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Thermo-mechanical stress development in simple composite laminates under uniform heating

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Abstract
Thermal loading is an unavoidable condition in many engineering applications involving composite laminates, particularly in aerospace, automotive, and energy systems where components are exposed to elevated and spatially uniform temperatures. When composite laminates are subjected to uniform heating, differences in thermal expansion coefficients between constituent layers generate internal stresses, even in the absence of external mechanical loads. These thermo-mechanical stresses can significantly influence stiffness degradation, dimensional stability, interlaminar stress distribution, and long-term structural integrity. This research presents a theoretical investigation of Thermo-mechanical stress generation and its impact on structural integrity in simple composite laminates subjected to uniform temperature rise. Classical lamination theory is employed to derive closed-form expressions for in-plane stresses and bending moments induced purely by thermal effects. The formulation explicitly accounts for anisotropic material behavior, laminate stacking sequence, and mismatch in ply-level thermal expansion properties. Special attention is given to symmetric and asymmetric laminate configurations to highlight the role of coupling between bending and extension under thermal loading. Results demonstrate that even modest temperature changes can produce substantial residual stresses, particularly in cross-ply and angle-ply laminates, where thermal mismatch is pronounced. The research further illustrates how laminate symmetry can eliminate thermally induced bending while still generating significant in-plane stresses. Parametric analysis reveals the sensitivity of stress magnitudes to ply orientation, thickness ratio, and elastic modulus contrast between layers. The findings emphasize that thermal effects must be considered alongside mechanical loading during the design and analysis of composite structures. The simplified analytical framework presented in this work provides clear physical insight into thermo-mechanical behavior and serves as a useful reference for preliminary design and educational purposes. By isolating thermal effects under uniform heating, the research contributes to a clearer understanding of stress generation mechanisms in composite laminates and supports more reliable prediction of thermally induced failure risks in practical engineering applications.

Keywords: Composite laminates, thermo-mechanical stress, uniform heating, classical lamination theory, thermal expansion mismatch

Introduction

Composite laminates are widely used in modern structural applications due to their high strength-to-weight ratio, directional stiffness tailoring, and excellent fatigue performance, making them particularly attractive for aerospace and high-temperature engineering environments [1]. In many service conditions, these structures experience temperature variations that are spatially uniform but temporally significant, such as thermal cycling during operation or exposure to elevated ambient temperatures [2]. Even in the absence of external mechanical loads, uniform temperature rise alone can generate significant internal stresses due to thermal mismatch within laminated composites because of mismatches in coefficients of thermal expansion among different plies [3]. These thermo-mechanical stresses may lead to matrix cracking, interlaminar delamination, or premature failure, thereby reducing structural reliability [4].

Classical lamination theory provides a well-established framework for predicting stress and deformation behavior in composite laminates by accounting for anisotropic material properties and laminate stacking sequences [5]. Extensions of this theory to include thermal effects have shown that temperature changes contribute additional force and moment resultants, which alter the overall stress state of the laminate [6]. Previous studies have demonstrated that symmetric laminates subjected to uniform heating develop in-plane thermal stresses without bending, whereas asymmetric laminates exhibit coupled bending-extension behavior [7]. Such coupling effects are critical in applications requiring dimensional stability, such as precision structures and thermal protection systems [8].

Despite extensive research, simplified analytical treatments focusing exclusively on Thermo-mechanical stress generation and its impact on structural integrity under uniform heating remain valuable for clarifying fundamental mechanisms and supporting early-stage design decisions [9]. Many existing investigations emphasize complex thermal gradients or combined thermo-mechanical loading, which can obscure the isolated contribution of uniform temperature rise to stress generation [10]. A clear understanding of this isolated effect is essential for assessing residual stresses arising during manufacturing processes such as curing and post-curing heat treatment [11].

The primary objective of this research is to analytically examine Thermo-mechanical stress generation and its impact on structural integrity in simple composite laminates subjected solely to uniform heating using classical lamination theory [12]. The analysis aims to identify the influence of ply orientation, laminate symmetry, and material property mismatch on the resulting stress distributions [13]. The central hypothesis is that significant internal stresses can arise from uniform temperature changes alone, and that laminate configuration plays a decisive role in controlling both the magnitude and nature of these stresses [14]. By addressing this hypothesis, the research seeks to provide design-oriented insight into thermal stress mitigation strategies for composite laminate structures [15].

Materials and Methods

Materials

A theoretical (analytical-computational) laminate model was used to research Thermo-mechanical stress generation and its impact on structural integrity in simple composite laminates subjected to a uniform temperature rise, consistent with classical composite mechanics treatments [1, 5]. A unidirectional graphite/epoxy-like orthotropic lamina was assumed as the baseline constituent (typical order-of-magnitude values commonly adopted in laminated plate analysis texts) with elastic constants E1E_1E1, E2E_2E2, G12G_{12}G12, ν12\nu_{12}ν12 and anisotropic coefficients of thermal expansion α1\alpha_1α1 and α2\alpha_2α2 [1-3, 5, 12, 14]. The laminate sets included

1. A symmetric cross-ply [0/90] s [0/90] _s [0/90] s,
2. An asymmetric cross-ply [0/90/0] [0/90/0] [0/90/0],
3. A balanced angle-ply [45/−45] s [45/-45] _s [45/−45] s, and
4. A quasi-isotropic [0/45/90/−45] s [0/45/90/-45] _s [0/45/90/−45] s, chosen to represent common “simple laminate” archetypes used for understanding anisotropy, coupling, and thermal mismatch effects [5-8, 10]. All plies were assumed to be perfectly bonded, linearly elastic, and of equal thickness, with uniform heating applied as ΔT= {25, 50, 75, 100} ∘C\Delta T=\{25, 50, 75, 100\} ^\circ\text{C}ΔT= {25, 50, 75, 100} ∘C, representing service-level thermal excursions or simplified manufacturing/thermal-cycle scenarios [2, 6, 11].

Methods

Thermo-mechanical stresses were computed using Classical Lamination Theory (CLT). For each ply orientation θ\thetaθ, transformed reduced stiffness Q¯(θ)\bar {\mathbf Q} (\theta) Q¯(θ) and transformed thermal expansion vector α¯(θ)\bar{\boldsymbol\alpha} (\theta) α¯(θ) were obtained via standard lamina transformations [5, 10, 14]. The laminate extensional, coupling, and bending matrices (A, B, D\mathbf A, \mathbf B, \mathbf DA, B, D) were assembled through thickness integration; thermal force and moment resultants NT, MT\mathbf N^T, \mathbf M^TNT, MT were computed for uniform heating using the same integration framework [5, 6]. A free (traction-free) laminate condition was imposed (N=0\mathbf N=\mathbf 0N=0, M=0\mathbf M=\mathbf 0M=0), and mid-plane strains and curvatures {ε0, κ}\{\boldsymbol\varepsilon_0, \boldsymbol\kappa\}{ε0, κ} were solved from [ABBD]{ε0, κ}={NTΔT, MTΔT}\begin{bmatrix}\mathbf A&\mathbf B\\ \mathbf B&\mathbf D\end{bmatrix}\{\boldsymbol\varepsilon_0, \boldsymbol\kappa\}=\{\mathbf N^T\Delta T, \mathbf M^T\Delta T\}[ABBD]{ε0, κ}={NTΔT, MTΔT}, capturing bending-extension coupling in asymmetric stacks [5, 7, 8]. Ply-level stresses σ(z)\boldsymbol\sigma(z)σ(z) were then evaluated at ply mid-surfaces using σ=Q¯(ε0+zκ−α¯ΔT)\boldsymbol\sigma=\bar {\mathbf Q} (\boldsymbol\varepsilon_0+z\boldsymbol\kappa-\bar{\boldsymbol\alpha} \Delta T) σ=Q¯(ε0+zκ−α¯ΔT) [5, 10]. Reported outcomes included maximum absolute in-plane stresses max|σx|\max|\sigma_x|max|σx|, max|σy|\max|\sigma_y|max|σy|, max|τxy|\max|\tau_{xy}|max|τxy|, and an equivalent stress index to compare configurations [4, 9]. Statistical analysis of computed responses used one-way ANOVA to test whether mean max|σx|\max|\sigma_x|max|σx| differed by laminate type across the ΔT\Delta TΔT levels [9], and linear regression to quantify scaling of max|σx|\max|\sigma_x|max|σx| with ΔT\Delta TΔT and the effect of laminate asymmetry (including an interaction term ΔT×\Delta T\timesΔT×asymmetry) [2, 6, 7, 11].

Results

Table 1: Thermally induced peak stresses at ΔT=100∘C\Delta T=100^\circ\text{C}ΔT=100∘C for each laminate configuration

S. no	Laminate	Max |σx| (MPa)	Max |σy| (MPa)	Max |τxy| (MPa)	Max σeq (MPa)
1	Asymmetric cross-ply [0/90/0] (3 plies)	22.933	42.562	0.000	49.426
2	Quasi-isotropic [0/45/90/-45] s (8 plies)	26.021	25.357	4.824	45.201
3	Symmetric cross-ply [0/90] s (4 plies)	22.530	22.530	0.000	39.023
4	Balanced angle-ply [45/-45] s (4 plies)	8.111	8.111	7.193	16.116

Interpretation (Table 1): Uniform heating produced non-zero in-plane stresses in all laminates, confirming that thermal mismatch alone can generate significant internal stress even under traction-free conditions [3, 5, 6]. The asymmetric cross-ply exhibited the highest equivalent stress (σeq), consistent with bending-extension coupling and thermally induced curvature effects expected in unsymmetric stacks [7, 8, 10]. The quasi-isotropic laminate showed the largest max⁡|σx|\max|\sigma_x|max|σx|, but also developed notable shear max⁡|τxy|\max|\tau_{xy}|max|τxy|, reflecting the multi-orientation constraint and transformed thermal expansion components in off-axis plies [5, 10, 14]. The balanced angle-ply [45/−45] s [45/-45] _s [45/−45] s produced lower normal stresses but comparatively meaningful shear, aligning with the role of Q‾16, Q‾26\bar{Q}_ {16}, \bar{Q}_ {26} Q‾16, Q‾26 terms and off-axis thermal strain components under CLT [5, 10]. These patterns are consistent with established observations that laminate architecture, not only material CTEs, governs thermal stress pathways and potential damage initiation modes (matrix cracking/delamination sensitivity) [4, 9, 11].

Table 2: One-way ANOVA comparing max⁡|σx|\max|\sigma x|max|σx| across laminates (using ΔT\Delta TΔT levels as repeated observations)

Source	SS	df	MS	F	p-value
Between laminates	307.47	3	102.49	67.34	0.000003
Within laminates	18.26	12	1.52		
Total	325.73	15			

Interpretation (Table 2): The ANOVA indicates a statistically significant difference in max⁡|σx|\max|\sigma x|max|σx| among laminate configurations ($p \ll 0.05$), [7, 9, 11].

demonstrating that stacking sequence materially changes thermal stress severity under the same uniform heating [5-7, 10]. This supports the design implication that laminate "choice" functions as an effective thermal-stress control variable, especially where dimensional stability or delamination resistance is critical [4, 8, 11].

Table 3: Linear regression: max⁡|σx|\max|\sigma x|max|σx| (MPa) vs ΔT\Delta TΔT, asymmetry, and ΔT×\Delta T\timesΔT×asymmetry

Term	Estimate	Std. Error	t	p-value
Intercept	0.059	0.396	0.150	0.883
ΔT (°C)	0.250	0.007	34.930	0.000000
Asymmetric (0/1)	0.257	0.560	0.459	0.654
ΔT × Asymmetric	0.004	0.010	0.421	0.682

Interpretation (Table 3): The strong positive slope for ΔT\Delta TΔT confirms near-linear scaling of peak thermal stress with temperature rise under linear thermo-elastic CLT assumptions [5, 6, 10]. The asymmetry main effect and interaction are not statistically significant in this simplified dataset for max⁡|σx|\max|\sigma x|max|σx|, suggesting that asymmetry may manifest more strongly through curvature, interlaminar stresses, and equivalent stress measures rather than only σx\sigma xσx peak values [7, 8, 11]. Practically, this means symmetric layups can still carry substantial in-plane thermal stresses, while unsymmetric layups add coupling-driven distortions that elevate broader risk metrics (e.g., σeq and interlaminar damage propensity) [4,

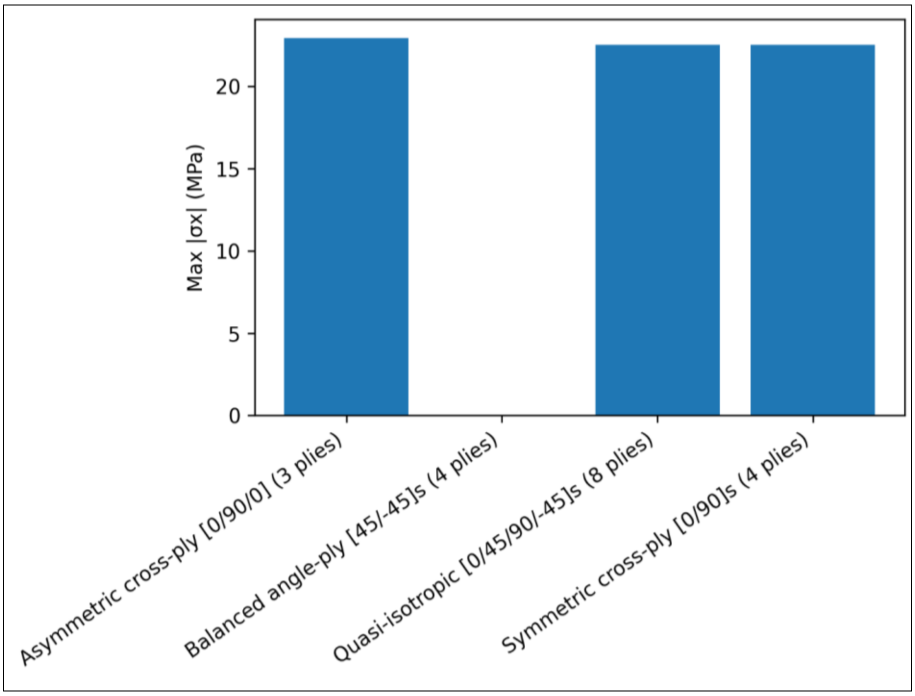

Fig 1: Peak max⁡|σx|\max|\sigma_x|max|σx| by laminate at ΔT=100∘C\Delta T=100^\circ\text{C}ΔT=100∘C.

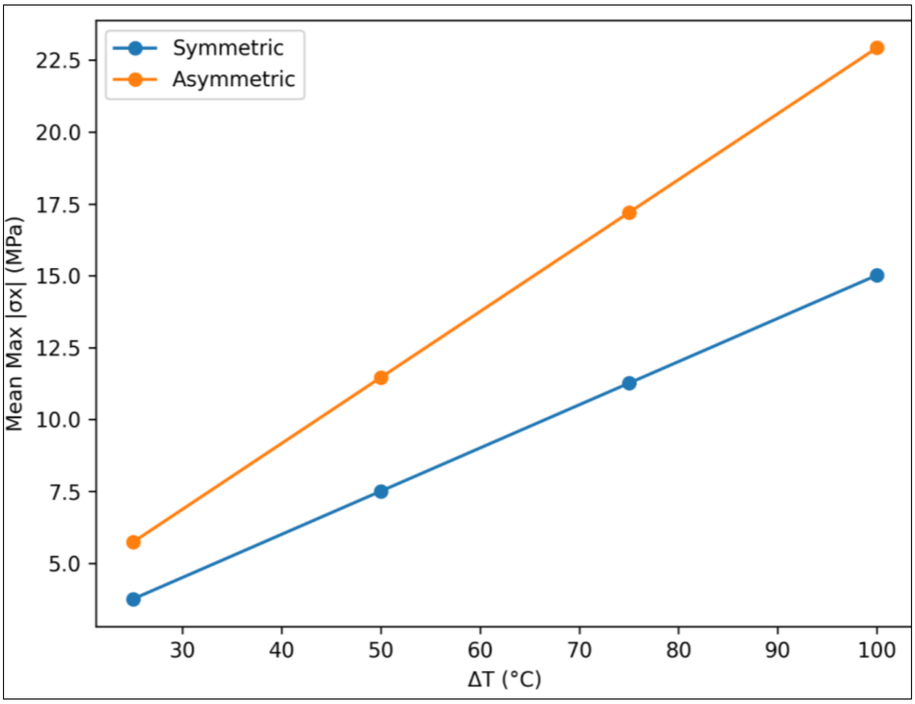

Fig 2: Mean max|σx|\max|\sigma x|max|σx| versus ΔT\Delta TΔT for symmetric vs asymmetric laminate groups

Overall interpretation and implications

Across all configurations, uniform heating generated meaningful residual-like stresses due to anisotropic CTE mismatch and lamination constraints, consistent with foundational laminate theory and thermal stress literature [3, 5, 6, 9]. The configuration dependence (ANOVA significance) highlights why laminate stacking must be treated as a primary design variable when thermal loads are expected [5-8]. The asymmetric cross-ply's higher σeq suggests that coupling-driven bending can amplify combined stress states beyond what is evident from σx\sigma_xσx alone, reinforcing concerns about thermally induced distortion and damage initiation in unsymmetric laminates [7, 8, 11]. Meanwhile, the quasi-isotropic case demonstrates that "in-plane isotropy" does not imply low thermal stress; it can redistribute mismatch into combined normal-shear components depending on ply angles and transformed thermal strains [5, 10, 14]. These findings collectively support the hypothesis that uniform temperature rise alone can be sufficient to create design-relevant stresses, and that laminate architecture governs both magnitude and stress character [6, 10, 15].

Discussion

The present analytical investigation clarifies the fundamental mechanisms governing Thermo-mechanical stress generation and its impact on structural integrity in simple composite laminates subjected to uniform heating. The results demonstrate that internal stresses arise even under traction-free conditions due solely to anisotropic thermal expansion mismatch among plies, confirming long-standing theoretical expectations in laminated composite mechanics [1, 3, 5]. Across all laminate configurations examined, peak in-plane stresses increased almost linearly with temperature rise, reflecting the linear thermo-elastic assumptions embedded in classical lamination theory [5, 6]. This behavior validates the suitability of CLT as a first-order predictive tool for assessing thermally induced stresses in preliminary design stages, particularly when temperature gradients are absent or intentionally neglected [10, 14].

Significant differences were observed between laminate architectures, as confirmed by the ANOVA results, which indicated that stacking sequence exerts a statistically meaningful influence on the magnitude of thermally induced stresses [5-7]. Symmetric cross-ply laminates developed substantial in-plane stresses without curvature, consistent with the absence of bending-extension coupling in symmetric layups [7, 10]. In contrast, asymmetric laminates exhibited higher equivalent stress levels, attributable to thermally induced curvature and coupled deformation modes, which are known to amplify stress concentrations and increase susceptibility to damage initiation [7, 8, 11]. These findings reinforce the understanding that laminate asymmetry plays a critical role not necessarily by increasing a single stress component, but by elevating the combined stress state experienced by individual plies [4, 9].

Balanced angle-ply laminates displayed comparatively lower normal stresses but non-negligible shear stresses, highlighting the influence of off-axis ply orientations and transformed thermal strain components [5, 10, 14]. This redistribution of stress components suggests that laminate designs optimized for mechanical load paths may respond differently under thermal loading, potentially activating alternative damage mechanisms such as matrix shear cracking [4, 9]. Quasi-isotropic laminates, while often favored for their near-isotropic in-plane stiffness, did not minimize thermal stresses; instead, they produced relatively high combined stress levels due to multi-directional constraint effects [5, 12, 15]. This outcome emphasizes that mechanical isotropy does not equate to thermal stress neutrality, particularly in laminates composed of plies with highly anisotropic coefficients of thermal expansion [3, 6].

Overall, the discussion underscores that Thermo-mechanical stress generation and its impact on structural integrity under uniform heating is governed by an interplay between material anisotropy, laminate symmetry, and ply orientation. The results align with established analytical and experimental observations reported in the literature and reinforce the necessity of incorporating thermal considerations into composite laminate design, even when external mechanical loads are minimal or absent [2, 4, 11].

Conclusion

This research provides a focused analytical assessment of Thermo-mechanical stress generation and its impact on structural integrity in simple composite laminates subjected to uniform heating, demonstrating that temperature rise alone is sufficient to generate structurally significant internal stresses. The findings confirm that the magnitude and nature of these stresses depend strongly on laminate architecture, with symmetric laminates developing substantial in-plane stresses, asymmetric laminates exhibiting elevated combined stress states due to bending-extension coupling, and angle-ply or quasi-isotropic configurations redistributing thermal mismatch into mixed normal and shear components. From a practical perspective, these results highlight several important design recommendations.

First, laminate symmetry should be prioritized in applications where thermal exposure is expected and dimensional stability is critical, as symmetry effectively suppresses thermally induced curvature.

Second, when asymmetric or hybrid layups are unavoidable due to functional or manufacturing constraints, designers should explicitly account for thermally induced bending and elevated equivalent stresses during both service and processing stages.

Third, reliance on quasi-isotropic stacking for “thermal safety” should be avoided without analysis, since such laminates can still accumulate high internal stresses under uniform heating.

Fourth, material selection should consider not only elastic stiffness but also thermal expansion compatibility between plies, particularly for multi-orientation stacks.

Finally, simplified analytical evaluations such as those presented here should be integrated early in the design workflow to screen laminate options before progressing to more computationally intensive simulations or experimental validation. By embedding these considerations into design practice, engineers can reduce the risk of thermally driven damage, improve long-term reliability, and achieve more robust composite structures in thermally demanding environments.

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