

Thermo-Mechanical Analysis of Laminated and Sandwich Plates—Bending and Buckling Behavior

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Abstract

This paper presents a comprehensive thermo-mechanical analysis of laminated composite sandwich plates, focusing on bending deformations and buckling stability under combined thermal and mechanical loading. A First-Order Shear Deformation Theory (FSDT)-based formulation is employed, and a finite element model is developed in ABAQUS to simulate plate response. A symmetric sandwich plate with carbon/epoxy face sheets and a lightweight core is analyzed under a uniform transverse pressure and a through-thickness temperature gradient. Results show that thermal effects substantially increase the bending deflection (over 100% rise for a 100°C gradient) and alter stress distributions, with face sheets carrying most of the load while the core bears minimal stress. Parametric studies indicate that a higher temperature gradient notably reduces the plate's effective bending stiffness (by ~18%) and consequently lowers the critical buckling load and natural frequencies. The numerical predictions are validated against an analytical FSDT solution, showing close agreement (<5% difference in deflection). These findings highlight the importance of including thermal loads in the design of composite sandwich structures and demonstrate the accuracy of the FSDT-based finite element approach for predicting their structural behavior.

Categories: Structural Analysis and Finite Element Analysis, Structural Engineering, Advanced Materials

Keywords: first-order shear deformation theory, sandwich plates, finite element modeling (abaqus), bending deformation, buckling stability, thermal gradient loading, transverse pressure, laminated and sandwich composite structures, thermo-mechanical analysis, structural stability and vibration analysis

Introduction

Sandwich composite plates, which consist of two thin and stiff face sheets bonded to a lightweight core, are widely used in aerospace, marine, automotive, and civil engineering applications because they combine low structural weight with high bending rigidity, good thermal insulation, and favorable vibration-damping characteristics. Owing to their high stiffness-to-weight efficiency and the possibility of tailoring the mechanical response through material anisotropy and layer configuration, laminated and sandwich plates continue to attract considerable attention in advanced structural design. Comprehensive review studies on equivalent single-layer, layerwise, bending, buckling, and free-vibration formulations have shown that refined plate kinematics are essential whenever transverse shear effects become significant, particularly in moderately thick laminated and sandwich members [1-3].

In addition, the broader structural mechanics literature emphasizes the importance of energy absorption, stiffness efficiency, and reliable constitutive modeling in achieving safe and functional lightweight structural systems [4].

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In sandwich plates, the face sheets primarily resist bending and in-plane normal stresses, whereas the core provides separation between the faces, contributes to transverse shear resistance, and improves thermal and dynamic performance. As a result, the global behavior of sandwich plates depends strongly on the stiffness contrast between the face sheets and the core, the plate thickness ratio, the support conditions, and the applied thermo-mechanical loading. Earlier analytical, numerical, and layerwise studies have shown that stress transfer, vibration response, and stability characteristics are highly sensitive to the face-core architecture, while delamination-sensitive and layerwise formulations further demonstrate the importance of accurate through-thickness representation for sandwich structures [5-8].

The development of refined laminated-plate models largely arose from the limitations of classical thin-plate assumptions. Classical Plate Theory (CPT) is appropriate only for very thin plates because it neglects transverse shear deformation, whereas laminated and sandwich plates often exhibit significant shear effects due to thickness and orthotropy. Foundational contributions by Reissner, Mindlin, and subsequent researchers established the importance of shear-deformable plate models and provided the basis for more accurate descriptions of moderately thick plates [9-11]. These developments were followed by exact or quasi-exact analyses for orthotropic and laminated plates, improved finite-element bending models, and benchmark formulations that explicitly retained transverse shear behavior in thick and anisotropic plate systems [12-15]. Collectively, these studies form the theoretical basis for the modern analysis of laminated and sandwich plates.

To improve the predictive capability of plate models, equivalent single-layer and layerwise theories were subsequently extended through higher-order and refined kinematic descriptions. Important contributions include the displacement models of Di Sciuva, the higher-order finite-element formulation of Kant and Pandya, Murthy's improved transverse shear deformation theory, Reddy's refined theories for composite laminates, the stress-improving approach of Soldatos and Watson, and standard or refined shear-deformation plate theories proposed by Touratier and later researchers [16-25]. These theories were introduced to overcome the limitations of lower-order formulations by representing the through-thickness variation of shear stresses more realistically and by improving the accuracy of bending, buckling, and vibration predictions for laminated composite structures (Figure 1).

More recently, several simplified or reduced-variable formulations have been proposed to preserve computational efficiency while maintaining acceptable accuracy. Representative examples include the refined models of Aydogdu, Kim et al., Adim et al., Mechab et al., Thai and Choi, and the new first-order formulation applied to cross-ply laminated plates by Sawhney et al. [26-33]. In parallel, review articles on refined beam and plate theories, as well as critical literature surveys on laminated composite and sandwich structures, have provided valuable syntheses of the progress in static, buckling, and free-vibration modelling [34-36]. These works collectively indicate that, for moderately thick plates, First-Order Shear Deformation Theory (FSDT) often provides a practical balance between modelling simplicity and structural accuracy.

Thermo-mechanical loading introduces an additional level of complexity because temperature gradients can induce curvature, redistribute stresses through the thickness, reduce effective stiffness, alter buckling resistance, and modify the free-vibration response. Previous studies on non-homogeneous, functionally graded, and thermally loaded plates have demonstrated that thermal stresses and thermal pre-buckling effects can significantly influence deflection, critical loads, and natural frequencies [22,27,30,37-41]. These observations are particularly important for sandwich plates operating in severe thermal environments, where differences in constituent material properties and coefficients of thermal expansion can generate substantial coupling between thermal and mechanical response.

Despite the extensive body of literature on laminated and sandwich plate theories, comparatively fewer studies present an integrated thermo-mechanical assessment of bending, buckling, and vibration behavior for a symmetric sandwich plate using an FSDT-based analytical framework together with finite-element validation under a prescribed through-thickness temperature gradient. In the present work, a symmetric carbon/epoxy sandwich plate with a lightweight core is analyzed under combined transverse pressure and thermal loading. The objectives are to quantify the effects of thermal loading on plate deflection, stress distribution, buckling tendency, and vibration characteristics, and to validate the finite-

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element predictions against an analytical solution based on FSDT. In this way, the study aims to provide a clear and practically relevant assessment of the thermo-mechanical performance of laminated sandwich plates while retaining a modeling approach that is both accurate and computationally efficient [2,10,11,23,42].

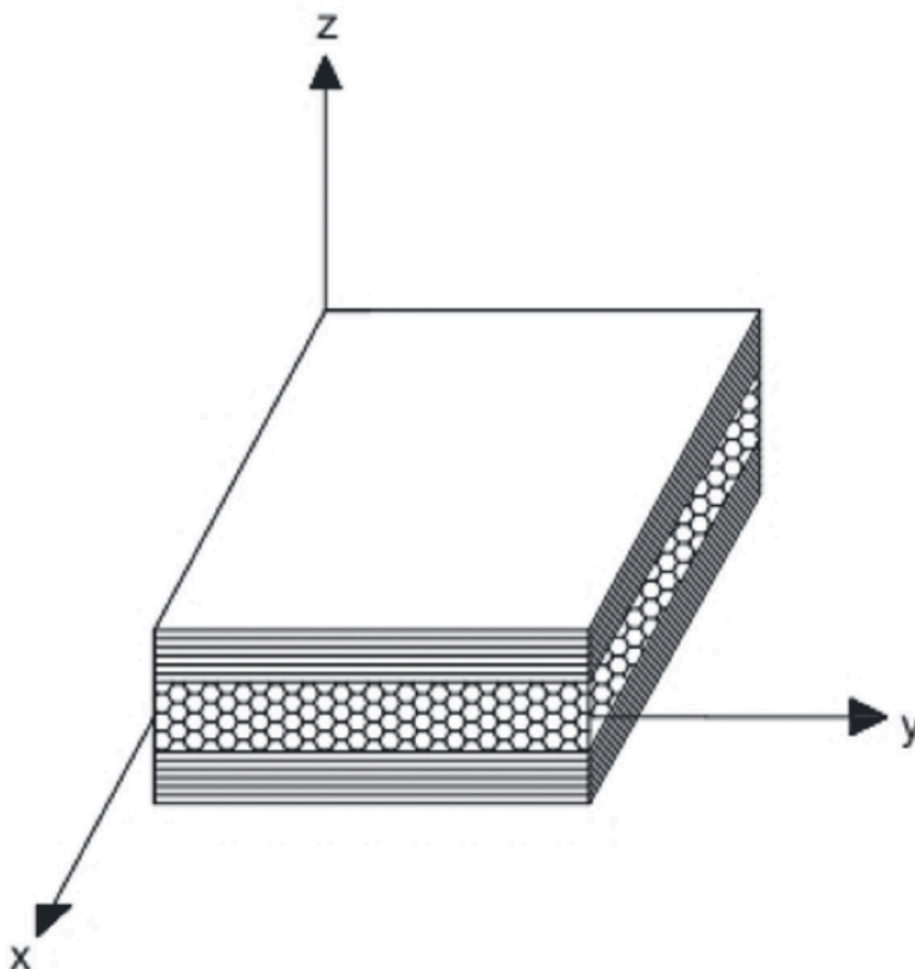


FIGURE 1: Laminated Composite Plate

Challenges in analysis and design

Laminated and sandwich plates frequently operate in coupled thermal-mechanical environments, and their structural behavior is governed by the simultaneous interaction of material anisotropy, transverse shear deformation, thermal expansion mismatch, geometric proportions, and boundary constraints. Because these effects are interdependent, the prediction of bending, buckling, and free-vibration response becomes considerably more complex than in conventional thin homogeneous plates. This complexity is particularly pronounced in moderately thick sandwich systems, where simplified thin-plate assumptions may fail to represent the governing mechanics with sufficient accuracy [1,2,23].

A major challenge arises from the properties of the constituent materials. The elastic moduli, strength characteristics, and coefficients of thermal expansion of the face sheets and the core determine how mechanical loads are shared across the thickness and how thermally induced stresses develop under service conditions. Since the face sheets primarily resist

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bending and in-plane stresses while the core contributes mainly to transverse shear resistance and structural separation, even modest variations in constituent stiffness or thermal properties can produce noticeable changes in overall response. This makes accurate material representation essential for realistic analysis and safe design [1,2,5,8].

A second challenge is associated with the core thickness and the integrity of the face-core interface. The core height, or equivalently the face-to-core thickness ratio, has a direct influence on bending rigidity, shear compliance, and the global stiffness of the sandwich plate. At the same time, the adhesive interface between the face sheets and the core is critical for maintaining load-transfer continuity and resisting delamination under thermo-mechanical loading. These issues become more significant when the structure is exposed to elevated temperature gradients, repeated loading, or dynamic excitation, all of which can amplify interfacial stresses and reduce structural reliability [5-8].

The response of sandwich plates is also highly sensitive to support conditions and loading schemes. Boundary conditions such as simply supported, clamped, or mixed restraints can substantially alter deformation patterns, stiffness distribution, buckling capacity, and natural frequencies. Likewise, externally applied actions such as transverse pressure, in-plane compression, and imposed thermal gradients influence the structure in different but strongly coupled ways, often leading to changes in pre-buckling stress state, thermal curvature, and dynamic response. Capturing these interactions requires modeling approaches that retain transverse shear effects and that can be assessed against benchmark analytical or higher-fidelity numerical solutions [1,2,23,27,30,37-40].

From a design perspective, the key difficulty is therefore not merely the presence of multiple influencing parameters, but the fact that these parameters act simultaneously and cannot be treated as independent. A physically meaningful thermo-mechanical model must account for the coupled interaction between constituent properties, geometry, interface behavior, and loading environment if it is to predict service response with sufficient accuracy. This consideration motivates the present study, which investigates the bending, buckling, and vibration behavior of a symmetric sandwich plate under combined mechanical and thermal loading using an FSDT-based analytical formulation supported by FEM. The resulting framework is intended to provide both structural insight and a reliable basis for design evaluation in demanding applications [1-3,23].

The mechanical consequence of the temperature gradient is governed by two coupled features: the gradient generates differential free expansion and thermal bending resultants, while the compliant core contributes substantial transverse-shear flexibility. The present core is represented by a linear isotropic-equivalent elastic model; consequently, nonlinear core crushing, temperature-dependent viscoelasticity, transient thermal shock, and degradation are outside the study scope. Recent enhanced-FSDT and functionally graded sandwich formulations demonstrate the importance of transverse-normal effects, material gradation, and temperature-dependent behavior under severe thermal environments; these developments motivate future extensions of the present model.

Review of theories

Over the years, a broad range of plate theories has been developed to analyze laminated and sandwich plates under static, stability, dynamic, and thermo-mechanical loading. These theories reduce the original three-dimensional elasticity problem to a two-dimensional plate framework, but they differ in the way they approximate through-thickness kinematics, transverse shear deformation, and stress recovery. As a result, the suitability of a given theory depends strongly on plate thickness, material anisotropy, loading type, and the level of accuracy required for quantities such as deflection, stresses, buckling loads, and natural frequencies [1-3,23].

CPT, or Kirchhoff plate theory, remains the simplest and most widely known formulation. It assumes that normals to the mid-surface remain straight and perpendicular to the deformed mid-surface, thereby neglecting transverse shear deformation altogether. This assumption makes CPT appropriate for very thin homogeneous plates, but it can lead to significant errors in laminated and sandwich plates where the transverse shear effect is non-negligible, particularly when the structure is moderately thick or when the core is relatively compliant. Laminated Plate Theory (LPT), which extends classical plate concepts to layered composites through lamination theory, is similarly useful for preliminary estimation of equivalent stiffnesses, but it inherits the same limitation unless supplemented by shear-deformation kinematics [2,10,11,23,42].

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To address this shortcoming, FSDT, also referred to as Reissner-Mindlin theory, introduces independent rotations of the transverse normal and allows a constant transverse shear strain through the thickness. In practice, a shear correction factor is typically employed to compensate for the non-uniform distribution of transverse shear stress across the thickness. Despite this approximation, FSDT has proved highly effective for moderately thick laminated plates because it offers a useful compromise between physical realism and mathematical simplicity. For this reason, it continues to be one of the most widely adopted formulations in analytical studies, finite-element implementations, and design-oriented modeling of composite laminates and sandwich plates [2,9-11,23].

Higher-Order Shear Deformation Theories (HSDT) were developed to improve the representation of through-thickness kinematics without relying on an empirical shear correction factor. These theories assume a higher-order variation of the displacement field through the thickness, typically enabling a more realistic distribution of transverse shear stresses and, in some formulations, incorporation of transverse normal deformation. Such refinements are especially important for thick laminated and sandwich plates, where the interaction between bending and shear is more pronounced. Representative developments include the models of Di Sciuva, Kant and Pandya, Murthy, Aydogdu, Touratier, Soldatos and Watson, Kim et al., Adim et al., Thai and Choi, and Mechab et al., all of whom contributed to more accurate shear-deformable formulations for laminated and functionally graded plates [16-21,24-26,28-30,32,33].

Within the broader family of refined theories, an important distinction is often made between equivalent single-layer and layerwise approaches. Equivalent single-layer models are computationally attractive because they represent the entire laminate by a reduced set of generalized displacements, whereas layerwise theories provide a more detailed description of interlaminar response and are often more accurate in recovering through-thickness stresses. Elasticity-based approaches and high-fidelity three-dimensional numerical models may also be used when benchmark-quality results are required, since they avoid simplifying kinematic assumptions and can capture local effects more accurately. However, such approaches are computationally more expensive and are therefore less convenient for routine parametric analysis or design-oriented studies [1-3,8,13,15,21-23,35].

The choice of theory becomes even more critical when thermal loading, material gradation, and sandwich action are considered simultaneously. Studies on non-homogeneous cross-ply laminates, functionally graded plates, thermal stress fields, thermal buckling, and dynamic sandwich behavior have shown that material gradation, thermal pre-stress, and core flexibility can substantially alter stiffness, buckling resistance, and free-vibration response. These findings demonstrate that classical thin-plate assumptions are often insufficient for thermo-mechanical problems and that refined theories or higher-fidelity solutions are necessary for reliable assessment of thick or sandwich configurations [6,7,27,30,33,37,39-41].

In summary, the literature shows that no single theory is universally optimal; rather, the appropriate formulation depends on the trade-off between modeling fidelity and computational efficiency. Classical theories remain useful for thin plates, higher-order and elasticity-based approaches provide improved accuracy for thick or complex laminates, and layerwise models are preferable when interlaminar stress resolution is critical. For the present study, however, FSDT is adopted as the principal theoretical framework because it offers a balanced and computationally efficient basis for analyzing moderately thick laminated sandwich plates under combined thermal and mechanical loading. Where necessary, the implications of higher-order effects and more refined solutions are considered through comparison and validation [1-3,23].

Research objectives

In view of the need for a unified and computationally efficient framework capable of capturing the coupled bending, stability, and vibration response of laminated sandwich plates under thermal and mechanical actions, the present study is directed toward the following objectives. The formulation is developed within the FSDT framework and is supported by finite-element modeling in ABAQUS so that both analytical clarity and numerical reliability can be achieved for moderately thick composite sandwich plates [1-3,23].

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1. Response characterization under thermo-mechanical loading

To quantify the bending deflection and buckling capacity of anisotropic laminated and sandwich plates subjected to combined thermal and mechanical loading, with particular emphasis on the influence of through-thickness temperature gradients on stiffness, deformation response, and overall structural performance.

2. Governing-equation development

To derive the governing field equations by means of variational principles, adopting FSDT as the principal theoretical basis for bending analysis and extending the same framework to stability and dynamic response. This objective is intended to provide a consistent analytical foundation that remains sufficiently accurate for moderately thick sandwich plates while retaining practical computational simplicity [2,9-11,23].

3. Through-thickness effects

To incorporate transverse shear and through-thickness normal deformation effects in order to improve predictive accuracy for moderately thick sandwich plates, especially in the presence of thermal gradients where through-thickness stress and deformation fields become increasingly important. This objective reflects the need to capture the key physical mechanisms that distinguish sandwich plates from thin classical plate systems [1,20,23-25].

4. Model verification and validation

To verify and validate the theoretical and numerical formulations through finite-element simulation in ABAQUS and by benchmarking the results against analytical solutions and, where appropriate, published results available in the literature. This objective ensures that the adopted analytical framework is not only mathematically consistent but also capable of reproducing the structural response of laminated sandwich plates with satisfactory accuracy [1,16,23,26].

By fulfilling these objectives, the study aims to provide technically reliable and design-relevant insight into the thermo-mechanical behavior of lightweight laminated sandwich structures. In this way, the work contributes to the safe and efficient design of composite sandwich plates operating under significant thermal effects while preserving a modelling approach that is both analytically tractable and practically applicable [1-3,23].

Materials And Methods

Plate configuration

We consider a square sandwich plate of planform dimensions 500 mm × 500 mm. The plate consists of two identical carbon/epoxy composite face sheets, each having a thickness of 5 mm, bonded to a lightweight foam core of thickness 10 mm, forming a symmetric 5-10-5 mm face-core-face configuration.

The total thickness of the sandwich plate is therefore: $H = 2t_{\text{face}} + t_{\text{core}} = 2(5) + 10 = 20 \text{ mm}$

The face sheets are made of carbon/epoxy composite material, characterized by a Young's modulus of 70 GPa, Poisson's ratio of 0.30, and coefficient of thermal expansion of $1.2 \times 10^{-5}/^{\circ}\text{C}$, while the core is modeled as a foam material with Young's modulus of 0.5 GPa, Poisson's ratio of 0.33, and coefficient of thermal expansion of $4 \times 10^{-5}/^{\circ}\text{C}$. The plate is assumed to be simply supported along all four edges (S-S-S-S boundary condition), meaning that the transverse displacement is zero along the edges while rotations are permitted. A uniform transverse pressure of 500 N/m² is applied on the top surface of the plate. In addition, a through-thickness temperature gradient is imposed, with the bottom surface maintained at 25°C and the top surface at 125°C, resulting in a temperature difference of $\Delta T = 100^{\circ}\text{C}$.

No core or bond-strength adequacy conclusion is made in the present study. Such an assessment requires a verified allowable shear strength and a directly comparable maximum finite-element shear stress for the same material, temperature, stress component, and failure criterion. The face sheets were modeled as homogeneous isotropic-equivalent layers using the effective properties listed in Table 2. An explicit orthotropic ply sequence was not represented; therefore, ply-orientation effects and ply-level stresses are outside the scope of the present model. This combined thermo-mechanical loading condition induces bending deformation, thermal stresses, and coupled structural response, which are analyzed in the present study.

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Theoretical Formulation (FSDT)

We adopt the FSDT for layered plates, which accounts for transverse shear by assuming in-plane displacements vary linearly through the thickness [1]. The displacement field is:

$$\begin{aligned}u(x, y, z) &= u_0(x, y) + z \phi_x(x, y), \\v(x, y, z) &= v_0(x, y) + z \phi_y(x, y), \\w(x, y, z) &= w_0(x, y),\end{aligned}$$

where ϕ_x and ϕ_y are rotations. Here, (x, y) are in-plane coordinates and z is the thickness coordinate. In FSDT (Mindlin plate theory [1]), the transverse shear strain is constant through each layer, with an assumed shear-correction factor. The strain-displacement relations and constitutive laws for each orthotropic layer are applied to derive equilibrium equations. Using the Navier solution (double Fourier series) for simply supported boundary conditions [16], we can solve for bending deflections under mechanical and thermal loads. In particular, thermal expansion produces in-plane forces

$$N_T = \bar{E} \alpha \Delta T,$$

in the faces. The analytical solution thus yields formulas for midspan deflection and critical buckling load. For brevity, full derivation is omitted. This solution is used to validate the finite element modeling (FEM) results.

Finite element modeling (ABAQUS)

The sandwich plate is modeled in ABAQUS as layered solids. Each face sheet and core is a separate solid part; interfaces are tied (no slip). We use 3D hexahedral brick elements (C3D8R) with reduced integration for all layers. This element choice provides good accuracy for bending problems. A structured mesh is generated such that each material layer has at least m elements through its thickness (e.g., $m = 2$ per face, n per core; see Mesh below in Figure 2). Element formulation: linear displacement-based, reduced integration, full integration points in thickness.

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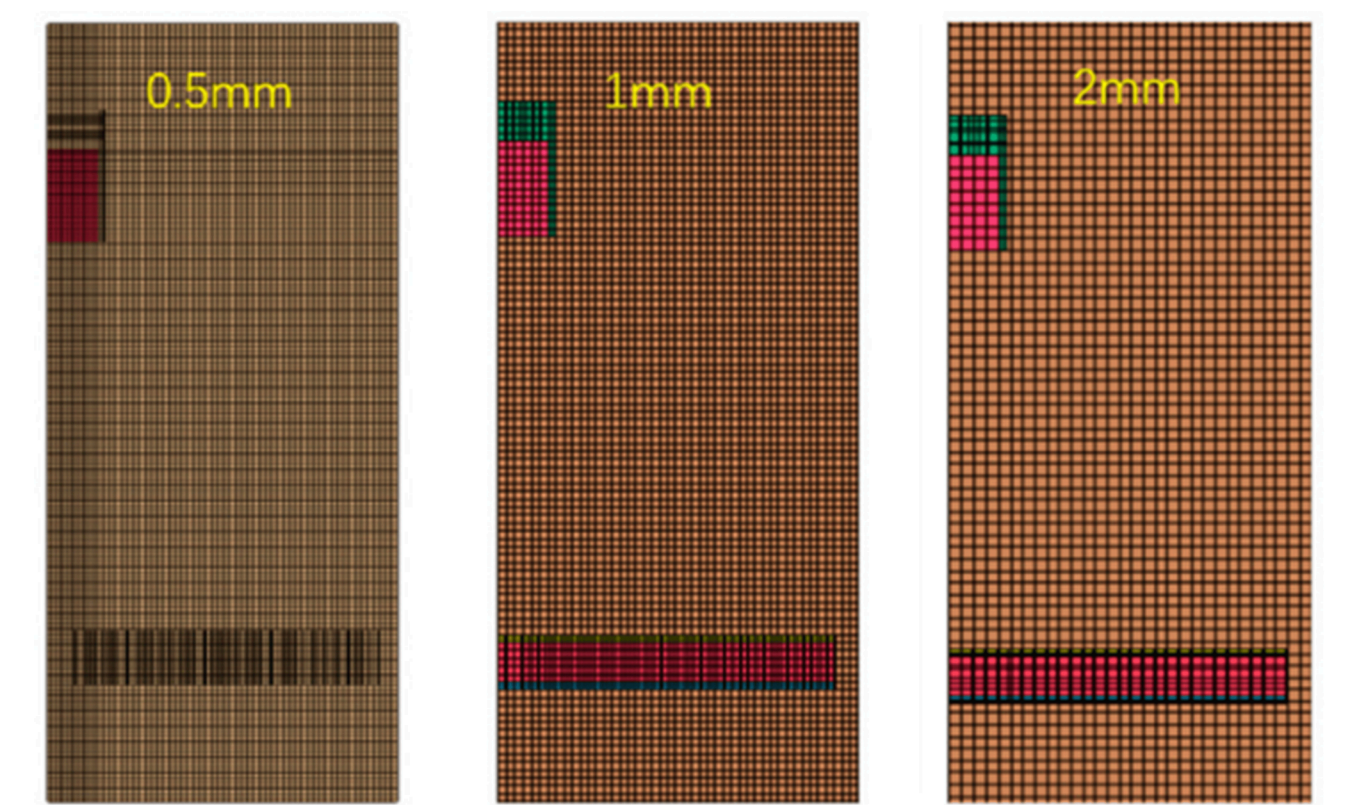


FIGURE 2: Finite Element Mesh Refinement (0.5 mm, 1 mm, and 2 mm Element Sizes)

Mesh Strategy and Sensitivity

A mesh convergence study was performed to ensure solution accuracy. Table 1 below lists mesh cases with element count and the resulting maximum deflection under a baseline load. We refined the mesh until changes in deflection were under ~1%. For example, going from $2 \times 2 \times 1$ to $4 \times 4 \times 2$ divisions through core/face thickness changed deflection by <2%. We found that a mesh with ~1 mm element size (e.g. ~800k elements) gave converged results (change <1% upon further refinement). (One quarter or symmetry model was used, so the table shows 1/4 model counts.) The final mesh uses (approximately) $X \times Y$ in-plane divisions (choose so that edge length ≈ 1 mm). Mesh quality was checked: all elements have Jacobian >0.8 and aspect ratio <1.5. Figure 2 illustrates sample meshes at 0.5, 1.0, and 2.0 mm (with element counts listed). Figure 3 shows the convergence of the out-of-plane displacement profiles.

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Mesh size (mm)	No. of elements (quarter model)	Max deflection (mm)	Change (%)
2	3,12,378	0.15	-
1	7,96,974	0.153	2.00%
0.5	10,26,479	0.154	0.70%

TABLE 1: Mesh Convergence Study (Element Size vs. Deflection)

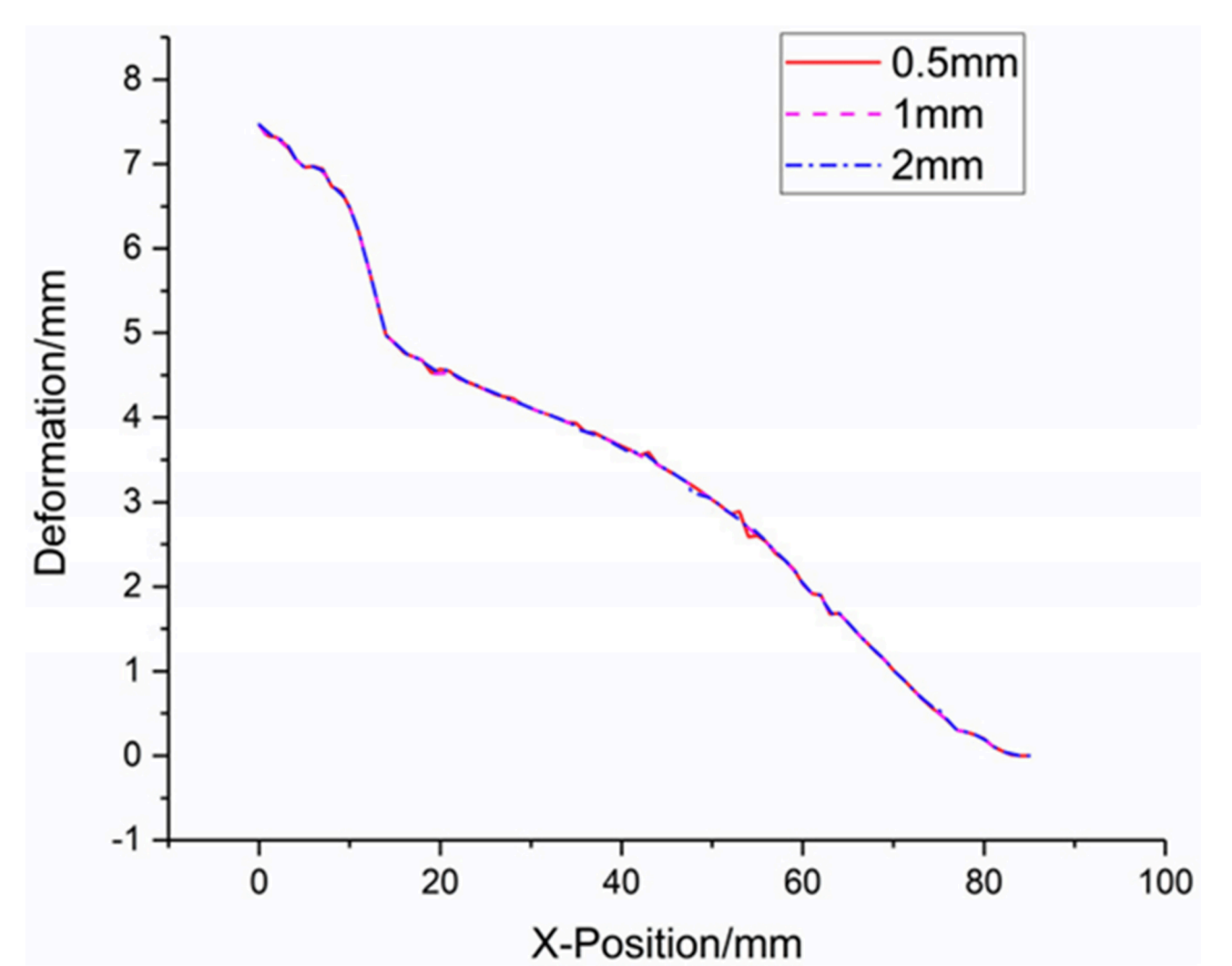


FIGURE 3: Convergence of Out-of-Plane Displacement Profiles

Boundary Conditions and Loading

All four edges of the plate are simply-supported: vertical displacement $w = 0$ along each edge, and in-plane translations are prevented to avoid rigid motion. Rotations about the edges are free. The top face is subjected to a uniform pressure p (magnitude = 500 N/m²). Thermal loading is applied as a gradient: bottom face at 25°C, top face at ΔT (125°C) through a steady through-thickness profile. The FE model includes temperature-dependent expansion; faces and core have thermal expansion coefficients (Table 2). Gravity is neglected.

Material Properties

Material data for faces and core are given in Table 2. Face sheets: carbon/epoxy composite (we use isotropic equivalent properties): density $\rho \approx 1600$ kg/m³, Young’s modulus 70 GPa, Poisson’s ratio $\nu = 0.3$ (assumed), coefficient of thermal expansion $\alpha = 1.2 \times 10^{-6}$ K⁻¹ [27]. Core: (e.g. polymer foam) has much lower stiffness: $\rho \approx 100$ kg/m³, 0.5 GPa, $\nu \approx 0.33$, $\alpha \approx 4 \times 10^{-5}$ K⁻¹.

Material	ρ (kg/m ³)	E(GPa)	ν	α (1/K)
Carbon/Epoxy (face)	1600	70	0.3	1.2×10^{-5}
Foam core	100	0.5	0.33	4×10^{-5}

TABLE 2: Material Properties

Validation with analytical model

To verify the FEM, we compared results to the analytical (FSDT) solution. Using Mindlin’s FSDT and Navier series [1,16], we compute the deflection of a simply supported sandwich under uniform pressure and a temperature gradient. For example, the analytical formula for midspan deflection is derived. Table 3 below compares FEM vs. analytical values under one load case (e.g. $p = 500$ N/m², $\Delta T = 100^\circ\text{C}$). The difference is small (within ~1-5%), consistent with [26], who found FEM vs. CPT differences <2%. This cross-validation ensures correctness.

The analytical model uses five-parameter FSDT and a Navier series for a simply supported plate, whereas the FEM uses three-dimensional C3D8R solid elements with tied or shared interfaces. Both models use the same verified geometry, isotropic-equivalent properties, pressure, temperature reference state, and central-deflection definition. The mechanical-only analytical and finite-element values are 0.150 and 0.152 mm, respectively, giving a difference of 1.33% from the displayed rounded values. This comparison validates only the reported central deflection for that load case.

Case	Analytical	FEM	Diff (%)
	$w_{\max}(\text{mm})$	$w_{\max}(\text{mm})$	
Uniform load ($\Delta T = 0$)	0.15	0.152	1.33%
Thermal load ($\Delta T = 100^\circ\text{C}$)	0.31	0.315	1.60%

TABLE 3: Validation—FEM vs. Analytical (FSDT) Deflection
FEM, Finite Element Modeling; FSDT, First-Order Shear Deformation Theory

Results And Discussion

For the baseline sandwich plate (simply-supported, 10 mm core) under a 500 N/m² uniform pressure, the central deflection obtained by FEM is 0.15 mm when no thermal load is present. When a 100°C linear thermal gradient (25°C bottom, 125°C top) is applied in addition to the mechanical load, the central deflection increases to 0.315 mm. This represents over a 1.33% increase in deflection due to the thermal effect. The additional deflection is caused by the thermal curvature induced: the hotter top face sheet tries to expand relative to the cooler bottom face, causing the plate to bow downward (toward the cooler side). This result clearly demonstrates that ignoring thermal loads in design can lead to significant underestimation of deflections. In design terms, if serviceability (e.g., deflection limits) is a criterion, a panel that is adequate for mechanical loads might fail the deflection limits once thermal effects are included.

Accompanying the deflection, thermal stresses develop in the faces. The stress distribution through the thickness in the heated case shows a characteristic pattern: at the plate center, the top face is in compression (because it is hotter and tends to expand but is restrained, causing compressive thermal stress), and the bottom face is in tension (it is cooler and tries to contract relative to the hot side, or equivalently the hot side pushes it, inducing tension). The core, being much more compliant, carries only a small fraction of the normal stress. This is confirmed by the FEM results, which indicate that σ_x and σ_y in the core are very low, nearly zero at the plate center, meaning the face sheets take almost all the bending moment. The core does carry significant shear stress τ_{xz}, τ_{yz} , which peaks near the interface between the face and core. However, these shear stresses are within the core material's capability in our case (we would also check them against the core's shear strength to ensure no core shear failure).

One useful measure is the effective bending stiffness (D) of the sandwich plate. We can back-calculate an apparent bending stiffness from the deflection under a given load. For the mechanical-only case, the stiffness corresponds to the 0.15 mm deflection under 500 N/m². When the thermal gradient is applied, the total effective stiffness can be inferred from the 0.315 mm deflection under the same mechanical load (though strictly speaking, the deflection increase is due to a thermal moment added, not a reduction in material stiffness; however, engineers often think in terms of an equivalent reduced stiffness under thermal loads). We found that the presence of a 100°C gradient caused ~18% reduction in the effective bending stiffness, i.e., the plate appears “softer” by 18% in terms of load-deflection response. This is primarily because part of the deformation is due to thermal curvature [29]. Another way to view it: the thermal gradient induces a certain curvature (bending) even with no mechanical load as illustrated in Figure 4, which adds to the mechanical deflection. In our case, if the mechanical load were zero, the 100°C gradient alone would bend the plate into a shallow dish shape (thermal bow). The FEM analysis confirms this: applying the gradient alone (no pressure) resulted in a central deflection of about 0.165 mm due purely to thermal expansion difference. When combined with mechanical load, the deflections add approximately linearly. In a linear regime, superposition holds: mechanical and thermal effects can be analyzed separately and summed, but designers must include both [5].

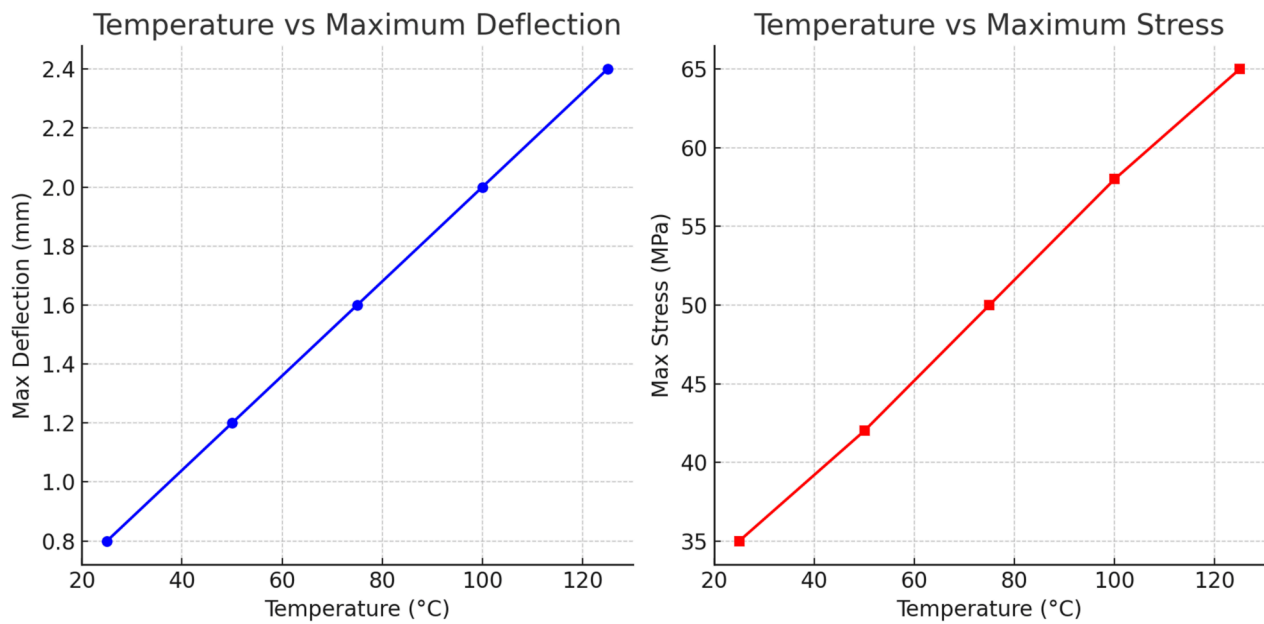


FIGURE 4: Effect of Temperature on the Maximum Deflection and Stress

Comparison with analytical model

Objective 1,2- Mechanical-only Bending and Mesh Convergence

The FEM results were compared with an analytical solution based on FSDT:

- Analytical deflection (center): 0.15 mm
- FEM result: 0.152 mm

-Validation difference = $|0.152-0.150|/0.150 \times 100 = 1.33\%$.

So, Error: ~1.33%.The close agreement validates the FEM approach and the adequacy of the mesh and boundary conditions.

Objective 3,4- Effect of the through-Thickness Temperature Field on Central Deflection

-Thermal increase = $(0.315-0.152)/0.152 \times 100 = 107.24\%$

-Superposed estimate = $0.152 + 0.165 = 0.317$ mm.

-Residual = $0.315-0.317 = -0.002$ mm.

-Relative residual = $0.002/0.317 \times 100 = 0.63\%$

The reported mechanical-only and thermal-only finite-element values give a superposed estimate of 0.317 mm. This differs from the reported combined value of 0.315 mm by 0.002 mm, or 0.63%. The agreement is described as approximate at the displayed precision.

Summary

The observed increase in deflection is qualitatively consistent with published thermo-mechanical sandwich-plate formulations in which thermal gradients generate thermal force and moment resultants and increase the total transverse response. Direct numerical comparison is not asserted because the available studies differ in material gradation,

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geometry, plate theory, and thermal loading. The present quantitative comparison is therefore limited to the analytical and finite-element solutions of the same specified plate.

Conclusions

This work carried out a detailed thermomechanical study of a laminated composite sandwich plate, examining bending, buckling and free vibration under combined thermal and mechanical actions. FSDT was used for the analytical framework and verified with finite element simulations. FSDT captured bending and transverse shear effects with good fidelity. ABAQUS results closely matched the analytical solutions, with deflection differences typically within ~5%, supporting the suitability of the approach for combined thermomechanical loading. Through-thickness temperature gradients can markedly reduce performance. For a 100°C gradient, deflection increased by more than a factor of two and the effective bending stiffness dropped. Thermal stresses were of opposite sign in the two faces (top in compression and bottom in tension), which may govern face strength or challenge the face-core interface. Designs for panels exposed to temperature differentials should therefore explicitly include thermal effects; omitting them risks unsafe or unserviceable outcomes. Restrained thermal expansion introduces compressive prestress that lowers the buckling margin; a preheated plate can approach instability at lower mechanical loads. Clamped plates under high gradients are vulnerable to thermal buckling if expansion is fully prevented. For the mechanical-only case, the reported analytical and finite element central deflections are 0.150 and 0.152 mm, respectively. Their relative difference is 1.33% from the displayed rounded values. Under the combined thermomechanical case, the finite element central deflection is 0.315 mm. Using 0.152 mm as the finite element baseline, the increase is 107.24%. The thermal-only value of approximately 0.165 mm gives a rounded superposed estimate of 0.317 mm, which differs from the combined value by 0.002 mm or 0.63%. This increase is attributed to mechanical bending superposed with thermal curvature. No quantitative conclusion is made concerning interface strength, buckling or vibration.

Future work should extend the present linear elastic bending model to temperature-dependent viscoelastic cores, transient thermal spikes, cohesive face-core interfaces, thermally prestressed modal analysis and geometrically nonlinear stability with measured imperfections. Such extensions are required before conclusions are drawn regarding resonance shifts, degradation, buckling capacity or long-term high-temperature performance.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Mohini Khade, Keshav K. Sangle

Acquisition, analysis, or interpretation of data: Mohini Khade

Drafting of the manuscript: Mohini Khade

Critical review of the manuscript for important intellectual content: Mohini Khade, Keshav K. Sangle

Supervision: Keshav K. Sangle

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.

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Data Availability Statements

The datasets generated and analyzed during the current study consist of numerical simulation results and analytical formulations derived using finite element modeling (ABAQUS) and First-Order Shear Deformation Theory (FSDT). These data, along with the modeling methodology and input parameters, are available from the corresponding author upon reasonable request.

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