

Article

Towards Full Orthotropy in Laminated Composites: The Tailored Antisymmetric Concept

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Abstract

Orthotropic laminates are highly desirable in composite structures because they eliminate bending–twisting coupling, simplify structural behavior, improve analytical predictability, and facilitate structural design, optimization, and certification. However, achieving fully orthotropic behavior in laminated composites remains challenging because conventional laminate architectures generally retain stiffness couplings arising from anisotropic ply orientations and stacking-sequence effects. This work introduces the Tailored Antisymmetric Composite (TAC) concept, a laminate architecture that provides the closest practical approximation to full orthotropy while preserving broad stiffness-tailoring capability and manufacturability. TAC laminates are constructed from tailored antisymmetric sublaminates that enforce $D_{16} = D_{26} = 0$ while maintaining extremely small extension–bending coupling terms B_{16} and B_{26} . Representative TAC and symmetric Quad laminates were compared analytically, statistically, and experimentally. Monte Carlo simulations comprising 100,000 realizations with realistic $\pm 0.1^\circ$ AFP/ATL fiber-orientation deviations showed that the distributions of the extension–bending coupling terms B_{16}^* and B_{26}^* remained nearly indistinguishable for both laminate architectures, with probability-density overlap coefficients between 0.87 and 0.98. In contrast, the bending–twisting coupling terms D_{16}^* and D_{26}^* were 140–600 times lower in TAC laminates than in the corresponding Quad laminates, and their statistical distributions exhibited complete separation. Experimental measurements of post-cure warpage confirmed that TAC laminates achieved dimensional stability comparable to symmetric Quad laminates while exhibiting lower variability. These results demonstrate that TAC laminates combine exact elimination of bending–twisting coupling with negligible extension–bending coupling, statistical robustness to realistic manufacturing variability, and excellent dimensional stability, establishing TAC as a practical and systematic route toward full orthotropy in laminated composite structures.

Keywords: tailored antisymmetric composites (TAC); orthotropic laminates; extension-bending coupling; bending–twisting coupling; classical lamination theory

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1. Introduction

Quadriaxial (Quad) laminates, composed of unidirectional plies oriented at 0° , $\pm 45^\circ$, and 90° , have been the standard architecture for aerospace composite structures for more

than six decades because they provide an effective compromise between stiffness, strength, manufacturability, and certification maturity [1–4]. Their widespread adoption has been reinforced by well-established industrial design rules, including symmetry, the 10% rule, blending requirements, and ply-drop constraints, which together have produced reliable and highly manufacturable structural configurations [5–13]. Despite their success, conventional Quad laminates are not fully orthotropic. Except for special stacking sequences such as cross-ply laminates, they generally retain non-zero bending–twisting coupling terms D_{16} and D_{26} , which influence structural response, cure distortion, buckling, vibration, aeroelastic behavior, and wave propagation [14,15].

The mechanics of laminate coupling are well established within Classical Laminate Theory (CLT), where the structural response is described by the extensional, extension–bending coupling, and bending stiffness matrices **A**, **B**, and **D** [16–19]. Symmetric laminates eliminate extension–bending coupling because the **B** matrix vanishes identically. However, symmetry alone does not eliminate bending–twisting coupling, and practical Quad laminates containing off-axis plies generally exhibit non-zero D_{16} and D_{26} . Consequently, laminate designers have traditionally faced a compromise between eliminating extension–bending coupling through symmetry or reducing bending–twisting coupling using non-symmetric architectures.

This compromise has motivated extensive research into fully orthotropic laminate architectures. Early work by Bartholomew [20] established the theoretical conditions required for bending orthotropy, while the ESDU design procedures [21] translated these concepts into practical engineering guidelines. Subsequently, Caprino and Crivelli-Visconti [18,22] identified antisymmetric laminate configurations capable of eliminating bending–twisting coupling while preserving desirable in-plane mechanical properties. Fully orthotropic laminates offer important practical advantages over conventional balanced symmetric laminates, including reduced manufacturing distortion and improved compression–buckling performance [23]. For example, anti-symmetric laminates have been shown to improve consolidation by more than 6% in tapered C-section beams while substantially reducing processing-induced warpage [24,25]. Valot [26] later demonstrated that, with the exception of cross-ply laminates, antisymmetric stacking sequences constitute the only general laminate family capable of simultaneously aligning the principal extensional and bending stiffness directions. Building upon these developments, Vannucci [27,28] employed polar formalism to characterize uncoupled laminate families, Verchery [29] introduced invariant representations for anisotropic laminates, and Grediac and co-workers [30] further demonstrated that uncoupled non-symmetric laminates occupy a substantially larger design space than previously recognized.

Subsequent investigations extended these concepts toward practical structural applications. Several authors proposed orthotropic laminate families based on combinations of symmetric angle-ply and non-symmetric cross-ply subsequences [31,32], while others investigated their damage tolerance, impact resistance, and compression-after-impact performance [33–35]. A comprehensive review of non-symmetric laminate architectures was presented in [36], highlighting both their attractive theoretical characteristics and the practical difficulties that have limited their industrial adoption. In particular, many previously proposed orthotropic laminates rely on complex or irregular stacking sequences that are difficult to manufacture, optimize, or integrate into conventional aerospace design practices.

Recently, Tailored Antisymmetric Composites (TAC) were introduced as a new family of ultra-thin antisymmetric laminates specifically developed to overcome these practical limitations [37,38]. Unlike previous uncoupled laminate concepts, TAC laminates are constructed from simple repeating antisymmetric building blocks that preserve broad stiffness-tailoring capability while enforcing $D_{16} = D_{26} = 0$ exactly by construction. At

the same time, the extension–bending coupling terms B_{16} and B_{26} remain extremely small and decrease rapidly with laminate thickness, allowing TAC laminates to approach the mechanical behavior of an ideal orthotropic laminate while remaining compatible with conventional automated manufacturing processes.

Although the fundamental TAC concept has been previously introduced [37,38], its robustness under realistic manufacturing variability has not been investigated. In particular, it remains unknown whether the theoretical advantages of TAC laminates are preserved under the fiber-orientation deviations typically associated with Automated Fiber Placement (AFP) and Automated Tape Laying (ATL), and whether their residual extension–bending coupling remains comparable to that of conventional symmetric Quad laminates.

The objective of the present work is therefore to evaluate whether TAC laminates constitute the closest practical approximation to fully orthotropic laminated composites currently available. Representative hard, neutral, and soft Quad laminates are first converted into equivalent TAC laminates using a genetic-algorithm optimization procedure. Their coupling behavior is then compared analytically, followed by a Monte Carlo study comprising 100,000 realizations incorporating realistic AFP/ATL angular deviations. Finally, experimental measurements of post-cure warpage are used to validate the analytical and statistical predictions. Together, these results provide a comprehensive assessment of the structural performance and manufacturing robustness of the TAC concept relative to conventional symmetric Quad laminates.

Limitations of Conventional Symmetric Laminates

The widespread adoption of symmetric Quad laminates reflects their proven reliability rather than their ability to provide optimal structural performance under all loading and manufacturing conditions. During the last three decades, numerous analytical, numerical, and experimental investigations have shown that laminate symmetry, although effective in eliminating extension–bending coupling, does not remove all undesirable coupling mechanisms and may restrict structural tailoring in several important engineering applications. The principal limitations identified in the literature are summarized below.

1. Residual bending–twisting coupling.

The most fundamental limitation of conventional symmetric laminates is the persistence of the bending–twisting coupling terms D_{16} and D_{26} . Early studies by Tsai and Hahn [14] and Herakovich [15] demonstrated that symmetric laminates containing off-axis plies generally retain flexural anisotropy, even when extension–bending coupling is eliminated. Caprino and Crivelli-Visconti [18,22] further showed that true bending orthotropy requires special laminate architectures rather than symmetry alone. Consequently, bending loads may induce twisting deformations and torsional loading may produce bending responses, increasing structural anisotropy and complicating structural analysis.

2. Geometric non-symmetry and structural response.

Many aerospace structures, including stiffened panels, C-sections, spars, tapered beams, and localized reinforcements, are geometrically non-symmetric even when fabricated from symmetric laminates. Kim and Hong [39], Kim et al. [40], and Tsai and co-workers [41] demonstrated that geometric asymmetry can generate significant coupling effects that are not eliminated by laminate symmetry alone. Experimental studies on tapered composite members further showed that appropriately tailored non-symmetric laminates may exhibit improved consolidation quality, reduced warpage, and higher structural efficiency than equivalent symmetric configurations [24,25,42]. Furthermore,

anisotropic laminate tailoring has been successfully employed to mitigate cure-induced warpage during manufacturing [43].

3. Manufacturing distortion of curved structures.

Manufacturing studies have shown that warpage, spring-in, and spring-back of curved composite components are governed primarily by the interaction between laminate anisotropy, thermal gradients, and cure shrinkage rather than by laminate symmetry alone. Classical investigations by Wisnom [14,44] established the fundamental mechanisms governing cure distortion, while subsequent experimental work [45–50] demonstrated that tailored non-symmetric laminates can significantly reduce twisting, spring-in, and thickness variability in curved aerospace components.

4. Damage tolerance and impact performance.

The influence of laminate symmetry on impact damage has received increasing attention in recent years. Studies by Sasikumar [51] demonstrated that non-symmetric laminate architectures permit redistribution of delamination interfaces through the laminate thickness, reducing the tendency for large surface delaminations that degrade compression-after-impact (CAI) strength. Compared with conventional symmetric laminates, tailored non-symmetric stacking sequences have been shown to improve post-impact structural performance by relocating damage toward less critical interior interfaces.

5. Functional and multifunctional laminate design.

Recent developments in multifunctional composite structures have expanded the role of antisymmetric laminates beyond conventional load-bearing applications. Verma [52] first proposed the integration of shape-memory alloy (SMA) actuators into antisymmetric laminates for adaptive stiffness control. Subsequent investigations [53–61] demonstrated that SMA-reinforced antisymmetric laminates can modify natural frequencies, reduce vibroacoustic radiation, and actively tailor structural response. These multifunctional capabilities are difficult to achieve using conventional symmetric Quad architectures because of their restricted bending behavior.

6. Buckling sensitivity.

The influence of bending–twisting coupling on structural stability has been extensively investigated. Classical buckling analyses [62–67] established that non-zero D_{16} and D_{26} alter eigenmode shapes and reduce critical buckling loads. More recent numerical and experimental investigations [68–77] confirmed that even relatively small bending–twisting coupling terms increase sensitivity to geometric imperfections, loading eccentricity, and boundary conditions, leading to earlier instability and more complex post-buckling behavior.

7. Restricted laminate optimization.

Modern laminate optimization increasingly relies on genetic algorithms, lamination parameters, topology optimization, and other computational design methods. However, the symmetry requirement significantly reduces the available design space because each ply placed above the laminate mid-plane must be mirrored below it. As discussed by Vannucci [27,28], Verchery [29], and Grediac [30], relaxing the symmetry constraint substantially enlarges the number of feasible laminate configurations while preserving desirable stiffness characteristics. This expanded design freedom provides additional opportunities for simultaneously optimizing stiffness, stability, vibration response, and manufacturability.

The limitations summarized above should not be interpreted as shortcomings of symmetric Quad laminates, which remain highly successful engineering solutions and continue to dominate aerospace structural design. Rather, they demonstrate that residual bending–twisting coupling and the geometric constraints imposed by symmetry continue

to motivate the development of alternative laminate architectures capable of approaching fully orthotropic behavior while preserving practical manufacturability. The following sections investigate one such architecture through a comprehensive analytical, statistical, and experimental comparison with conventional symmetric Quad laminates.

2. Materials and Methods

2.1. Materials

The material employed is AS4/8552 (Hexcel Corporation, West Valley City, UT, USA), with its elastic properties detailed in Table 1, and a ply thickness of 0.125 mm.

Table 1. AS4/8552 elastic properties [78].

Property	Value
E_{11}	131.53 GPa
E_{22}	9.23 GPa
ν_{12}	0.3
G_{12}	4.82 GPa

2.2. Definition of TAC Laminates

Classical Laminate Theory (CLT) [1–3] relates the in-plane force and bending moment resultants acting on a laminate to the corresponding mid-plane strains and curvatures through

$$\begin{bmatrix} \mathbf{n} \\ \mathbf{m} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \boldsymbol{\epsilon} \\ \boldsymbol{\kappa} \end{bmatrix} \quad (1)$$

where $\mathbf{n}$ and $\mathbf{m}$ are the vectors of in-plane force and bending moment resultants per unit width, respectively; $\mathbf{A}$ is the extensional stiffness matrix; $\mathbf{D}$ is the bending stiffness matrix; and $\mathbf{B}$ is the extension–bending coupling matrix. The strain vector $\boldsymbol{\epsilon}$ represents the mid-plane membrane deformation, whereas $\boldsymbol{\kappa}$ contains the laminate curvatures. The $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ matrices completely characterize the linear elastic response of a laminate within Classical Laminate Theory. Detailed derivations are available in Refs. [1–3].

The physical meaning of these matrices is particularly important in the present work. The $\mathbf{A}$ matrix governs the in-plane tensile and shear response, the $\mathbf{D}$ matrix controls bending and twisting stiffness, and the $\mathbf{B}$ matrix couples membrane deformation with bending. A non-zero $\mathbf{B}$ matrix implies that an in-plane load generates bending or twisting, while an applied bending moment simultaneously produces in-plane deformation. Eliminating or minimizing this coupling is often desirable because it simplifies structural behavior, improves dimensional stability, and facilitates analytical design.

For an antisymmetric laminate, Classical Laminate Theory predicts

$$A_{16} = A_{26} = D_{16} = D_{26} = B_{11} = B_{12} = B_{22} = B_{66} = 0 \quad (2)$$

leaving only the coupling terms B_{16} and B_{26} potentially non-zero. Consequently, antisymmetric laminates naturally eliminate most extension–bending coupling, and their mechanical behavior is governed almost entirely by these two remaining coupling coefficients.

To enable meaningful comparisons between laminates of different thicknesses, the stiffness matrices are normalized according to

$$\mathbf{A}^*, \mathbf{B}^*, \mathbf{D}^* = \left[\frac{A_{ij}}{h}, \frac{2B_{ij}}{h^2}, \frac{12D_{ij}}{h^3} \right] \quad (3)$$

where h is the total laminate thickness. This normalization removes the trivial dependence of the stiffness matrices on laminate thickness so that different stacking sequences can be compared solely on the basis of their intrinsic mechanical behavior.

A laminate is classified as a Tailored Antisymmetric Composite (TAC) if it consists of antisymmetric sublaminates whose remaining normalized coupling terms satisfy

$$J^* = \frac{\max(|B_{16}^*|, |B_{26}^*|)}{\text{Trace}} = 2.0 \times 10^{-4} \quad (4)$$

where the Trace parameter is defined as [79–81]:

$$\text{Trace} = A_{11}^* + A_{22}^* + 2A_{66}^* \quad (5)$$

The parameter J^* provides a dimensionless measure of the residual extension–bending coupling remaining in an antisymmetric laminate. The numerator represents the largest of the two coupling terms that survive antisymmetry, while the denominator scales these values by the overall in-plane stiffness level of the laminate. Consequently, J^* quantifies the coupling independently of material system, laminate thickness, or absolute stiffness magnitude, making it suitable for comparing laminates with different architectures.

The threshold $J^* = 2.0 \times 10^{-4}$ defines the TAC laminate family. Earlier work proposed a limit of 2.0×10^{-2} , which was experimentally validated as sufficiently small for practical engineering applications [7,16,38]. The present work adopts a value that is 100 times smaller, thereby ensuring that the remaining extension–bending coupling becomes practically negligible while preserving the characteristic advantages of antisymmetric laminates. As demonstrated in later sections, laminates satisfying this criterion exhibit coupling levels comparable to those of fully symmetric laminates while simultaneously retaining the unique design flexibility offered by antisymmetric stacking sequences.

For clarity and computational efficiency, the laminate search performed in this study was restricted to antisymmetric sublaminates containing 6–8 plies with integer-valued fiber orientations. This restriction applies only to the optimization procedure adopted herein. The TAC concept itself is general and may be extended to laminates containing any number of plies and continuous (real-valued) fiber orientations.

2.3. Genetic Algorithm Design Procedure

To identify the TAC laminate that best reproduces the in-plane stiffness characteristics of a given symmetric Quad laminate, the optimization problem was formulated as a discrete stacking-sequence search over integer fiber orientations. Such problems are characterized by a highly non-convex objective function, multiple local minima, and discrete design variables, making conventional gradient-based optimization methods difficult to apply directly. Consequently, stochastic optimization techniques have become widely adopted for composite laminate design and stacking-sequence optimization. Among these, genetic algorithms (GAs) have consistently demonstrated excellent performance in solving discrete laminate optimization problems because they require no gradient information, effectively explore large combinatorial design spaces, and exhibit reduced sensitivity to local minima [5,6,8–13].

In the present study, each candidate TAC laminate is represented by three or four independent fiber-orientation variables corresponding to the upper antisymmetric sublaminate. An initial population of candidate stacking sequences is generated randomly and evolved through successive generations using the standard genetic operators of tournament selection, uniform crossover, mutation, and elitism. At each generation, every candidate laminate is evaluated using Classical Laminate Theory, and its normalized extensional stiffness matrix is compared with that of the target Quad laminate.

The optimization seeks TAC laminates that simultaneously reproduce the normalized in-plane stiffness of the reference Quad laminate while satisfying the TAC uncoupling criterion. The objective function is defined as

$$J^* = \frac{\max(|B_{16}^*|, |B_{26}^*|)}{\text{Trace}} \quad (6)$$

subject to

$$J^* = 2 \times 10^{-4} \quad (7)$$

The optimization terminates when a laminate satisfying the prescribed coupling criterion is identified. A detailed step-by-step example of the optimization procedure is provided in Appendix A, including genome encoding, population initialization, selection, crossover, mutation, constraint handling, and convergence toward the final TAC stacking sequence.

Appendix A provides a detailed, step-by-step example for the case of a six-ply symmetric laminate. Starting from the baseline configuration $[10^\circ/-20^\circ/90^\circ]_s$, the GA converged after 41 generations to the TAC stack

$$[+10^\circ/-19^\circ/+86^\circ/-86^\circ/+19^\circ/-10^\circ].$$

All intermediate stacking sequences evaluated during the optimization are listed in Table 2, enabling full reproducibility of the search.

Table 2. Intermediate stacking sequences using GA.

Generation	Best $[q_1, q_2, q_3]$	OF
0	$[10^\circ/-20^\circ/90^\circ]$	1.95×10^{-2}
8	$[13^\circ/-23^\circ/88^\circ]$	7.42×10^{-3}
17	$[14^\circ/-18^\circ/87^\circ]$	2.71×10^{-3}
29	$[12^\circ/-19^\circ/86^\circ]$	6.08×10^{-4}
41	$[10^\circ/-19^\circ/86^\circ]$	1.73×10^{-4}

The GA was implemented using a population size of 80 candidate laminates. Each chromosome contained three or four integer-valued fiber-orientation variables, depending on whether a 6-ply or 8-ply TAC sublaminates was being optimized. The initial population was generated by perturbing the starting Quad angles within the admissible orientation range. Tournament selection with a tournament size of four was used to select parent laminates. Uniform crossover was then applied with a crossover probability of $p_c = 0.80$, and each gene was mutated with probability $p_m = 0.10$ by adding a randomly selected integer angular perturbation. Elitism was used by carrying the best individual from each generation directly into the next generation. The optimization was terminated when the coupling index satisfied $J^* = 2.0 \times 10^{-4}$, while maintaining the required agreement between the normalized in-plane stiffness matrix of the TAC laminate and that of the target Quad laminate. To confirm convergence robustness, each optimization case was repeated several times using different random seeds; the same final laminate, or an equivalent laminate with indistinguishable J^* and in-plane stiffness terms, was obtained in all successful runs. The present implementation was deterministic for the reported example once the random seed was fixed; future work will include systematic repeated-run statistics to further quantify convergence robustness.

The corresponding normalized in-plane stiffness matrices for both the baseline and TAC laminates are compared in Equation (8), expressed in GPa. By applying the same methodology, TAC substitutes can likewise be derived for seven-ply and eight-ply laminates.

$$\mathbf{A}_{[+10^\circ/-20^\circ/90^\circ]_s}^* = \begin{bmatrix} 80.144 & 7.947 & -4.749 \\ 7.947 & 51.190 & -1.420 \\ -4.749 & -1.420 & 9.908 \end{bmatrix} \mathbf{A}_{[+10^\circ/-19^\circ/+86^\circ/-86^\circ/+19^\circ/-10^\circ]}^* = \begin{bmatrix} 80.938 & 7.803 & 0 \\ 7.803 & 50.684 & 0 \\ 0 & 0 & 9.836 \end{bmatrix} \quad (8)$$

The material employed is AS4/8552, with its elastic properties detailed in Table 1.

2.4. Monte Carlo Methodology

Twelve Monte Carlo simulations, each comprising 100,000 random perturbations, were performed to quantify the extension–bending coupling terms B_{16}^* , B_{26}^* , D_{16}^* and D_{26}^* under realistic AFP/ATL fiber-placement angular errors. The simulations cover three laminate stiffness regimes (hard, soft, and neutral), two laminate architectures (Quad and TAC), and two extension–bending coupling terms, resulting in a total of twelve independent cases.

All composite manufacturing processes, including the most precise AFP/ATL systems, introduce some degree of ply-angle misalignment [82–98]. Measurements reported for multiple AFP/ATL-manufactured panels indicate a representative fiber-placement tolerance of $\pm 0.1^\circ$. Accordingly, for each laminate regime (hard, soft, and neutral) and each architecture (Quad and TAC), 100,000 random fiber-orientation deviations uniformly distributed between -0.1° and $+0.1^\circ$ were applied to compute the resulting values of $\text{abs}[B_{16}^*]$, $\text{abs}[B_{26}^*]$, $\text{abs}[D_{16}^*]$ and $\text{abs}[D_{26}^*]$.

2.5. Experimental Procedure

An experimental evaluation was conducted to evaluate the warping behavior of ultra-thin composite plates, fabricated using TAC and Quad laminates, during cooling from 180°C to 22°C after curing [37]. Four 0.5×0.5 m plates, two with TAC laminates and two with Quad laminates, each consisting of 8 plies, were manufactured at FIDAMC (Madrid, Spain) using an Torreslayup 11 axes Gantry CNC tape layer machine (MTorres, Pamplona, Spain).

The test campaign intentionally pushed warpage toward its theoretical upper bound by employing the thinnest balanced-symmetric Quad laminate that is practically allowable. Because warpage increases as laminate thickness decreases, this minimum thickness constraint applies equally to both Quad and TAC architectures. For Quad lay-ups, the lower bound is eight plies (≈ 1 mm); accordingly, the 8-ply TAC panels were benchmarked directly against 8-ply Quad panels of identical thickness.

Warping was quantified by placing each cured plate on a precision-ground marble surface plate and measuring the maximum gap with a dial micrometer. Two TAC laminates with the sequence $[+21^\circ/-31^\circ/-12^\circ/+54^\circ/-54^\circ/+12^\circ/+31^\circ/-21^\circ]$ and two identically sized plates with a conventional symmetric Quad lay-up $[+45^\circ/0^\circ/-45^\circ/90^\circ]_s$ were fabricated and assessed after curing.

2.6. Workflow of the Proposed Methodology

To clarify the overall methodology, Figure 1 summarizes the step-by-step workflow used in this study. The procedure begins with the selection of a reference Quad laminate, followed by CLT-based stiffness evaluation, TAC generation through antisymmetric sublaminates design, genetic-algorithm optimization, ideal coupling comparison, Monte Carlo assessment under realistic fiber-orientation variability, and experimental warpage validation.

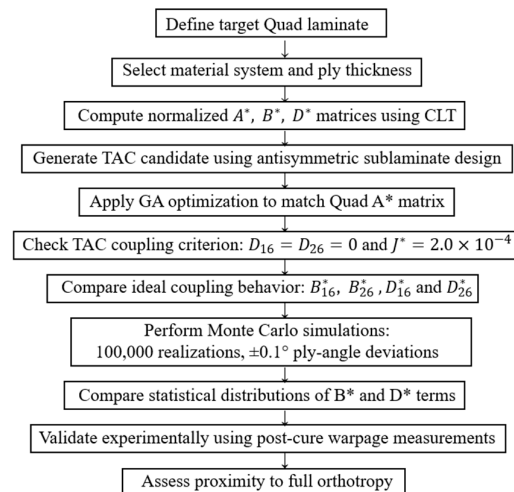


Figure 1. Workflow used in this study.

3. Results

3.1. Ideal Laminate Comparison

This section compares the coupling behavior and homogenization characteristics of representative Quad and TAC laminates for the three stiffness regimes considered in this work: hard, soft, and neutral. For each regime, a representative Quad laminate is paired with a TAC laminate whose normalized in-plane stiffness matrix closely matches that of the reference Quad. The comparison focuses on the extension–bending coupling terms B_{16}^* and B_{26}^* , the bending–twisting coupling terms D_{16}^* and D_{26}^* , and the convergence of the normalized bending stiffness matrix D^* toward the normalized extensional stiffness matrix A^* as the number of laminate repetitions increases.

To ensure identical total thickness, the 8-ply TAC unit cell is repeated to match the thickness of the corresponding 16-, 24-, and 32-ply Quad laminates. All results correspond to the AS4/8552 material system, and normalized stiffness coefficients are expressed in GPa.

3.1.1. Hard Laminates

As a representative hard laminate, the symmetric Quad stacking sequence

$$[0^\circ/+45^\circ/0^\circ/-45^\circ/90^\circ/0^\circ/90^\circ/0^\circ]_s$$

was converted into the TAC laminate

$$[+3^\circ/-7^\circ/-85^\circ/+47^\circ/-47^\circ/+85^\circ/+7^\circ/-3^\circ]_2$$

using the design methodology described in Section 2, yielding $J^* = 2.35 \cdot 10^{-5}$. The normalized extensional stiffness matrices of both laminates are compared in Equation (9). The corresponding matrices are very similar, indicating that the TAC laminate reproduces the in-plane stiffness characteristics of the reference Quad laminate.

$$\begin{aligned}
 \mathbf{ABD}_{\text{Quad}}^* &= \begin{bmatrix} 78.77 & 9.80 & 0 & 0 & 0 & 0 \\ 9.80 & 48.04 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12.14 & 0 & 0 & 0 \\ 0 & 0 & 0 & 88.37 & 13.34 & \mathbf{3.96} \\ 0 & 0 & 0 & 13.34 & 31.68 & \mathbf{3.96} \\ 0 & 0 & 0 & \mathbf{3.96} & \mathbf{3.96} & 15.57 \end{bmatrix} \\
 \mathbf{ABD}_{\text{TAC}}^* &= \begin{bmatrix} 76.84 & 10.78 & 0 & 0 & 0 & \mathbf{0.0017} \\ 10.78 & 48.83 & 0 & 0 & 0 & \mathbf{-0.0005} \\ 0 & 0 & 12.82 & \mathbf{0.0017} & \mathbf{-0.0005} & 0 \\ 0 & 0 & \mathbf{0.0017} & 86.54 & 8.92 & \mathbf{0} \\ 0 & 0 & \mathbf{-0.0005} & 8.92 & 42.36 & \mathbf{0} \\ \mathbf{0.0017} & \mathbf{-0.0005} & 0 & \mathbf{0} & \mathbf{0} & 11.14 \end{bmatrix}
 \end{aligned} \tag{9}$$

Figure 2 shows the variation in the coupling terms with laminate thickness. For the TAC laminate, the extension–bending coupling terms B_{16}^* and B_{26}^* decrease progressively as the number of repeats increases. For the Quad laminate, the extension–bending coupling terms remain zero, while the bending–twisting coupling terms D_{16}^* and D_{26}^* decrease with increasing ply count but remain non-zero throughout the thickness range considered.

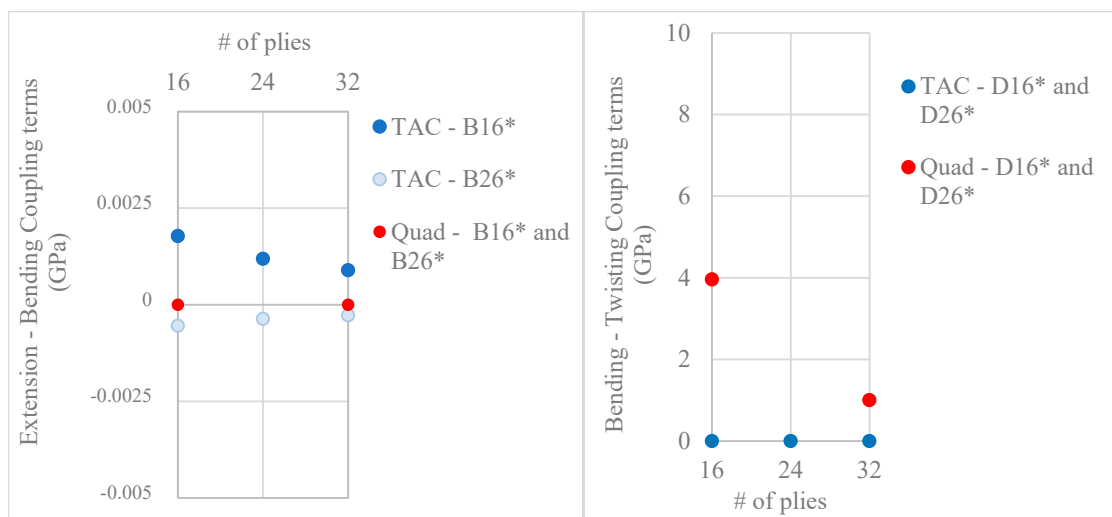


Figure 2. Evolution of laminate coupling terms with ply count: extension–bending (**left**) and bending–twisting (**right**) for the hard laminate case.

Figure 3 presents the convergence of the normalized bending stiffness coefficients toward the corresponding normalized extensional stiffness coefficients. For the TAC laminate, all four normalized stiffness components exhibit monotonic convergence as the laminate thickness increases. The Quad laminate follows the same overall trend, although the convergence rate differs among the individual stiffness coefficients.

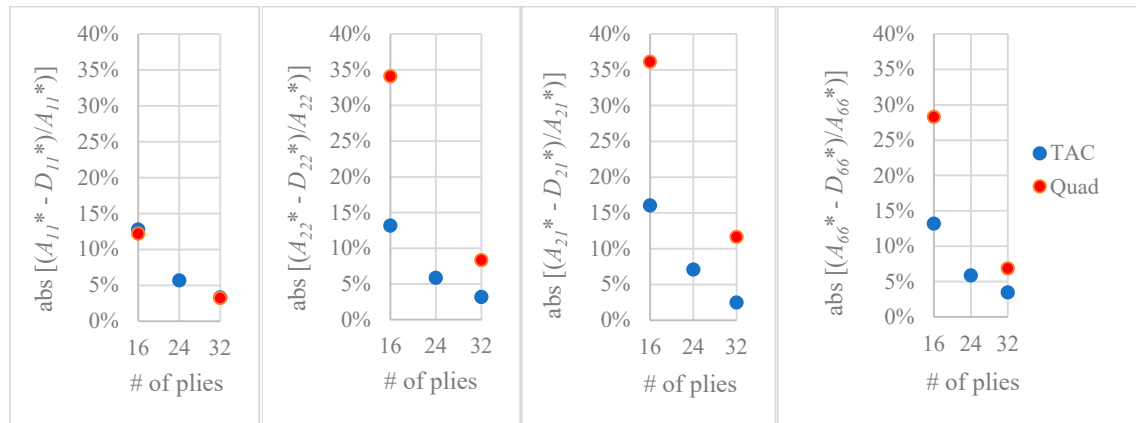


Figure 3. Convergence of normalized bending stiffness D^* toward A^* for TAC and Quad hard laminates.

3.1.2. Soft Laminates

A representative soft Quad laminate was converted into its corresponding TAC laminate using the same optimization procedure described previously, producing the laminate pair summarized in Equation (10). The normalized extensional stiffness matrices of the two laminates remain in close agreement.

$$[+45^\circ/0^\circ/-45^\circ/+45^\circ/-45^\circ/+45^\circ/90^\circ/-45^\circ]_s$$

and

$$[+41^\circ/-21^\circ/-56^\circ/-63^\circ/+63^\circ/+56^\circ/+21^\circ/-41^\circ]_2$$

$$\mathbf{ABD}^*_{\text{Quad}} = \begin{bmatrix} 48.75 & 24.46 & 0 & 0 & 0 & 0 \\ 24.46 & 48.75 & 0 & 0 & 0 & 0 \\ 0 & 0 & 26.80 & 0 & 0 & 0 \\ 0 & 0 & 0 & 63.57 & 24.20 & 7.21 \\ 0 & 0 & 0 & 24.20 & 34.75 & 7.21 \\ 0 & 0 & 0 & 7.21 & 7.21 & 26.42 \end{bmatrix} \quad (10)$$

$$\mathbf{ABD}^*_{\text{TAC}} = \begin{bmatrix} 48.01 & 24.13 & 0 & 0 & 0 & 0.0039 \\ 24.13 & 50.47 & 0 & 0 & 0 & 0.0002 \\ 0 & 0 & 26.35 & 0.0039 & 0.0002 & 0 \\ 0 & 0 & 0.0039 & 51.67 & 24.63 & 0 \\ 0 & 0 & 0.0002 & 24.63 & 45.80 & 0 \\ 0.0039 & 0.0002 & 0 & 0 & 0 & 26.85 \end{bmatrix}$$

The evolution of the coupling terms is shown in Figure 4. As in the hard laminate case, the extension–bending coupling terms of the TAC laminate decrease with increasing laminate thickness. The Quad laminate maintains zero extension–bending coupling, whereas its bending–twisting coupling terms remain non-zero over the entire ply-count range.

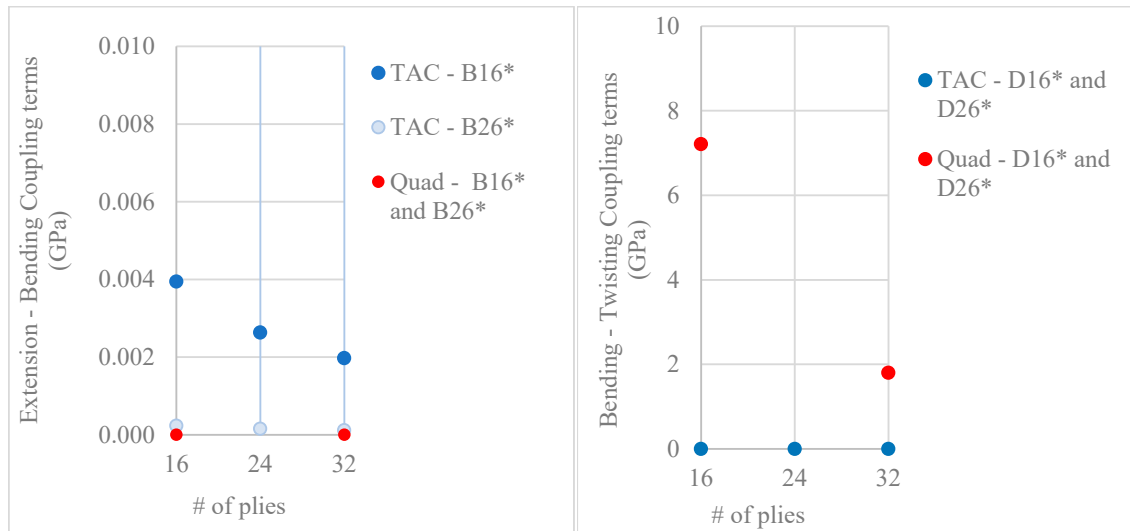


Figure 4. Evolution of laminate coupling terms with ply count: extension–bending (**left**) and bending–twisting (**right**) for the soft laminate case.

Figure 5 illustrates the convergence of the normalized bending stiffness matrix. Both laminate architectures approach the corresponding extensional stiffness matrix as additional laminate repeats are introduced. The convergence is observed for all stiffness components, although the rates differ among the individual terms.

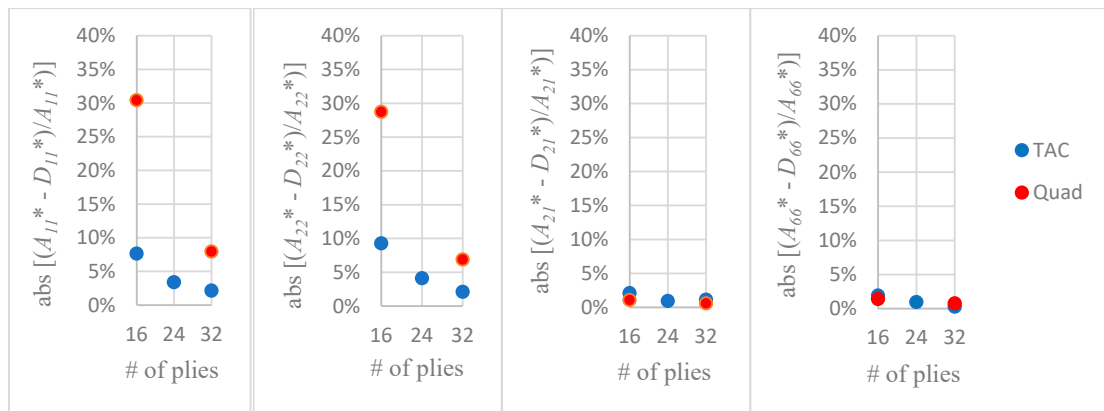


Figure 5. Convergence of normalized bending stiffness D^* toward A^* for TAC and Quad soft laminates.

3.1.3. Neutral Laminates

The neutral laminate comparison was performed using the representative Quad laminate and its optimized TAC counterpart given in Equation (11). The normalized extensional stiffness matrices again exhibit close agreement, indicating equivalent in-plane mechanical behavior.

$$[+45^\circ/0^\circ/90^\circ/-45^\circ/0^\circ/+45^\circ/90^\circ/-45^\circ/0^\circ/90^\circ]_s$$

and

$$[+9^\circ/+83^\circ/-29^\circ/-62^\circ/+62^\circ/+29^\circ/-83^\circ/-9^\circ]_2$$

$$\begin{aligned}
 \mathbf{ABD}_{\text{Quad}}^* &= \begin{bmatrix} 63.45 & 9.91 & 0 & 0 & 0 & 0 \\ 9.91 & 63.45 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12.13 & 0 & 0 & 0 \\ 0 & 0 & 0 & 69.08 & 14.37 & 7.93 \\ 0 & 0 & 0 & 14.37 & 48.91 & 7.93 \\ 0 & 0 & 0 & 7.93 & 7.93 & 16.59 \end{bmatrix} \\
 \mathbf{ABD}_{\text{TAC}}^* &= \begin{bmatrix} 63.33 & 9.61 & 0 & 0 & 0 & -0.0040 \\ 9.61 & 64.17 & 0 & 0 & 0 & -0.0021 \\ 0 & 0 & 11.83 & -0.0040 & -0.0021 & 0 \\ 0 & 0 & -0.0040 & 69.67 & 8.53 & 0 \\ 0 & 0 & -0.0021 & 8.53 & 60.01 & 0 \\ -0.0040 & -0.0021 & 0 & 0 & 0 & 10.75 \end{bmatrix}
 \end{aligned} \tag{11}$$

Figure 6 presents the variation in the coupling terms with laminate thickness. Similar trends to those observed for the hard and soft laminates are obtained. The extension–bending coupling terms of the TAC laminate decrease with increasing ply count, while the Quad laminate maintains zero values for these terms. Conversely, the bending–twisting coupling terms remain zero for the TAC laminate and decrease, but remain non-zero for the Quad laminate.

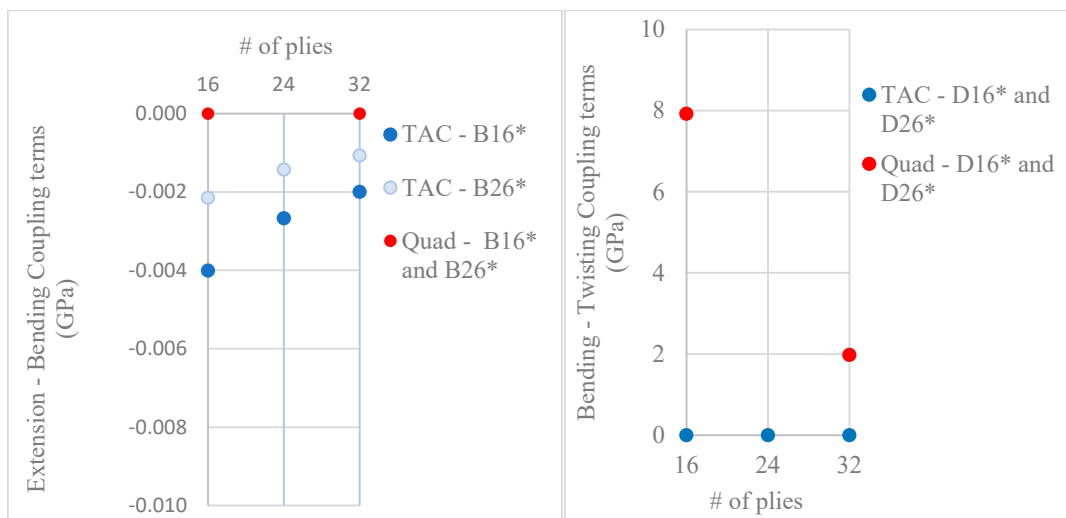


Figure 6. Evolution of laminate coupling terms with ply count: extension–bending (**left**) and bending–twisting (**right**) for the neutral laminate case.

The convergence of the normalized bending stiffness matrix is shown in Figure 7. Increasing laminate thickness produces progressive convergence toward the normalized extensional stiffness matrix for both laminate architectures. The convergence behavior is observed for all normalized stiffness coefficients considered.

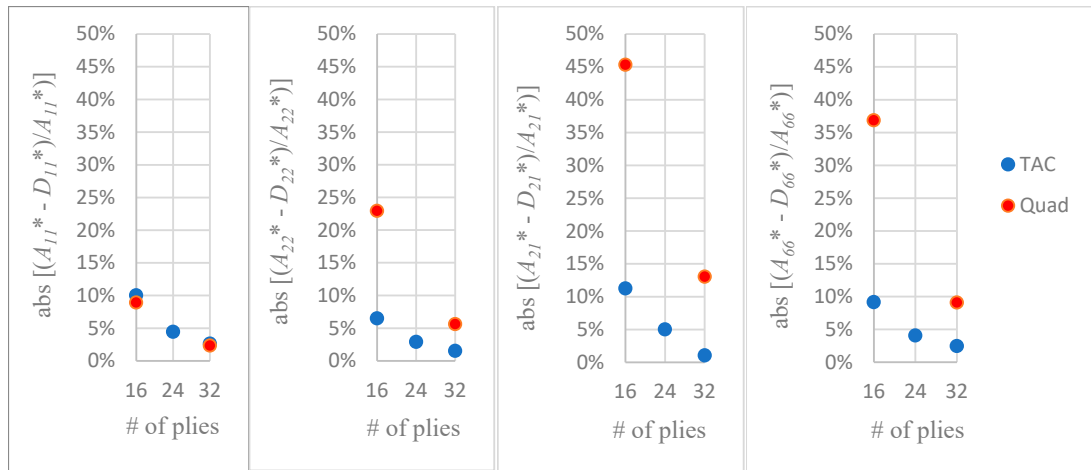


Figure 7. Convergence of normalized bending stiffness D^* toward A^* for TAC and Quad neutral laminates.

3.1.4. Summary of Ideal Laminate Behavior

The three representative laminate families exhibit similar qualitative trends. In all cases, the TAC laminates retain very small extension–bending coupling terms while maintaining identically zero bending–twisting coupling. The corresponding Quad laminates exhibit zero extension–bending coupling and non-zero bending–twisting coupling throughout the thickness range investigated.

For both laminate architectures, increasing the number of laminate repetitions reduces the difference between the normalized bending and extensional stiffness matrices. The convergence behavior is observed for the hard, soft, and neutral laminate families, with the corresponding trends presented in Figures 2, 4 and 6.

3.2. Monte Carlos Analysis

Monte Carlo simulations were performed to quantify the influence of realistic AFP/ATL fiber-orientation deviations ($\pm 0.1^\circ$) on the extension–bending coupling terms of Quad and TAC laminates. Each simulation consisted of 100,000 random realizations for the hard, neutral, and soft laminate families described previously. The statistical analysis includes the mean, standard deviation, confidence intervals, Kolmogorov–Smirnov (KS) statistic, and probability-density overlap coefficient (OVL). Histograms, empirical cumulative distribution functions (CDFs), and probability-density overlaps are presented to compare the statistical distributions of the two laminate architectures.

3.2.1. Results for the Extension-Bending Term B_{16}^*

Table 3 presents the statistical analysis of the coupling term $\text{abs}[B_{16}^*]$ under $\pm 0.1^\circ$ fiber-orientation misalignment for the hard, neutral, and soft laminates classes. The results reveal a coherent and physically meaningful progression of behavior that Table 3 summarizes the statistical characteristics of the normalized extension–bending coupling term B_{16}^* for the hard, neutral, and soft laminate families.

For the hard laminate, Quad and TAC produced nearly coincident distributions of $\text{abs}[B_{16}^*]$. The mean values were 0.01119 GPa for the Quad laminate and 0.01099 GPa for the TAC laminate, while the corresponding standard deviations differed by only 0.00017 GPa. The 95% confidence intervals for the mean were nearly overlapping, indicating similar expected values for both laminate architectures under the imposed angular perturbations.

The two-sample Kolmogorov–Smirnov statistic was 0.010. Since the KS statistic represents the maximum vertical distance between two empirical cumulative distribution functions, this value indicates that the two CDFs differ by no more than approximately 1% over the full range of $\text{abs}[B_{16}^*]$. For very large sample sizes, such as the $N = 100,000$ simulations used here, statistical tests may detect very small distributional differences even when the practical effect size is negligible; therefore, the KS statistic was interpreted together with the distribution overlap rather than by the p -value alone.

The probability-density overlap coefficient was approximately 0.98. The overlap coefficient is commonly used as a measure of agreement or similarity between probability distributions; values close to unity indicate that two distributions share most of their probability mass [99,100]. Therefore, the combination of nearly identical means, nearly coincident confidence intervals, a KS statistic of 0.010, and an overlap coefficient of 0.98 shows that the Quad and TAC laminates exhibit practically equivalent $\text{abs}[B_{16}^*]$ response in the hard-laminate regime.

For the neutral laminate, the TAC laminate exhibited lower average coupling than the corresponding Quad laminate. Both the mean value and the standard deviation decreased relative to the Quad configuration. The KS statistic increased to approximately 0.038, while the probability-density overlap coefficient decreased to approximately 0.96.

For the soft laminate, the statistical differences between the two laminate architectures became larger. The TAC laminate exhibited a lower mean value of B_{16}^* , together with a reduced standard deviation and lower upper-percentile values. The overlap coefficient decreased to approximately 0.87, indicating a greater separation between the two statistical distributions.

Table 3. Statistical comparison of the extension–bending coupling term $\text{abs}[B_{16}^*]$ for Quad and TAC laminates under $\pm 0.1^\circ$ AFP/ATL angular misalignment. Units in GPa.

	Hard Laminate		Soft Laminate		Neutral Laminate	
	Quad	TAC	Quad	TAC	Quad	TAC
Mean	0.01119	0.01099	0.00914	0.00707	0.00967	0.00891
Median	0.0096	0.00944	0.00788	0.00603	0.00831	0.00771
Std	0.00822	0.00804	0.00669	0.00526	0.00713	0.00645
min	1.0×10^{-7}	1.9×10^{-7}	7.8×10^{-7}	7.9×10^{-8}	5.7×10^{-8}	1.0×10^{-7}
max	0.0522	0.0491	0.04207	0.03527	0.04581	0.04102
95th percentile	0.02694	0.02642	0.02197	0.01717	0.02335	0.02123
KS test— p -value	5.41×10^{-5}		0		0	
Welch t -test— p -value	2.09×10^{-8}		0		0	
Levene’s test— p -value	3.61×10^{-9}		0		0	
95% CIs for the mean	[0.0111392, 0.0112407]	[0.0109372, 0.0110366]	[0.0091023, 0.00091850]	[0.0070358, 0.0071008]	[0.0096305, 0.00097185]	[0.0088717, 0.0089513]
OVL of PDFs	0.97995		0.8725		0.9586	

The corresponding distributions are presented in Figures 8–10. Figure 8 shows the probability histograms for the hard laminate, where both laminate architectures exhibit narrow distributions concentrated at low coupling values. Figure 9 presents the corresponding empirical cumulative distribution functions, which follow similar trends throughout the range of observed values. Figure 10 illustrates the overlap between the probability-density functions of the two laminates, showing substantial coincidence of the two distributions.

Across the three laminate families, the magnitude of B_{16}^* remained small under the assumed manufacturing variability. Differences between Quad and TAC laminates in-

creased progressively from the hard to the soft stiffness regime, as reflected by the corresponding statistical parameters reported in Table 3.

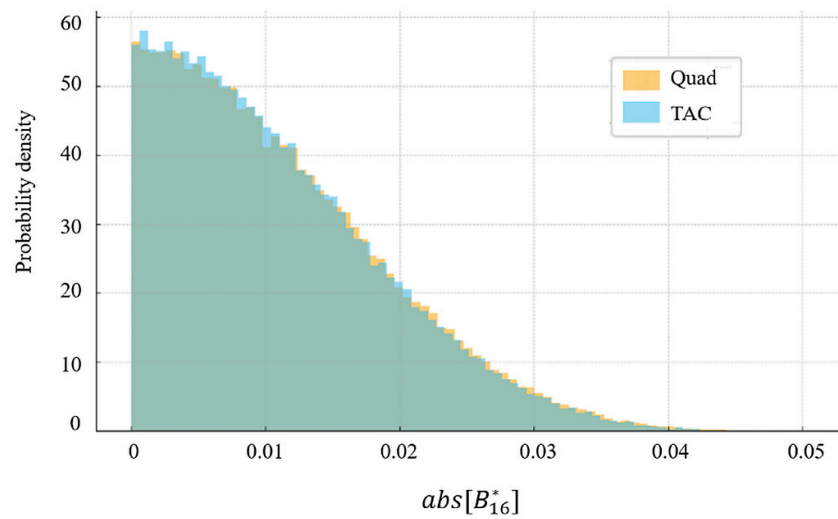


Figure 8. Histogram for $\text{abs}[B_{16}^*]$ Quad and TAC hard laminate. Units in GPa.

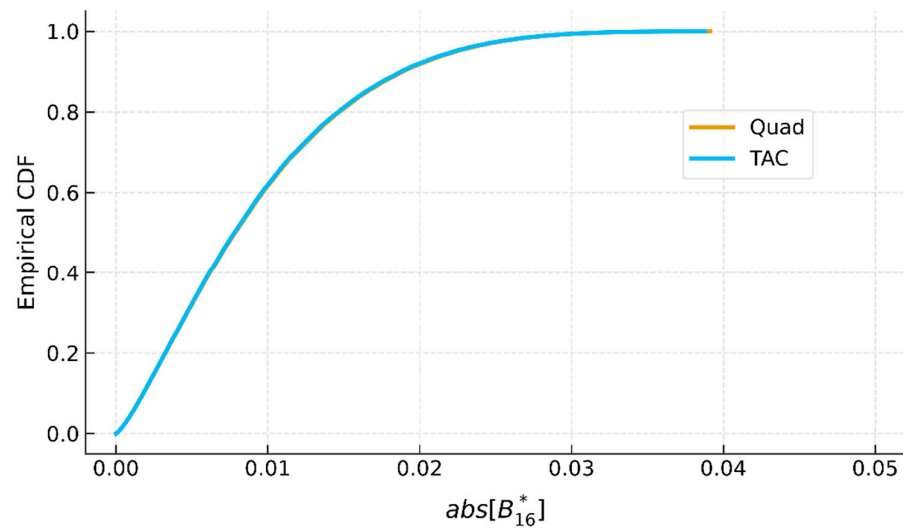


Figure 9. Empirical CDF for $\text{abs}[B_{16}^*]$ Quad and TAC hard laminate. Units in GPa.

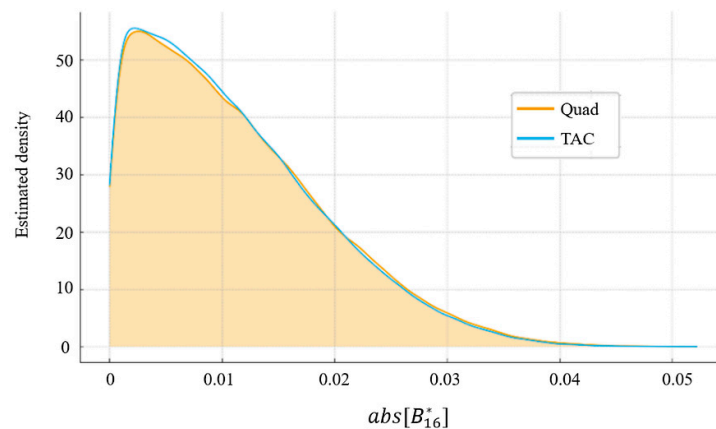


Figure 10. PDF Overlap for $\text{abs}[B_{16}^*]$ Quad and TAC hard laminate. Units in GPa.

3.2.2. Results for the Extension-Bending Term B_{26}^*

Table 4 summarizes the statistical characteristics of the normalized extension–bending coupling term B_{26}^* obtained from the Monte Carlo simulations for the hard, neutral, and soft laminate families.

For the hard laminate, both laminate architectures produced low values of B_{26}^* throughout the 100,000 realizations. The Quad laminate exhibited a slightly lower mean value than the TAC laminate, although both distributions remained concentrated near zero with relatively small standard deviations. The upper-percentile values and maximum values were also of comparable magnitude. The Kolmogorov–Smirnov statistic indicated only a modest difference between the two empirical distributions, while the probability-density overlap coefficient remained above 0.90.

For the neutral laminate, the statistical characteristics of the Quad and TAC laminates remained similar. The TAC laminate exhibited a slightly higher mean value than the corresponding Quad laminate, whereas the standard deviations differed only marginally. The empirical distributions showed a high degree of overlap, as reflected by the overlap coefficient of approximately 0.97. The KS statistic remained small, indicating only minor differences between the cumulative distribution functions.

For the soft laminate, the relative behavior changed. The TAC laminate exhibited lower average values of B_{26}^* than the corresponding Quad laminate, together with reduced statistical dispersion. The median, upper-percentile values, and maximum values were also lower for the TAC laminate. The separation between the two distributions increased compared with the hard and neutral laminate families, resulting in a larger KS statistic and a reduced probability-density overlap coefficient.

Table 4. Statistical comparison of the extension–bending coupling term $\text{abs}[B_{26}^*]$ for Quad and TAC laminates under $\pm 0.1^\circ$ AFP/ATL angular misalignment. Units in GPa.

	Hard Laminate		Soft Laminate		Neutral Laminate	
	Quad	TAC	Quad	TAC	Quad	TAC
Mean	0.00580	0.00691	0.00610	0.00519	0.00787	0.00817
Median	0.00499	0.00597	0.00524	0.00448	0.00675	0.00709
Std	0.00429	0.00503	0.00452	0.00377	0.00575	0.00592
min	3.0×10^{-8}	4.1×10^{-8}	7.6×10^{-8}	3.7×10^{-7}	5.0×10^{-8}	7.3×10^{-8}
max	0.02781	0.03099	0.02852	0.02176	0.03634	0.03614
95th percentile	0.01402	0.01650	0.01476	0.01242	0.01887	0.01946
KS test— p -value	5.41×10^{-5}		0.00000		0.00000	
Welch t -test— p -value	2.09×10^{-8}		0		0	
Levene’s test— p -value	3.61×10^{-9}		0		0	
95% CIs for the mean	[0.0057748, 0.0058277]	[0.0068756, 0.0069376]	[0.0051676, 0.0061327]	[0.0070358, 0.0052143]	[0.0078319, 0.0079030]	[0.0081381, 0.0082112]
OVL of PDFs	0.90990		0.92096		0.97189	

Figures 11–13 illustrate the statistical distributions for the soft laminate. Figure 11 presents the probability histograms of B_{26}^* , showing that both laminate architectures remain concentrated at relatively small coupling values, although the Quad laminate exhibits a broader distribution extending toward larger values. Figure 12 compares the empirical cumulative distribution functions of the two laminates. Figure 13 shows the corresponding overlap between the probability-density functions.

Overall, the magnitude of B_{26}^* remained small for both laminate architectures under the assumed $\pm 0.1^\circ$ fiber-orientation variability. The statistical differences between Quad and TAC laminates were limited for the hard and neutral laminate families and became

more evident for the soft laminate, where the TAC laminate exhibited lower average values and reduced statistical dispersion.

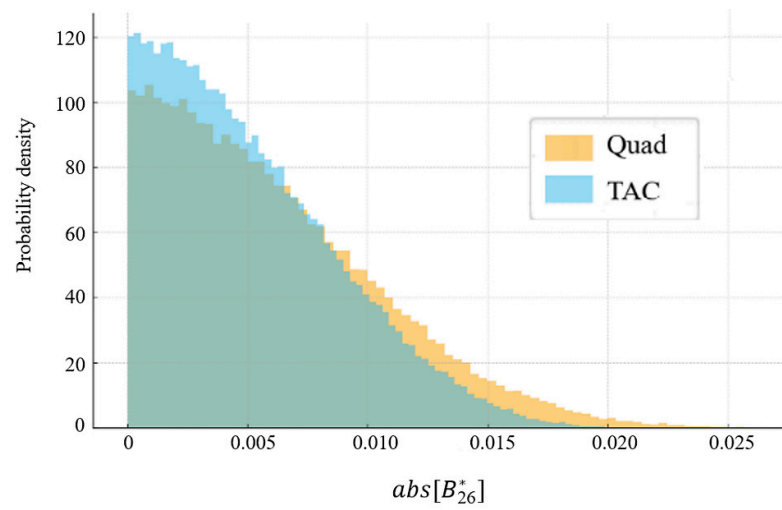


Figure 11. Histogram for $\text{abs}[B_{26}^*]$ Quad and TAC soft laminate. Units in GPa.

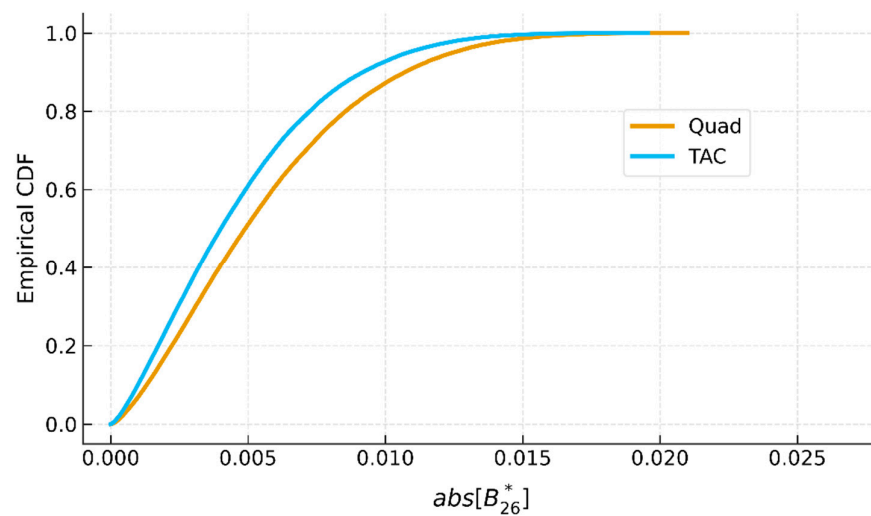


Figure 12. Empirical CDF for $\text{abs}[B_{26}^*]$ Quad and TAC soft laminate. Units in GPa.

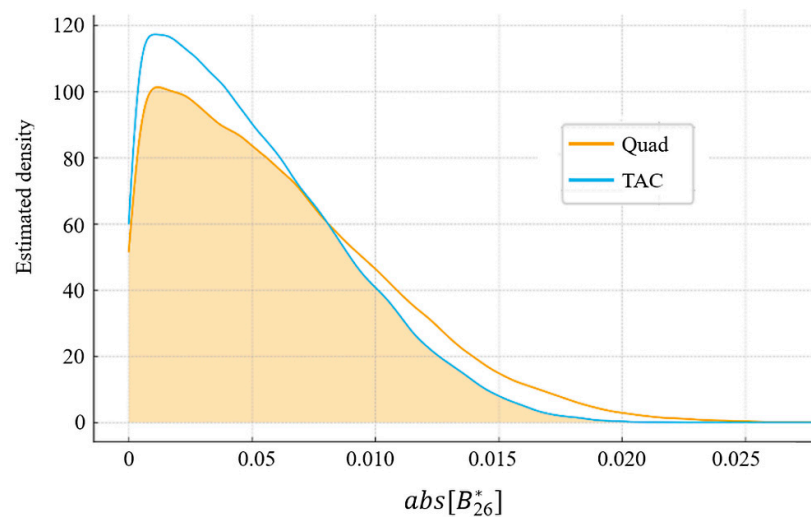


Figure 13. PDF Overlap for $\text{abs}[B_{26}^*]$ Quad and TAC soft laminate. Units in GPa.

3.2.3. Results for the Bending-Twisting Term D_{16}^*

Table 5 summarizes the statistical characteristics of the normalized bending–twisting coupling term D_{16}^* obtained from 100,000 Monte Carlo simulations for the hard, neutral, and soft laminate families under $\pm 0.1^\circ$ fiber-orientation misalignment.

For all three laminate families, the Quad laminates exhibited substantially larger D_{16}^* values than the corresponding TAC laminates. The TAC distributions remained concentrated close to zero, whereas the Quad distributions were located at much higher coupling levels.

For the hard laminate, the Quad and TAC distributions were fully separated. The minimum D_{16}^* value obtained for the Quad laminate was larger than the maximum value obtained for the TAC laminate.

The same behavior was observed for the neutral laminate, where the two distributions again showed complete separation across the full range of Monte Carlo realizations.

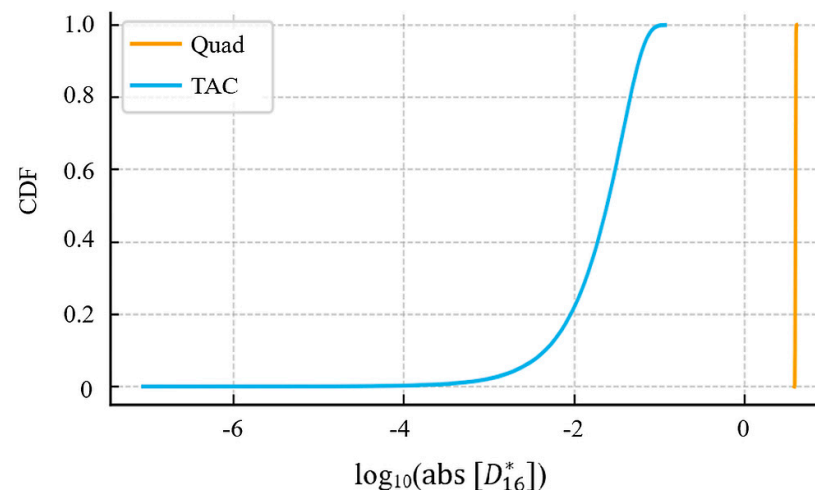
For the soft laminate, the TAC laminate also remained close to zero, while the Quad laminate maintained substantially larger D_{16}^* values throughout the statistical distribution.

Table 5. Statistical comparison of the bending–twisting coupling term $\text{abs}[D_{16}^*]$ for Quad and TAC laminates under $\pm 0.1^\circ$ AFP/ATL angular misalignment. Units in GPa.

	Hard Laminate		Soft Laminate		Neutral Laminate	
	Quad	TAC	Quad	TAC	Quad	TAC
Mean	3.96343	0.02803	7.20556	0.01416	7.92613	0.02219
Median	3.96347	0.02416	7.20560	0.01216	7.92614	0.01935
Std	0.03419	0.02043	0.02700	0.01047	0.02744	0.01576
min	4.08248	0.00000	7.11431	0.00000	7.82670	0.00000
max	3.84652	0.11648	7.30434	0.06994	8.02059	0.08137
95th percentile	4.01987	0.06706	7.25014	0.03429	7.97147	0.05195

Figure 14 presents the probability distributions of D_{16}^* for the hard, neutral, and soft laminate families. In all three cases, the TAC and Quad distributions are separated, with TAC consistently occupying the lower-coupling range.

Across all stiffness regimes, D_{16}^* remained very small for TAC laminates and substantially larger for the corresponding Quad laminates.

**Figure 14.** Log-Scale CDF for $\text{abs}[D_{16}^*]$ Quad and TAC hard laminate. Units in GPa.

3.2.4. Results for the Bending-Twisting Term D_{26}^*

Table 6 summarizes the statistical characteristics of the normalized bending–twisting coupling term D_{26}^* obtained from 100,000 Monte Carlo simulations for the hard, neutral, and soft laminate families under $\pm 0.1^\circ$ fiber-orientation misalignment.

For all three laminate families, the Quad laminates exhibited substantially larger values of D_{26}^* than the corresponding TAC laminates. The TAC distributions remained concentrated close to zero, whereas the Quad laminates consistently produced much higher coupling values.

For the hard laminate, the statistical distributions of the Quad and TAC laminates were completely separated. The minimum value obtained for the Quad laminate exceeded the maximum value predicted for the TAC laminate.

The same behavior was observed for the neutral laminate, where the statistical distributions again showed complete separation over the entire range of Monte Carlo realizations.

For the soft laminate, the TAC laminate continued to exhibit values of D_{26}^* close to zero, while the Quad laminate maintained substantially larger coupling values throughout the statistical distribution.

Table 6. Statistical comparison of the bending–twisting coupling term $\text{abs}[D_{26}^*]$ for Quad and TAC laminates under $\pm 0.1^\circ$ AFP/ATL angular misalignment.

	Hard Laminate		Soft Laminate		Neutral Laminate	
	Quad	TAC	Quad	TAC	Quad	TAC
Mean	3.96310	0.01295	7.20566	0.01388	7.92618	0.01823
Median	3.96310	0.01125	7.20565	0.01207	7.92616	0.01592
Std	0.01313	0.00929	0.01686	0.00997	0.02090	0.01300
min	3.91868	0.00000	7.14313	0.00000	7.85678	0.00000
max	4.00874	0.05394	7.26580	0.05466	7.99531	0.06880
95th percentile	3.98471	0.03058	7.23350	0.03284	7.96068	0.04282

Figure 15 presents the probability distributions of D_{26}^* for the hard, neutral, and soft laminate families. In all cases, the distributions corresponding to the TAC and Quad laminates remained completely separated, with the TAC laminate consistently exhibiting the lower coupling levels.

Across the three laminate families, the normalized bending–twisting coupling term D_{26}^* remained close to zero for the TAC laminates, whereas significantly larger values were obtained for the corresponding Quad laminates under the same manufacturing variability.

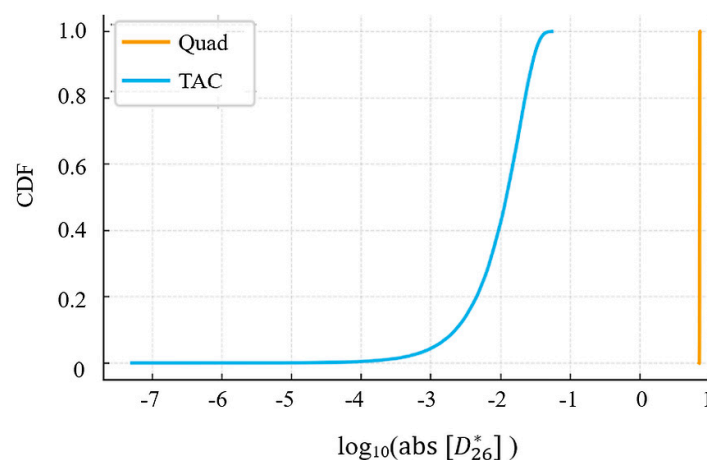


Figure 15. Log-Scale CDF for $\text{abs}[D_{26}^*]$ Quad and TAC soft laminate. Units in GPa.

3.2.5. Summary of Monte Carlo Results

The Monte Carlo simulations performed under $\pm 0.1^\circ$ fiber-orientation misalignment provide a statistical comparison of the extension–bending and bending–twisting coupling behavior of Quad and TAC laminates across the hard, neutral, and soft laminate families.

For the extension–bending coupling terms, B_{16}^* and B_{26}^* , both laminate architectures exhibited small coupling values under the assumed manufacturing variability. The statistical differences between Quad and TAC laminates depended on the laminate stiffness, with the largest differences occurring for the soft laminate family.

In contrast, the normalized bending–twisting coupling terms, D_{16}^* and D_{26}^* , exhibited complete statistical separation between the two laminate architectures for all three laminate families. The TAC laminates consistently produced values close to zero, whereas the corresponding Quad laminates exhibited substantially larger coupling values. This behavior was observed for all statistical parameters reported in Tables 5 and 6 and for the probability distributions shown in Figures 14 and 15.

Overall, the Monte Carlo simulations indicate that the extension–bending coupling terms remain small for both laminate architectures under realistic AFP/ATL fiber-orientation variability, whereas the bending–twisting coupling terms differ markedly between the Quad and TAC laminates throughout the hard, neutral, and soft laminate families.

3.3. Experimental Validation

Warping was quantified as the out-of-plane deviation from a nominally flat reference plane (in mm), using two replicates for each stacking sequence (Table 7).

Table 7. TAC vs. Quad warping measurements after curing (mm).

Laminate	Warping Measurements		Mean	Standard Deviation
$[+21^\circ/-31^\circ/-12^\circ/+54^\circ/-54^\circ/+12^\circ/+31^\circ/-21^\circ]$	0.063	0.067	0.065	0.003
$[+45^\circ/0^\circ/-45^\circ/90^\circ]_s$	0.058	0.074	0.066	0.011

The near-identical mean values indicate that, in this thickness range and material system, TAC laminates exhibit no additional warpage penalty relative to symmetric quasi-isotropic baselines. This is notable because antisymmetric laminates are traditionally linked to high distortion due to non-zero **B** matrix terms. However, the TAC design mitigates the key coupling terms (B_{16} and B_{26}), achieving flatness comparable to symmetric Quads.

The TAC laminate's markedly lower scatter (3.0×10^{-3} mm vs. 1.1×10^{-2} mm) indicates improved repeatability in warpage behavior. This enhanced consistency can be attributed to two primary factors.

4. Discussion

The analytical, numerical, and experimental results consistently demonstrate that Tailored Antisymmetric Composite (TAC) laminates constitute the closest practical approximation to fully orthotropic laminated composites currently available while preserving broad stiffness-tailoring capability. Unlike conventional symmetric laminate architectures, which eliminate extension–bending coupling at the expense of retaining bending–twisting coupling, TAC laminates simultaneously eliminate bending–twisting coupling exactly and maintain extension–bending coupling at extremely small levels. This combination fundamentally changes the traditional compromise that has governed laminate design for decades.

A central result of this study is that TAC laminates satisfy

$$D_{16} = D_{26} = 0 \quad (12)$$

by construction, independently of material properties or laminate thickness. Since these coupling terms govern bending–twisting interaction, their elimination removes one of the principal sources of anisotropic structural behavior in practical laminated composites. Although the extension–bending coupling terms B_{16} and B_{26} are not identically zero, they remain extremely small and decrease rapidly as the laminate thickness increases through repetition of the antisymmetric building block. Consequently, TAC laminates approach the behavior of an ideal orthotropic laminate while retaining the freedom to tailor membrane stiffness over virtually the entire design space.

The comparison with conventional Quad laminates highlights the practical significance of this behavior. Symmetric Quad laminates achieve $B = 0$ exactly, but generally retain non-zero values of D_{16} and D_{26} . These bending–twisting coupling terms persist even for relatively thick laminates and only decrease gradually with increasing ply count. By contrast, TAC laminates exhibit the opposite behavior: the small extension–bending coupling terms become rapidly negligible, whereas the bending–twisting coupling terms remain identically zero for every laminate thickness considered. From a structural standpoint, this represents a more favorable compromise because bending–twisting coupling generally has a greater influence on structural response than the very small residual values of B_{16} and B_{26} .

The homogenization study provides an additional advantage of the TAC architecture. The normalized bending stiffness matrix converges toward the normalized extensional stiffness matrix considerably faster than in conventional Quad laminates. For the representative laminates investigated, effective homogenization was consistently achieved after only three repetitions of the TAC building block (24 plies), whereas Quad laminates generally required larger ply counts and still exhibited slower convergence for several stiffness components. This rapid convergence simplifies laminate characterization because membrane and bending properties become nearly identical with relatively few plies, facilitating both analytical modeling and structural optimization.

The Monte Carlo simulations further demonstrate that TAC laminates possess excellent robustness with respect to realistic AFP and ATL manufacturing variability. Although symmetric Quad laminates theoretically exhibit zero extension–bending coupling, this advantage largely disappears once realistic fiber-placement errors are introduced. Under $\pm 0.1^\circ$ orientation deviations, TAC laminates consistently produced extension–bending coupling values comparable to or lower than those of the corresponding Quad laminates. The improvement becomes increasingly pronounced as laminate stiffness decreases from hard to soft configurations, indicating that the antisymmetric architecture distributes orientation errors more uniformly through the thickness and reduces the sensitivity of coupling to manufacturing imperfections. These results suggest that the theoretical advantages of TAC laminates are largely maintained under realistic manufacturing conditions.

The experimental observations are fully consistent with the analytical predictions and Monte Carlo simulations. Post-cure warpage measurements showed that TAC laminates exhibit extension–bending coupling levels comparable to those of conventional symmetric Quad laminates despite their non-symmetric construction. The 500×500 mm TAC and Quad panels exhibit measured out-of-plane flatness deviations of only 0.065 mm and 0.066 mm, respectively. According to ISO 2768-2 [101] (Geometrical tolerances), flatness tolerances for plates of this characteristic length fall into three standard tolerance classes: H (fine), K (medium), and L (coarse). For a 500 mm component, the corresponding allowable flatness deviations are 0.3 mm (class H), 0.6 mm (class K), and 1.0 mm (class L). The

measured flatness of both panels is more than four times smaller than the strictest class-H requirement, indicating exceptionally low warpage. The observed deformation is therefore extremely mild and spatially smooth, and can be considered negligible from both manufacturing and structural perspectives. These results confirm that both TAC and Quad laminates easily satisfy—and substantially exceed—the most stringent ISO 2768 flatness criteria, demonstrating excellent geometric stability despite their antisymmetric and tailored architectures.

This finding is particularly significant because laminate symmetry has traditionally been regarded as a prerequisite for minimizing warpage during manufacturing. The present results demonstrate that carefully tailored antisymmetric stacking sequences can achieve essentially the same manufacturing performance while simultaneously eliminating bending–twisting coupling, thereby overcoming one of the principal historical objections to non-symmetric laminates.

From a practical design perspective, TAC laminates offer several additional advantages. Their antisymmetric building blocks require only six to eight plies to generate hard, neutral, or soft laminate families, whereas conventional Quad architectures generally require significantly larger stacking sequences to achieve comparable stiffness tailoring. The reduced building-block size simplifies laminate design, decreases optimization complexity, and facilitates automated optimization procedures such as the genetic algorithm employed in the present work. Furthermore, because TAC laminates are assembled from repeated sublaminates, they are naturally compatible with modern automated manufacturing processes, including Automated Fiber Placement and Automated Tape Laying.

The present work focuses primarily on coupling behavior and homogenization, but the implications extend well beyond these specific properties. Eliminating bending–twisting coupling is expected to benefit numerous structural applications, including buckling, vibration, aeroelasticity, guided-wave propagation, precision composite structures, and lightweight aerospace components where unintended coupling often complicates analysis and degrades performance. The analytical framework developed here therefore provides a foundation for future investigations into these broader structural phenomena.

Overall, the results demonstrate that TAC laminates successfully reconcile two objectives that have historically been regarded as mutually exclusive: achieving nearly complete orthotropy while retaining extensive stiffness-tailoring capability. Rather than representing an alternative to conventional Quad laminates for isolated applications, TAC introduces a systematic laminate architecture capable of replacing traditional symmetric designs across a broad range of structural configurations. The combination of exact elimination of bending–twisting coupling, negligible extension–bending coupling, rapid homogenization, manufacturing robustness, and efficient stiffness tailoring establishes TAC laminates as a promising new design paradigm for advanced composite structures.

5. Conclusions

This study presented a comprehensive analytical, statistical, and experimental comparison between Tailored Antisymmetric Composite (TAC) laminates and conventional symmetric Quad laminates to evaluate their ability to approach fully orthotropic behavior.

The principal findings are summarized as follows:

1. TAC laminates eliminate bending–twisting coupling exactly by construction ($D_{16} = D_{26} = 0$), while maintaining extremely small extension–bending coupling terms.
2. Monte Carlo simulations incorporating 100,000 realizations with realistic $\pm 0.1^\circ$ fiber-orientation deviations showed that the extension–bending coupling terms B_{16}^* and B_{26}^* of TAC laminates remained statistically comparable to those of symmetric Quad laminates. In contrast, the bending–twisting coupling terms D_{16}^* and D_{26}^* were two

to three orders of magnitude lower, with complete statistical separation between the two laminate architectures.

3. Experimental warpage measurements confirmed that TAC laminates achieve dimensional stability comparable to conventional symmetric Quad laminates despite their antisymmetric construction.

Overall, the results demonstrate that TAC laminates provide the closest practical approximation to fully orthotropic laminated composites while preserving manufacturability and broad stiffness-tailoring capability. The proposed architecture therefore represents a promising alternative to conventional symmetric Quad laminates for advanced composite structures where structural coupling must be minimized.

The objective of the present work is to establish whether TAC laminates constitute a practical route toward full orthotropy by combining analytical modeling, Monte Carlo simulations, and experimental validation. While the present investigation is limited to laminate mechanics and coupling behavior, the resulting architecture provides a foundation for future developments in buckling-resistant structures, vibration tailoring, aeroelastic optimization, damage-tolerant design, guided-wave control, and other advanced composite applications.

Author Contributions: A.M.: Writing—review and editing, Writing—original draft, Methodology, Validation, Investigation. J.M.M.-A.: Writing—review and editing, Methodology, Validation, Investigation. J.C.: Writing—review and editing, Analysis, Methodology, Investigation. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The author Antonio Miravete is President of Composite Materials and Structures Consulting. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Example Application of a Genetic Algorithm to Obtain a TAC Laminate Starting from the Symmetric Laminate $[10^\circ/-20^\circ/90^\circ]_s$

The following sections detail every stage of the GA workflow used to convert the baseline symmetric laminate $[10^\circ/-20^\circ/90^\circ]_s$ into a TAC lay-up. Each phase—genome encoding, population initialization, fitness evaluation, selection, crossover, mutation, constraint handling, and final laminate reconstruction—is presented in order, making the decision-making logic fully transparent and allowing readers to follow how the algorithm steadily evolves candidate stacking sequences toward an uncoupled, minimum-warp TAC solution.

1. Start—Genome Design (encoding)

Material: AS4/8552

Objective function (OF): coupling index $J^* < 2.0 \cdot 10^{-4}$

g (or genome) = $[\theta_1, \theta_2, \theta_3] \in \{-89^\circ \text{ to } 90^\circ\}$

Total laminate: $[\theta_1, \theta_2, \theta_3, -\theta_3, -\theta_2, -\theta_1]$

with $\theta_1 = 10^\circ$, $\theta_2 = -20^\circ$ and $\theta_3 = 90^\circ$

2. Initialize population
 Population size: 80
 Perturbation: $D\theta$ from -5° to 5°
 Exploration: θ_1, θ_2 from -30° to $+30^\circ$
 θ_3 from $+60^\circ$ to 90°
3. Evaluate Fitness
 Derivation of B_{16}^* , B_{26}^* and Trace using AS4/8552 material properties
 For each chromosome, the objective function $OF = \max \{|B_{16}^*|, |B_{26}^*|\} / Trace$
4. Select Parent Sequences
 Select four individuals with replacement (Tournament of size 4).
 Copy the individual with the small of value in the mating pool.
 Repeat until the mating pool holds 80 parents.
5. Perform crossover
 Remove two parents from the mating-pool
 Generate a random real number r between 0 (inclusive) and 1 (exclusive), with equal probability anywhere in that range. If $r \leq 0.8$ (0.8 is the crossover probability, or the fraction of matings in which crossover is performed) then recombine, else child = Parent A
 For each of the three genes $(\theta_1, \theta_2, \theta_3)$, randomly comes from Parent A or Parent B
 Output a child chromosome $[\theta_1, \theta_2, \theta_3]$.
6. Apply mutation
 For each gene in the new child, generate a random real number r between 0 (inclusive) and 1 (exclusive), with equal probability anywhere in that range.
 If $r \leq 0.25 p_m$ (p_m is the chance that any single gene is nudged when a child is created), then add $D\theta$ chosen randomly from $\{-2^\circ, -1^\circ, +1^\circ, +2^\circ\}$
7. Constraint handling
 Confirm correct intervals
 Make sure $\theta_1, \theta_2, \theta_3$ are integer values
8. Update population
 Move the single best individual from generation g directly into the next generation list
 Append children created in steps 4, 5 and 6 until the new list contains 80 chromosomes
 Replace the working population point with this new list
 Increment generation counter
 If the requirement is met ($OF < 2.0 \cdot 10^{-4}$ or $gen \geq 300$), the flow follows directly to “Output TAC laminate” and then terminates. Otherwise, loop back to 2. Evaluate fitness.
9. Output TAC laminate
 The optimization has converged on the stacking sequence:

$$[+10^\circ / -19^\circ / +86^\circ / -86^\circ / +19^\circ / -10^\circ]$$

With a coupling index $J^* = 1.73 \cdot 10^{-4}$. This layup suppresses tensile–bending coupling below the design threshold while preserving bending stiffness, representing the optimal trade-off. The algorithm therefore terminates, returning this TAC laminate as the final solution.

References

1. Reddy, J.N.; Miravete, A. *Practical Analysis of Composite Structures*; CRC Press: Boca Raton, FL, USA, 1995.
2. Baker, A.A.; Scott, M.L. *Composite Materials for Aircraft Structures*, 3rd ed.; AIAA Education Series; AIAA: Washington, DC, USA, 2016.
3. Tsai, S.W.; Miravete, A. *Design and Analysis of Composite Materials*; Editorial Reverte Press: Barcelona, Spain, 1988. (In Spanish)
4. Herakovich, C.T. Mechanics of Composites: A Historical Review. *Mech. Res. Commun.* **2012**, *41*, 1–20. <https://doi.org/10.1016/j.mechrescom.2012.01.006>.
5. Abdalla, M.M.; Kassapoglou, C.; Gürdal, Z. Formulation of Composite Laminate Robustness Constraint in Lamination Parameters Space. In *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*; AIAA Paper; AIAA: Washington, DC, USA, 2009; pp. 2009–2478.
6. Irisarri, F.X.; Bassir, D.H.; Carrere, N.; Maire, J.F. Multiobjective Stacking Sequence Optimization for Laminated Composite Structures. *Compos. Sci. Technol.* **2009**, *69*, 983–990. <https://doi.org/10.1016/j.compscitech.2009.01.011>.
7. Miravete, A. Preferred Stacking Sequences for Homogenization. In *Simplifying the Design and Manufacture of Composite Laminates*; Stanford University: Stanford, CA, USA; RMIT University: Melbourne, Australia; Queen's University Belfast: Belfast, UK, 2023.
8. Liu, D.; Toropov, V.V.; Barton, D.C.; Querin, O.M. Weight and Mechanical Performance Optimization of Blended Composite Wing Panels Using Lamination Parameters. *Struct. Multidiscip. Optim.* **2015**, *52*, 549–562. <https://doi.org/10.1007/s00158-015-1244-x>.
9. Macquart, T.; Bordogna, M.T.; Lancelot, P.; de Breuker, R. Derivation and Application of Blending Constraints in Lamination Parameter Space for Composite Optimisation. *Compos. Struct.* **2016**, *135*, 224–235. <https://doi.org/10.1016/j.compstruct.2015.09.016>.
10. Macquart, T.; Werter, N.; de Breuker, R. Aeroelastic Design of Blended Composite Structures Using Lamination Parameters. *J. Aircr.* **2017**, *54*, 561–571. <https://doi.org/10.2514/1.c033859>.
11. Bordogna, M.T.; Lancelot, P.; Bettebghor, D.; de Breuker, R. Static and Dynamic Aeroelastic Tailoring with Composite Blending and Manoeuvre Load Alleviation. *Struct. Multidiscip. Optim.* **2020**, *61*, 2193–2216. <https://doi.org/10.1007/s00158-019-02446-w>.
12. Meddaikar, Y.M.; Irisarri, F.-X.; Abdalla, M.M. Laminate Optimization of Blended Composite Structures Using a Modified Shepard's Method and Stacking Sequence Tables. *Struct. Multidiscip. Optim.* **2017**, *55*, 535–546. <https://doi.org/10.1007/s00158-016-1508-0>.
13. Jsselmuiden, S.T.; Abdalla, M.M.; Seresta, O.; Gürdal, Z. Multi-Step Blended Stacking Sequence Design of Panel Assemblies with Buckling Constraints. *Compos. Part B Eng.* **2009**, *40*, 329–336. <https://doi.org/10.1016/j.compositesb.2008.12.002>.
14. Radford, D.W.; Diefendorf, R.J. Shape Instabilities in Composites Resulting from Laminate Anisotropy. *J. Reinf. Plast. Compos.* **1993**, *12*, 58–75. <https://doi.org/10.1177/073168449301200104>.
15. Yan, S.; Matveev, M.; Warrior, N. Process-Induced Distortion Prediction for Laminated Composites. In *Proceedings of Twenty-Third International Conference on Composite Materials (ICCM23)*, Belfast, UK, 30 July–4 August 2023.
16. Miravete, A. Lamination parameter plots. In *Proceedings of Composites Design Workshop XXVI*, Stanford University, Stanford, CA, USA, 22–26 January 2024.
17. Jones, R.M. *Mechanics of Composite Materials*, 2nd ed.; Taylor & Francis, Inc.: Abingdon, UK, 1999.
18. Caprino, G.; Crivelli-Visconti, I. A note on specially orthotropic laminates. *J. Compos. Mater.* **1982**, *16*, 395–399. <https://doi.org/10.1177/002199838201600504>.
19. Fukunaga, H.; Vanderplaats, G.N. Stiffness optimization of orthotropic laminated composites using lamination parameters. *AIAA J.* **1991**, *29*, 641–666. <https://doi.org/10.2514/3.59931>.
20. Bartholomew, P. Ply stacking sequences for laminated plates having in-plane and bending orthotropy. *Fibre Sci. Technol.* **1977**, *10*, 239–253. [https://doi.org/10.1016/0015-0568\(77\)90001-X](https://doi.org/10.1016/0015-0568(77)90001-X).
21. Engineering Sciences Data Unit. *Laminate Stacking Sequences for Special Orthotropy (Application to Fibre Reinforced Composites)*; ESDU Item No. 82013; Engineering Sciences Data Unit: London, UK, 1982.
22. Gunnink, J.W. Comment on “A Note on Specially Orthotropic Laminates”. *J. Compos. Mater.* **1983**, *17*, 508–510. <https://doi.org/10.1177/002199838301700603>.
23. Fukunaga, H.; Sekine, H.; Sato, M.; Iino, A. Buckling design of symmetrically laminated plates using lamination parameters. *Comput. Struct.* **1995**, *57*, 643–649. [https://doi.org/10.1016/0045-7949\(95\)00050-Q](https://doi.org/10.1016/0045-7949(95)00050-Q).
24. Fletcher, T.A.; Butler, R.; Dodwell, T.J. Anti-symmetric laminates for improved consolidation and reduced warp of tapered C-sections. *Adv. Manuf. Polym. Compos. Sci.* **2015**, *1*, 105–111. <https://doi.org/10.1179/2055035914Y.0000000010>.

25. Fletcher, T.A.; Butler, R.; Dodwell, T.J.; Erland, S. Non-Symmetric Stacking Sequences to Aid Manufacture. In Proceedings of 16th European Conference on Composite Materials, Seville, Spain, 22–26 June 2014.
26. Valot, E. Anisotropie du Comportement a Rupture de Composites a Structure Isotrope (Anisotropy of Failure Behaviour of Composites with Isotropic Structure). Ph.D. Thesis, University of Burgundy, Dijon, France, 2002.
27. Vannucci, P.; Verchery, G. A special class of uncoupled and quasi-homogeneous laminates. *Compos. Sci. Technol.* **2001**, *61*, 1465–1473. [https://doi.org/10.1016/s0266-3538\(01\)00039-2](https://doi.org/10.1016/s0266-3538(01)00039-2).
28. Grediac, M. On the stiffness design of thin woven composites. *Compos. Struct.* **2001**, *51*, 245–255. [https://doi.org/10.1016/S0263-8223\(00\)00135-5](https://doi.org/10.1016/S0263-8223(00)00135-5).
29. Grediac, M. On the design of some particular orthotropic plates with non-standard ply orientations. *J. Compos. Mater.* **2000**, *34*, 1665–1699. <https://doi.org/10.1106/v4u2-ltqe-q1jg-3wn2>.
30. Valot, E.; Vannucci, P. Some exact solutions for fully orthotropic laminates. *Compos. Struct.* **2005**, *69*, 157–166. <https://doi.org/10.1016/j.compstruct.2004.06.007>.
31. York, C.B. Buckling interaction in regular arrays of rigidly supported composite laminated plates with orthogrid, isogrid and anisogrid planform. *J. Am. Helicopter Soc.* **2007**, *52*, 343–359.
32. York, C.B. Characterization of Nonsymmetric Forms of Fully Orthotropic Laminates. *J. Aircr.* **2009**, *46*, 1114–1125. <https://doi.org/10.2514/1.32938>.
33. Baker, N.; Butler, R.; York, C.B. Damage tolerance of fully orthotropic laminates in compression. *Compos. Technol.* **2012**, *72*, 1083–1089. <https://doi.org/10.1016/j.compscitech.2011.09.010>.
34. Baker, N.; Butler, R. Compression After Impact Modeling of Damage Tolerant Composite Laminates. In *Proceedings of Conference 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 18th AIAA/ASME/AHS Adaptive Structures Conference, Orlando, FL, USA, 12–15 April 2010*; American Institute of Aeronautics and Astronautics (AIAA): Reston, VA, USA, 2010.
35. Rhead, A.; Butler, R.; York, C.B. Damage tolerance of asymmetric fully orthotropic laminates in compression. In Proceedings of 11th Deformation and Fracture of Composites and 5th Structural Integrity and Multi-Scale Modelling Conference, Cambridge, UK, 12–15 April 2011.
36. O'Donnell, M.P.; Weaver, P.M. Reconsidering Laminate Non-Symmetry. *AIAA J.* **2020**, *58*, 1811–1820. <https://doi.org/10.2514/1.J058751>.
37. Miravete, A.; Cuartero, J.; Guzman de Villoria, R.; Mejia-Ariza, J.M. Tailored Antisymmetric Composite Laminates: Achieving Ultra-thin design, Lightweight Performance, and Mitigated Coupling Effects. *Compos. Struct.* **2026**, *376*, 119386. <https://doi.org/10.1016/j.compstruct.2025.119836>.
38. Miravete, A. Metalite, a new class of composite laminates with unique properties. *Mech. Adv. Mater. Struct.* **2025**, *32*, 2343–2354. <https://doi.org/10.1080/15376494.2024.2378369>.
39. Minera, S.; Patni, M.; Weaver, P.M.; Pirrera, A.; O'Donnell, M.P. Comparing the effect of geometry and stiffness on the effective load paths in non-symmetric laminates. In *Proceedings of the AIAA SCITECH 2019, San Diego, CA, USA, 7–11 January 2019*; American Institute of Aeronautics and Astronautics Inc. (AIAA): Reston, VA, USA, 2019. <https://doi.org/10.2514/6.2019-1766>.
40. O'Donnell, M.P.; Weaver, P.M.; Cosentino, E. Debond Resisting Composite Stringers. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, USA, 23–26 April 2012.
41. Nettles, A. *Basic Mechanics of Laminated Composite Plates*; NASA TM-104000; National Aeronautics and Space Administration, Marshall Space Flight Center: Huntsville, AL, USA, 1994.
42. York, C.B. On tapered warp-free laminates with single-ply terminations. *Compos. Part A Appl. Sci. Manuf.* **2015**, *72*, 127–138. <https://doi.org/10.1016/j.compositesa.2015.01.022>.
43. Weaver, P.M. Anisotropic Laminates that Resist Warping during Manufacture. In Proceedings of the ICCM15—15th International Conference on Composite Materials, Durban, South Africa, 27 June–2 July 2005.
44. Wijskamp, S. Shape Distortions in Composites Forming. Ph.D. Dissertation, University of Twente, Enschede, The Netherlands, May 2005.
45. Fletcher, T. Certification and Design for Manufacture of Curved and Tapered Laminates. Ph.D. Dissertation, University of Bath, Bath, UK, 24 May 2017.
46. Radford, D.W. Shape Stability in Composites. Ph.D. Dissertation, Rensselaer Polytechnic Institute, Troy, NY, USA, 1987.
47. Radford, D.W.; Rennick, T.S. Components of manufacturing distortion in carbon fiber/epoxy angle brackets. In Proceedings of the 28th International SAMPE Technical Conference, Seattle, WA, USA, 7–10 October 1996.

48. Wiersma, H.W.; Peeters, L.J.B.; Akkerman, R. Prediction of spring-forward in continuous-fibre/polymer L-shaped parts. *Compos. Part A* **1998**, *29*, 1333–1342. [https://doi.org/10.1016/S1359-835X\(98\)00062-1](https://doi.org/10.1016/S1359-835X(98)00062-1).
49. Jain, L.K.; Mai, Y.-W. Stresses and deformations induced during manufacturing. Part I: Theoretical analysis of composite cylinders and shells. *Compos. Part A* **1997**, *31*, 672–695. <https://doi.org/10.1177/002199839703100703>.
50. O'Neill, J.M.; Rogers, T.G.; Spencer, A.J.M. Thermally induced distortions in the moulding of laminated channel sections. *Math. Eng. Ind.* **1988**, *2*, 65–72.
51. Sasikumar, A.; García-Rodríguez, S.M.; Arbeláez, J.J.; Trias, D. On how unsymmetrical laminate designs with tailored ply clusters affect compression after impact strength compared to symmetric baseline. *Compos. Struct.* **2020**, *238*, 111958. <https://doi.org/10.1016/j.compstruct.2020.111958>.
52. Verma, L.; Jefferson, J.J.; Sivakumar, S.M.; Balaganesan, G.; Vedantam, S.; Dhakal, H.N. Evaluation of quasi-static indentation response of superelastic shape memory alloy embedded GFRP laminates using AE monitoring. *Polym. Test.* **2021**, *93*, 106942. <https://doi.org/10.1016/j.polymertesting.2020.106942>.
53. Huang, Y.; Hu, J.; Wang, J.; Sun, J.; You, Y.; Huang, Q.; Xu, E. Sound Quality Performance of Orthogonal Antisymmetric Composite Laminates Embedded with SMA Wires. *Materials* **2023**, *16*, 3570. <https://doi.org/10.3390/ma16093570>.
54. Sattari, M.; Kadhodaei, M.; Akbarzadeh, S.; Gholami, R.; Beheshti, A. Wear in superelastic shape memory alloys: A thermo-mechanical analysis. *Wear* **2022**, *488–489*, 204139. <https://doi.org/10.1016/j.wear.2021.204139>.
55. Sun, M.; Chang, M.; Wang, Z.; Li, H.; Sun, X. Experimental and Simulation Study of Low-Velocity Impact on Glass Fiber Composite Laminates with Reinforcing Shape Memory Alloys at Different Layer Positions. *Appl. Sci.* **2018**, *8*, 2405. <https://doi.org/10.3390/app8122405>.
56. Liu, Y.; Wang, Z.; Li, H.; Sun, M.; Wang, F.; Chen, B. Influence of Embedding SMA Fibres and SMA Fibre Surface Modification on the Mechanical Performance of BFRP Composite Laminates. *Materials* **2018**, *11*, 70. <https://doi.org/10.3390/ma11010070>.
57. Pazhanivel, K.; Bhaskar, G.B.; Elayaperumal, A.; Anandan, P.; Arunachalam, S. Influence of SMA reinforcement on the impact resistance of GFRP composite laminates under different temperatures. *Bull. Mater. Sci.* **2016**, *29*, 889–899. <https://doi.org/10.1007/s12034-016-1201-3>.
58. Zhao, S.; Teng, J.; Wang, Z.; Sun, X.; Yang, B. Investigation on the Mechanical Properties of SMA/GF/Epoxy Hybrid Composite Laminates: Flexural, Impact, and Interfacial Shear Performance. *Materials* **2018**, *11*, 246. <https://doi.org/10.3390/ma11020246>.
59. Lei, H.; Wang, Z.; Tong, L.; Tang, X. Macroscopic Mechanical Characterization of SMAs Fiber-Reinforced Hybrid Composite Under Uniaxial Loading. *J. Mater. Eng. Perform.* **2013**, *22*, 3055–3062. <https://doi.org/10.1007/s11665-013-0584-1>.
60. Sun, M.; Chang, M.; Wang, Z.; Li, H.; Liu, Y. Simulation of Eccentric Impact of Square and Rectangular Composite Laminates Embedded with SMA. *Materials* **2018**, *11*, 2371. <https://doi.org/10.3390/ma11122371>.
61. Qiu, J.; Stiharu, I. Vibration and noise reduction of pipelines using shape memory alloy. *Sci. Eng. Compos. Mater.* **2022**, *29*, 165–175. <https://doi.org/10.1515/secm-2022-0015>.
62. Baucke, A.; Mittelstedt, C. Closed-form analysis of the buckling loads of composite laminates under uniaxial compressive load explicitly accounting for bending-twisting-coupling. *Compos. Struct.* **2015**, *122*, 498–509. <https://doi.org/10.1016/j.compstruct.2014.12.054>.
63. Nemeth, M.P. *Buckling Behavior of Long Anisotropic Plates Subjected to Full Restrained Thermal Expansion*; NASA Technical Paper 212131; Langley: Hampton, VA, USA, 2003.
64. Weaver, P.; Nemeth, M.P. Bounds on flexural properties and buckling response for symmetrically laminated composite plates. *J. Eng. Mech.* **2007**, *133*, 1178–1191. [https://doi.org/10.1061/\(ASCE\)0733-9399\(2007\)133:11\(1178\)](https://doi.org/10.1061/(ASCE)0733-9399(2007)133:11(1178)).
65. Mittelstedt, C. Stability behaviour of arbitrarily laminated composite plates with free and elastically restrained unloaded edges. *Int. J. Mech. Sci.* **2007**, *49*, 819–833. <https://doi.org/10.1016/j.ijmecsci.2006.11.011>.
66. Narita, Y.; Leissa, A.W. Buckling studies for simply supported symmetrically laminated rectangular plates. *Int. J. Mech. Sci.* **1990**, *11*, 909–924. [https://doi.org/10.1016/0020-7403\(90\)90063-O](https://doi.org/10.1016/0020-7403(90)90063-O).
67. Becker, W.; Hansel, W.; Oehm, M. Buckling analysis of non-orthotropic laminates by means of B-spline functions. *Tech. Mech.* **2000**, *21*, 31–40.
68. Nemeth, M.P. Buckling of symmetrically laminated plates with compression, shear and in-plane bending. *AIAA J.* **1992**, *30*, 2959–2965. <https://doi.org/10.2514/3.11643>.
69. Thangaratnam, K.R.; Palaninathan; Ramachandran, J. Thermal buckling of composite laminated plates. *Comput. Struct.* **1989**, *32*, 1117–1124. [https://doi.org/10.1016/0045-7949\(89\)90413-6](https://doi.org/10.1016/0045-7949(89)90413-6).
70. Loughlan, J. The influence of bend-twist coupling on the shear buckling response of thin laminated composite plates. *Thin-Walled Struct.* **1999**, *34*, 97–114. [https://doi.org/10.1016/S0263-8231\(99\)00009-9](https://doi.org/10.1016/S0263-8231(99)00009-9).

71. Loughlan, J. The shear buckling behaviour of thin composite plates with Particular reference to the effects of bend–twist coupling. *Int. J. Mech. Sci.* **2001**, *43*, 771–792. [https://doi.org/10.1016/S0020-7403\(00\)00030-8](https://doi.org/10.1016/S0020-7403(00)00030-8).
72. Loughlan, J. The compressive buckling performance of anti-symmetric composite laminates and the effect on behaviour of membrane–flexural coupling. *Aeronaut. J.* **2002**, *106*, 595–605. <https://doi.org/10.1017/S000192400001825X>.
73. Loughlan, J. The influence of mechanical couplings on the compressive stability of anti-symmetric angle-ply laminates. *Compos. Struct.* **2002**, *57*, 473–482. [https://doi.org/10.1016/S0263-8223\(02\)00116-2](https://doi.org/10.1016/S0263-8223(02)00116-2).
74. Ovesy, H.R.; Assaei, H. The effects of bend–twist coupling on the post-buckling characteristics of composite laminated plates using semi-energy finite strip approach. *Thin-Walled Struct.* **2007**, *45*, 209–220. <https://doi.org/10.1016/j.tws.2007.01.016>.
75. Rohwer, K. Einfluss der Biege-Torsionskopplung auf die Beullasten symmetrisch geschichteter Platten. In *Entwicklung und Anwendung von Faserverbund-Strukturen*; Report 87-02; Deutsche Gesellschaft für Luft-und Raumfahrt: Bonn, Germany, 1987; pp. 325–347.
76. Rohwer, K. *Reduction of the Buckling Loading of Plates Under Compressive Loading Due to Coupling of Bending and Torsion*; Report 45114–01; Industrie-Ausschuss Strukturberechnungsunterlagen (IASB): Bonn, Germany, 1991.
77. Seydel, E. The critical shear load of rectangular plates. *Z. Für Flugtech. Und Mot.* **1933**, *4*, 169–191.
78. National Center for Advanced Materials Performance. NCAMP Test Report Number: CAM-RP-2010-002 Rev A; National Center for Advanced Materials Performance, NIAR, Wichita State University: Wichita, KS, USA, 2011.
79. Vignoli, L.L.; Neto, R.M.C.; Savi, M.A.; Pacheco, P.; Kalamkarov, A. Trace theory applied to composite analysis: A comparison with micromechanical models. *Compos. Commun.* **2021**, *25*, 100715. <https://doi.org/10.1016/j.coco.2021.100715>.
80. Tsai, S.W.; Arteiro, A.; Melo, J.D. A Trace-based approach to design for manufacturing of composite laminates. *J. Reinf. Plast. Compos.* **2015**, *35*, 7. <https://doi.org/10.1177/0731684415624770>.
81. Romeo, G.; Danzi, F.; Tsai, S.W. Using Trace to scale the properties of composite materials. *JEC Compos. Mag.* **2014**, *51*, 42–45.
82. Sacco, C.; Radwan, A.B.; Harik, R.; Van Tooren, M. *Automated Fiber Placement Defects: Automated Inspection and Characterization*; NASA Report Number: NF1676L-29116; SAMPE: Covina, CA, USA, 2018.
83. Harik, R.; Brasington, A. *Automated Fiber Placement: Status, Challenges, and Evolution*; SAE International: Warrendale, PA, USA, 2025.
84. Heinecke, F.; Willberg, C. Manufacturing-Induced Imperfections in Composite Parts Manufactured via Automated Fiber Placement. *J. Compos. Sci.* **2019**, *3*, 56. <https://doi.org/10.3390/jcs3020056>.
85. Smith, R.; Qureshi, Z.; Scaife, R. Limitations of processing carbon fibre reinforced plastic/polymer material using automated fibre placement technology. *J. Reinf. Plast. Compos.* **2016**, *35*, 1527–1542. <https://doi.org/10.1177/0731684416659544>.
86. Bakhshi, N.; Hojjati, M. Effect of compaction roller on layup quality and defects formation in automated fiber placement. *J. Reinf. Plast. Compos.* **2019**, *39*, 3–20. <https://doi.org/10.1177/0731684419868845>.
87. Qiao, G.; Weiss, B.A. Industrial robot accuracy degradation monitoring and quick health assessment. *J. Manuf. Sci. Eng.* **2019**, *141*, 071006. <https://doi.org/10.1115/1.4043649>.
88. Croft, K.; Lessard, L.; Pasini, D.; Hojjati, M.; Chen, J.; Yousefpour, A. Experimental study of the effect of automated fiber placement induced defects on performance of composite laminates. *Compos. Part A Appl. Sci. Manuf.* **2011**, *42*, 484–491. <https://doi.org/10.1016/j.compositesa.2011.01.007>.
89. Anay, R.; Miller, D.; Tssema, A.; Wehbe, R.; Ziehl, P.; Tatting, B.; Gürdal, Z.; Harik, R.; Kidane, A. An experimental investigation concerning the effect of AFP defects on progressive damage in CFRP coupons. *Compos. Struct.* **2022**, *279*, 114725. <https://doi.org/10.1016/j.compstruct.2021.114725>.
90. Lukaszewicz, D.H.-J.L.; Ward, C.; Potter, K.D. The engineering aspects of automated prepreg layup: History, present and future. *Compos. Part B Eng.* **2012**, *43*, 997–1009. <https://doi.org/10.1016/j.compositesb.2011.12.003>.
91. Shirinzadeh, B.; Cassidy, G.; Oetomo, D.; Alici, G.; Ang, M.H. Trajectory generation for open-contoured structures in robotic fibre placement. *Robot. Comput. Integr. Manuf.* **2007**, *23*, 380–394. <https://doi.org/10.1016/j.rcim.2006.04.006>.
92. Gürdal, Z.; Tatting, B.F.; Wu, K.C. Tow-placement technology and fabrication issues for laminated composite structures. In *Proceedings of the Collection of Technical Papers—AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*; AIAA: Reston, VA, USA, 2005; pp. 2716–2733.
93. Jiang, M.; Wu, B.; Li, F. Path optimization for open-contoured structures in robotic fibre placement. In *Proceedings of the 32nd Youth Academic Annual Conference of Chinese Association of Automation*; Chinese Association of Automation: Beijing, China, 2017; pp. 207–212.

94. Farzaneh Kaloorazi, M.H.; Bonev, I.A.; Birglen, L. Simultaneous path placement and trajectory planning optimization for a redundant coordinated robotic workcell. *Mech. Mach. Theory* **2018**, *130*, 346–362. <https://doi.org/10.1016/j.mechmachtheory.2018.08.022>.
95. Khan, M.A.; Mitschang, P.; Schledjewski, R. Parametric study on processing parameters and resulting part quality through thermoplastic tape placement process. *J. Compos. Mater.* **2013**, *47*, 485–499. <https://doi.org/10.1177/0021998312441810>.
96. Oromiehie, E.; Prusty, B.G.; Compston, P.; Rajan, G. The influence of consolidation force on the performance of AFP manufactured laminates. In *Proceedings of the ICCM International Conferences on Composite Materials*; ICCM: Xi'an, China, 2017; Volume 2017.
97. Engelhardt, R.; Irmanputra, R.; Brath, K.; Aufenanger, N.; Drechsler, K. Thermoset prepreg compaction during automated fiber placement and vacuum debulking. *Proc. CIRP* **2019**, *85*, 153–158. <https://doi.org/10.1016/j.procir.2019.09.025>.
98. Jeffries, K.A. Enhanced robotic automated fiber placement with accurate robot technology and modular fiber placement head. *SAE Int. J. Aerosp.* **2013**, *6*, 774–779.
99. Inman, H.F.; Bradley, E.L. The overlapping coefficient as a measure of agreement between probability distributions and point estimation of the overlap of two normal densities. *Commun. Stat.-Theory Methods* **1989**, *18*, 3851–3874.
100. Pastore, M.; Calcagni, A. Measuring distribution similarities between samples: A distribution-free overlapping index. *Front. Psychol.* **2019**, *10*, 1089.
101. *ISO 2768-2:1989*; General Tolerances—Part 2: Geometrical Tolerances for Features Without Individual Tolerance Indications. International Organization for Standardization: Geneva, Switzerland, 1989.

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