational routines/coding to carry out numerical investigations in ABAQUS.
4. Check and validate the numerical results by comparing them with exact or benchmark solutions reported in the literature.

5. Methodology

5.1 Theoretical Development

The methodology begins with the development of refined shear deformation models that include both transverse shear and transverse normal effects. On this basis, the governing equations for bending, buckling, and free vibration are derived and then generalized to thermo-mechanical loading. The

formulation is set up to handle different thermal fields (uniform, linear through the thickness, or gradient-type) together with mechanical actions such as in-plane compression, lateral pressure, or combined loading, so that the full structural response of laminated and sandwich plates can be evaluated.

5.2 Element Consideration

Geometric Properties: Rectangular plates with dimensions $a \times b \times h$ (length, width, and thickness, respectively) are considered with multi-layered structures having anisotropic or orthotropic material properties for each layer.
Materials: Face sheets comprise high-strength materials such as fiber-reinforced composites or metals. For sandwich plates, cores consist of lightweight materials including foam, honeycomb, or balsa wood.
Loading and Boundary Conditions: Thermo-mechanical loads include uniform thermal gradients, in-plane edge loading, and transverse uniform loads. Simply supported or mixed boundary conditions are applied.
Behavior to Be Analyzed: The study examines bending, buckling under axial compressive loading, and vibration analysis under thermo-mechanical effects.

5.3 Illustrative Examples and Numerical Analysis

Analysis encompasses unsymmetrical, antisymmetric, and arbitrary lay-ups of laminated and sandwich plates. Performance evaluation of sandwich plates with soft cores under various load conditions is conducted. MATLAB code development obtains theoretical results, while ABAQUS finite element software validates and extends the analysis.

5.4 Sample Preparation and Laboratory Testing

Composite material specimens are prepared according to standard protocols. Mechanical and thermal laboratory tests obtain numerical results for material properties relevant to shelter performance. Test data analysis provides validation for theoretical and numerical models.

6. Material Properties

6.1 Face Sheet Materials

Face sheets constitute thin outer layers or skins of sandwich plates, made of high-strength materials such as fiber-reinforced polymers or metal laminates. They carry tensile and compressive stresses during bending, provide surface finish and structural strength, and typically comprise multiple plies in composite laminates. Face sheets serve as the primary load-bearing element for bending and in-plane stresses.

6.2 Core Materials

The core represents the thick, lightweight middle layer between face sheets, made from materials like foam, honeycomb, wood, or lightweight metals. It provides shear stiffness and strength to the sandwich structure, maintains spacing between face sheets to prevent buckling, and supports face sheets so they act together structurally. The core primarily carries shear stresses and stabilizes the face sheets.

7. Finite Element Analysis Using ABAQUS

A detailed finite element study was carried out in ABAQUS to evaluate the response of sandwich plates for different layups and core configurations. The analysis followed these steps:

1. **Geometry definition:** A rectangular plate was modelled with the required plan dimensions and thickness, as shown schematically in Fig. 1.
2. **Material assignment:** Properties were specified for each layer separately so that face sheets and core could be modelled with their actual stiffness characteristics.
3. **Boundary conditions:** Simply supported support conditions were imposed along all four edges (see Fig. 2).
4. **Meshing:** A structured mesh was generated, using suitable plate/shell or solid elements to capture through-thickness behaviour (Fig. 3).
5. **Loading:** The model was subjected to uniformly distributed transverse loads, and in separate cases to thermal loading or combined thermo-mechanical loading.
6. **Solution and post-processing:** The computed displacement fields, stress distributions, and strain contours were extracted and visualized to assess overall structural performance (Fig. 4).

4. Conclusions

The numerical study highlights a few clear patterns in the behaviour of the sandwich plates:

- **Core material role**
  Among the cores examined, plates with balsa cores showed the smallest deflections and lower stress levels, which points to their comparatively,

Table 1 *Material properties of face sheet materials*

Material	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	Thickness (mm)
CFRP [0°]	150	10	5	0.3	0.125
CFRP [90°]	10	150	5	0.3	0.125
CFRP [±45°]	15	15	40	0.3	0.25
Glass/Epoxy	45	12	5	0.3	0.2
Carbon/Epoxy	230	15	15	0.3	0.1

Table 2 *Material properties of core materials*

Core Type	E (MPa)	G (MPa)	Density (kg/m³)	Thickness (mm)
Aluminum Honeycomb	0.7	0.3	48	10
Nomex Honeycomb	0.5	0.2	32	15
PVC Foam	100	40	80	20
Balsa Wood	3000	150	150	12

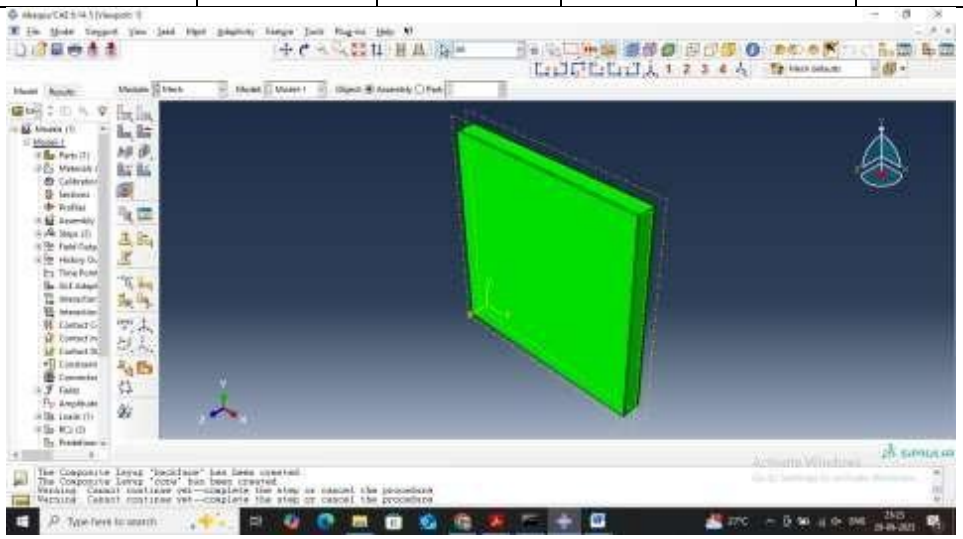


Figure 1: *Modeling of Plate*

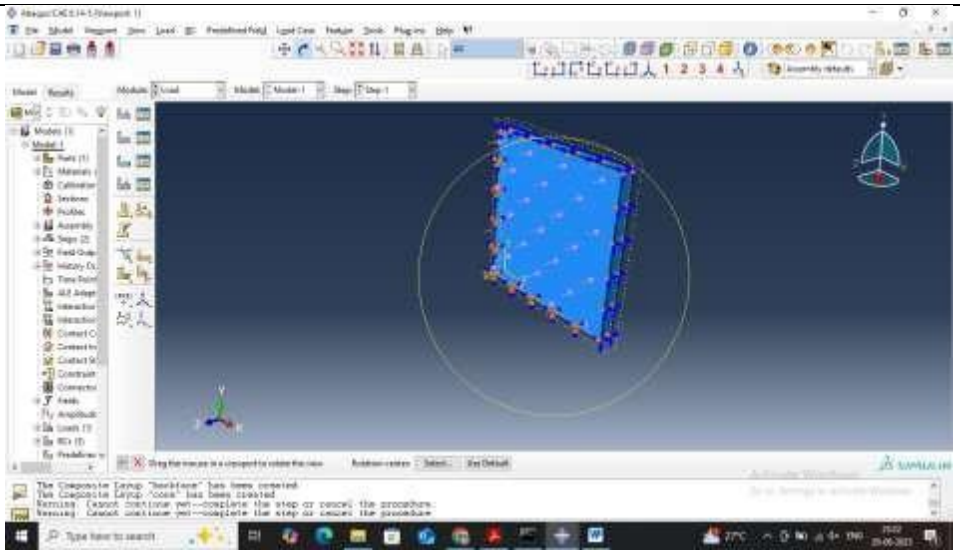


Figure 2:*Applying Boundary Conditions*

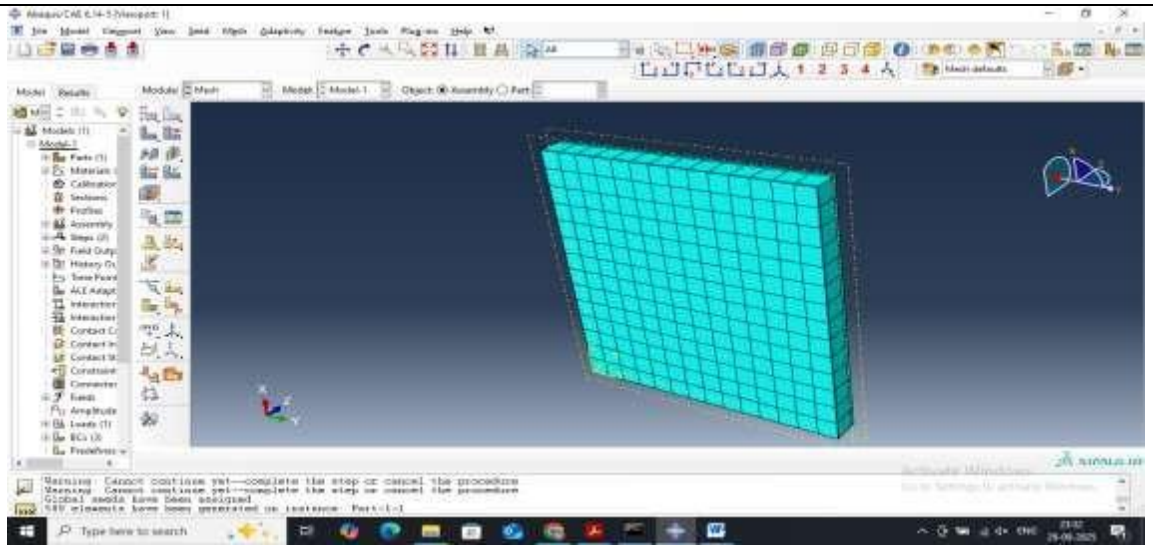


***Figure 3**: Mesh Generation*

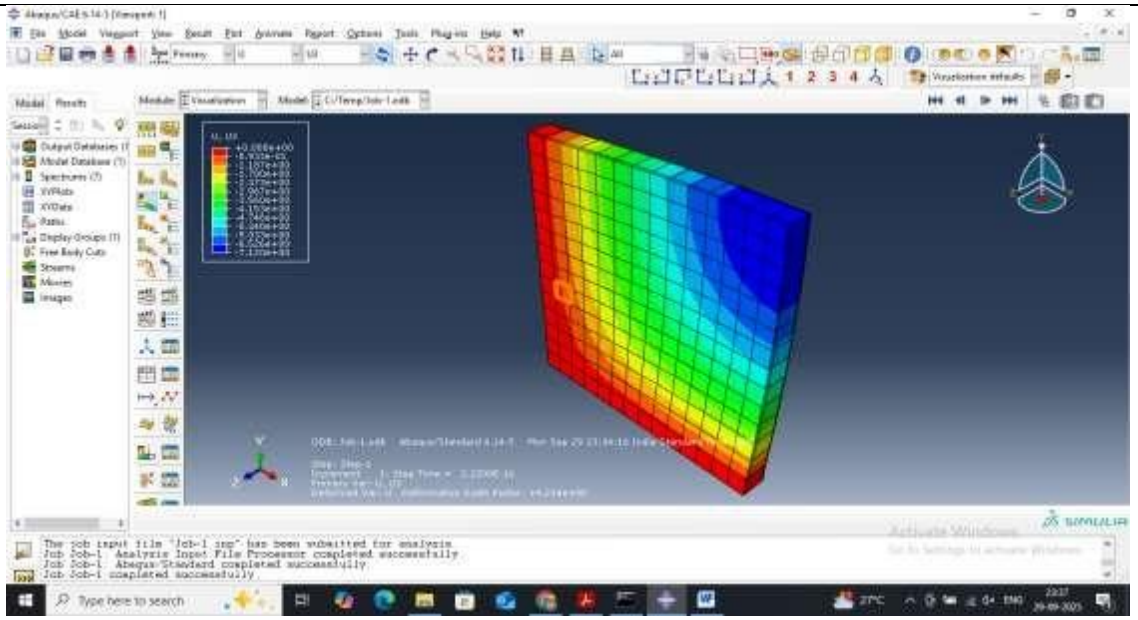


***Figure 4**: Result Visualization*

***Table 3** ABAQUS results for [0/90/C/90/0] sandwich plates*

Core Type	Aspect Ratio (S)	Max. Displacement w	Max. Stress σ_{xx}	Shear Stress $\tau_{x}z$	Core Stress
Honeycomb	5	1.1799	2.0279	0.6084	0.3042
	10	1.3835	2.2234	0.6670	0.3335
	20	1.7385	2.5353	0.7606	0.3803
Foam	5	1.0079	1.7324	0.5197	0.2599
	10	1.1452	1.8404	0.5521	0.2761
	20	1.4563	2.1237	0.6371	0.3186
Balsa Wood	5	0.7616	1.3089	0.3927	0.1963
	10	0.8594	1.3813	0.4144	0.2072

	20	1.1954	1.7432	0.5230	0.2615

Table 4 *ABAQUS results for [0/±45/90/C/90/±45/0] sandwich plates*

Core Type	Aspect Ratio (S)	Max. Displacement w	Max. Stress σ_{xx}	Shear Stress τ_{xz}	Core Stress
Honeycomb	5	1.2271	2.1091	0.6327	0.3164
	10	1.4571	2.3418	0.7025	0.3513
	20	1.9065	2.7803	0.8341	0.4170
Foam	5	1.0304	1.7710	0.5313	0.2657
	10	1.2901	2.0734	0.6220	0.3110
	20	1.6169	2.3580	0.7074	0.3537
Balsa Wood	5	0.8296	1.4258	0.4277	0.2139
	10	0.9957	1.6003	0.4801	0.2400
	20	1.2176	1.7756	0.5327	0.2663

higher stiffness. Honeycomb cores, by contrast produced the largest displacements and stresses, while foam cores fell between the two. This ordering is in line with the differences in elastic properties of the core materials.

- **Effect of aspect ratio**
  When the plate aspect ratio was increased from 5 to 20, all key response quantities—overall deflection, peak stress, shear stress, and stress in the core—rose steadily. This behaviour was observed for every core type and stacking sequence, confirming that geometric proportions have a strong influence on the design and sizing of sandwich plates.
- **Influence of laminate layup**
  The laminate with the sequence [0/±45/90/C/90/±45/0] showed slightly higher displacements and stresses than the simpler [0/90/C/90/0] arrangement. This indicates that introducing ±45° plies can marginally lower the in-plane stiffness, even though such plies may improve other aspects of performance, particularly resistance to shear and off-axis loading.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
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