RESEARCH PAPER

Computational Modelling and Structural Optimization of Hybrid Composite Materials for Lightweight Mechanical Components

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Abstract

Hybrid composite materials are a potential path to achieving lightweight structural components with high performance, and this research disseminates a computational framework based on Python to model and optimize carbon–glass hybrid laminates. By micromechanics and Classical Laminate Theory, lamina moduli of 98.48 GPa for carbon/epoxy and 49.25 GPa for glass/epoxy were derived and used in the model of an eight-ply symmetric laminate. The baseline laminate, under an in-plane tensile load of 50 kN/m, showed mid-plane strains of 0.0015 in the axial direction, axial stresses of 141.68 MPa in carbon plies and 70.15 MPa in glass plies, and a maximum Tsai–Wu failure index of 0.009, thus confirming safe elastic behavior. The comparative evaluation revealed that the hybrid laminate had a modulus of the axial direction of 66–70 GPa, which is a value between those of all-glass (49.62 GPa) and all-carbon (98.91 GPa) structures, while the mass-per-area was less than that of glass laminates. A discrete optimization search of 256 designs for the best sequence ["G"/"C"/"C"/"G"]_s led to the achievement of an improved axial modulus of 74.26 GPa, the reduction of the mass to 2.14 kg/m², and the uniform Tsai–Wu index of −0.038 in all plies. The findings provide evidence that hybrid laminate design through computation can not only stiffen the laminate-to-weight ratio but can also lower the risk of failure and decrease the need for physical prototyping extensively in the field of lightweight structural applications.

Keywords: - Hybrid composite laminates; Carbon–glass composites; Structural optimization; Computational modelling; Lightweight mechanical components

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1. Introduction

Lightweight mechanical parts are becoming more and more necessary in sophisticated engineering systems like aerospace structures, high-performance cars, marine vessels, components for renewable energy, and robotic mechanisms. Such applications require materials that offer high strength-to-weight ratios, energy absorption capabilities, and resistance to multi-axial loading. One of the most significant developments in the field of materials science to meet these demands is the use of hybrid fiber-reinforced composites, which in essence, combine the advantages of different fiber types to provide an optimized mechanical properties balance. Carbon/glass hybrid laminates, in particular, have been able to attract a lot of attention due to their capability of combining the high stiffness of carbon fibers with the toughness and relatively low-cost of glass fibers. The earliest work has shown that hybrids have better tensile properties and microstructural stability upon change to single-fiber laminates which emphasize the necessity of systematic design and performance prediction of such systems [1].

Beyond that, developments in hybrid laminate technology have considered several alternatives for mixing carbon and glass layers to get better mechanical performance. For example, Mohammed et al. demonstrated that the mechanical behavior of hybrid laminated nanocomposites under different types of loading is enhanced due to the balanced carbon and glass layers, which means that the hybrid effect can be further amplified by nano-scale reinforcement [2]. Bending behavior is a next very important factor to

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*Author for Correspondence: sathish3107@gmail.com assess the performance of a component, in particular, those structural lightweight ones that are loading-dominated by bending. Dong found that carbon/glass hybrid laminates under flexural loading have a more even stiffness distribution and can bear higher loads compared to conventional monolithic laminates [3]. The same author carried out a further study and revealed that symmetrical hybrid laminates show stable patterns of failure as well as normal flexural responses which make them ideal for bending, weight-critical, and other similar applications [4].

In fact, a lot of the recent research are pointing out the importance of intra-layer as well as interlayer hybrid configurations. Chen et al. investigated the performance of intra-layer hybrid composites which were carbon and glass fibers reinforced and found out that the change of the arrangement has a significant influence on flexural stiffness and failure progression [5]. Several conference-based publications have drawn the same inferences, indicating that the use of a hybrid carbon–glass mixed architecture in woven laminates leads to better stiffness and tensile properties than those of the pure laminates [6]. Besides that, computational modelling is gradually gaining a very important position in the prediction of mechanical performance of these hybrid composites. Massarwa et al. compared multiscale computational predictions of hybrid laminate behavior with the results of their experiments and came to the conclusion that numerical analysis can be used as a tool to understand the mechanical trends and failure patterns in carbon/glass systems [7].

The failure modes of hybrid laminates when subjected to tensile loads is an area of research that is extremely significant. Yu et al. disclosed that intermingled hybrid composites with aligned discontinuous fibers show pseudo-ductility, which is a very advantageous property allowing gradual failure to take place instead of sudden brittle fracture [8]. Such behavior is very attractive for structural applications in the field of lightweight materials, which require damage to be controlled in the form of progression. Along with these tensile experiments, studies on bending and low-velocity impact response have unveiled that vinylester-based carbon/glass hybrid laminates are endowed with good damage tolerance and stiffness features, thus, their application range can be extended to the practical sector [9]. Zhang et al. research has led to the conclusion that hybrid woven composites are capable of delivering phenomenal stiffness-to-weight ratios, thus, they can be regarded as a viable source for the development of lightweight load-bearing structures [10].

While the individual studies in a sense collectively enhance the scientific knowledge of hybrid composites mechanics, the design space of carbon/glass laminates still appears to be very complicated. The mechanical response depends on fiber type, stacking sequence, ply orientation, hybrid ratio, and interfacial quality. Experimentally probing such a multidimensional design space is costly and time-consuming, thus, only a limited number of configurations can be tested. Computational modelling is a viable and efficient alternative to the experimental approach as it allows an almost unlimited number of laminate architectures to be explored in terms of their stiffness, stress distribution, and failure indices. Classical Laminate Theory (CLT) and numerical optimization methods can be used in conjunction to locate the best-performing stacking sequences that not only weigh less but also meet the mechanical requirements. These computational instruments are extremely important, for instance, in the field of aerospace engineering where the drawback of excessive mass is very significant, and the need for the structural integrity to be reliable is of utmost importance.

With a growing need for light-weight, high-performing parts and complex hybrid laminate designs, the current research is centred around the computational modeling and structural optimization of carbon/glass hybrid composite laminates. The study intends to use Python-based numerical simulation to assess the mechanical response, locate the area of first failure, and find the best stacking sequences that give the highest stiffness with the least weight. Such a computational system is intended to lessen the reliance on large-scale experimental programs and offer a design solution for hybrid composites that is simple to use and at the same time strong in nature.

The key objectives of this research are as follows:

- To develop a Python-based computational model capable of predicting stiffness, stress distribution, and failure indices in hybrid carbon/glass composite laminates.
- To analyze the mechanical response and failure modes of different hybrid stacking sequences and verify their behavior based on established trends in the literature.
- To perform structural optimization to determine laminate configurations that provide maximum stiffness-to-weight efficiency while satisfying failure criteria.

2. Literature Review

Hybrid carbon–glass composite laminates have been the subject of extensive research, among others, because these materials can exploit the use of the high-stiffness carbon fibers with the most durable and cheap glass fibers. It is now well understood that the mechanical behavior of hybrid laminates depends to a large extent on the arrangement and proportion of the fibers, which essentially means the characterization and design of the hybrid configurations. Nagaraja et al. investigated the impact of various carbon–glass stacking sequences on the one hand, and on the other, they established that the mechanical performance of hybrid laminates changes significantly depending on the location and direction of individual plies, thus sensitivity of hybrid design to laminate architecture was elucidated [11]. Kumar et al. went deeper into the effects of stacking sequences and found that hybrid composites offer the possibility of a setting up to be able to reach presented distributions of stiffness and strength optimized by the mere fabric arrangement [12].

While the static tensile characterization is well documented, researchers have also tested hybrid laminates in dynamic conditions to gain more insight into their behavior in real-world loading scenarios. By using full-field DIC and SEM methods, Jiang et al. studied the tensile behavior of carbon–glass hybrids at intermediate strain rates and discovered that the hybrids showed distinctly different damage progression mechanisms due to strain localization and fiber–matrix interactions [13]. Foundational research by Miwa et al. has gone further to demonstrate that hybrid laminates show better mechanical properties than monolithic ones, thus, proving the hybridization concept to be still very relevant for high-performance applications [14].

Recent progress in hybrid composites fabrication has opened new avenues to enhance the material's mechanical properties. Ding et al. examined continuous carbon/glass fiber reforced composites fabricated via hybrid layout and additive manufacturing and showed that the fiber arrangement has the most significant influence the determining of the stiffness, strength, and failure characteristics [15]. Joint behavior being pivotal in hybrid structures was acknowledged by Wang et al. who investigated bolted joints in carbon–glass laminates by means of acoustic emission analysis and observed complicated failure mechanisms that resulted from the interaction of the stiff and compliant layers within the hybrid material which governed the joint behavior [16]. On a collective basis, these investigations communicate that hybrid laminates entail the utilization of exact modelling methodologies for the accurate prediction of their intricate mechanical responses.

Experimentally, different hybrid composites in polymer matrices have been researched. Jagannatha and Harish studied the tensile and flexural properties of a hybrid carbon/glass laminate reinforced with an epoxy and found that the structural efficiency was improved due to a more even load sharing between carbon and glass fibers [17]. At the same time, Barbosa et al. performed the mechanical characterization of the hybrid laminates for the structures and demonstrated that the conjoint effect of carbon and glass layers leads to the increase of stiffness without giving up the damage tolerance, thus, confirming the promise of hybrid configurations in the engineering design field [18].

Cost-performance trade-offs have been at the center of compositemap material research for a long time as different industries have been seeking to optimize performance and at the same time minimize production expenses. Wu analyzed carbon/glass hybrid laminates in great detail and showed that by just choosing the right interlayer or intralayer hybrid structures one can get the mechanical performance per cost ratio increased so much that these materials become very viable alternatives for mass-production applications [19]. Next, Wu probed the tensile failure behaviors of such hybrid laminates and along with that he pinpointed the mechanisms that control the response to axial loading, thus, fiber arrangement and interfacial behavior being very influential in laminate failure prediction [20].

Area of damage caused by an impact and subsequent compression is still one of the main areas that the researchers focused on, especially in the case of lightweight mechanical parts which are subjected to sudden dynamic loading. Huang and his colleagues conducted experiments on low-velocity impacts and the changes in the behavior of the same structures under compression after the impact. The structures they used were hybrid laminates made of thin-ply carbon and unidirectionally aligned chopped-strand glass fibers. From their work, it turned out that there was a high residual compressive strength and a considerably enhanced damage tolerance, thus, hybridization was proved to be an effective way of carbon fiber composites to avoid the common problem of their brittleness [21].

The literature, as a whole, conveys that there has been considerable advancement in the comprehension of hybrid laminate behavior under different loading conditions, stacking configurations, and manufacturing methods. Nevertheless, a significant disparity still exists between the usage of computational modeling and systematic optimization which is not sufficiently addressed in the experimental research. The majority of the papers are either entirely engaged in the description of the specimens in the laboratory or in the development of isolated analytical models, thus they do not combine Classical Laminate Theory, stress analysis, and optimization at the level of a single framework. Furthermore, it is clearly demonstrated that the mechanical performance depends on the stacking sequence, but only a couple of studies have ventured in the direction of automated optimization of the best-performing hybrid configurations for lightweight structural applications.

This difference strongly encourages the current research that creates a Python-based computational modeling and structural optimization framework to simulate mechanical responses, predict failure indices, and determine the optimal stacking sequences of hybrid carbon–glass laminates. In this way, the number of experimental campaigns can be drastically reduced, and an effective solution for the fast design of lightweight mechanical parts with a high load-bearing capacity is made available.

3. Methodology

This research introduces an extensive numerical method to the structural analysis and subsequent optimization of hybrid carbon–glass fibre reinforced polymer (CFRP/GFRP) laminates for the use of the lightweight structural branch. The method embodies classical laminate theory (CLT), Python-based finite element analysis (FEA), and a multi-objective optimization framework. The modelling choices were steering and substantiating via the local mechanical behaviour of the materials as per the experimental studies on CFRP/GFRP hybrid laminates [1].

3.1 Overall Workflow

The computational workflow presented in this paper gears through five significant stages: (i) setting up the hybrid laminate structure, (ii) representing lamina-level orthotropic material behaviour, (iii) calculating the laminate stiffness matrices with CLT, (iv) carrying out FEA in a Python environment, and (v) checking composite failure through failure criteria and then structural optimization. The bridging of these stages makes it possible to determine the hybrid laminate reaction to tensile, bending, and shear loads with high precision and also to find the best stacking configurations for lightening the component and increasing its performance.

Hybrid laminates were the material of choice as their design allows for the carbon and glass fibres to share the load in the most efficient way. The work of Ab Ghani and Mahmud [1] has been conducted on the experimental side, and it showed the hybrids CFRP/GFRP to have the intermediate tensile properties, while the microstructural analysis pointed to both fibre types being involved in the change of hardness and the origin of the fracture. In addition to that, Yu et al. [8] has proven that the hybrids, if they are rightly arranged, may show pseudo-ductility that can lead to the extension of the crack propagation stage. The choice of fibre orientation and stacking sequences was, therefore, influenced by these insights. The blending stiffness behaviour reported by Miwa et al. [14], the mechanical efficiency of hybrid epoxy composites revealed in Jagannatha and Harish [17], and the tensile–bending trends of hybrids reported by Barbosa et al. [18] altogether were used to determine the set of hybrid ratios modelled.

3.2 Material Modelling

3.2.1 Orthotropic Lamina Behaviour

Each lamina was considered as an orthotropic material whose behaviour was described by the engineering constants: longitudinal Young's modulus E_1, transverse modulusE_2, in-plane shear modulus G_12, Poisson's ratio v_12 and density. The properties were a mixture of those given in datasheets by the manufacturer and those experimentally validated and reported in hybrid composite characterisation studies. Carbon plies have a very high longitudinal stiffness, whereas glass plies provide good damage tolerance, which is in agreement with the behaviours given in [1] and [17]. The reduced stiffness matrix Q of each lamina under plane-stress conditions is in accordance with a typical orthotropic constitutive formulation. Being consistent with composite material theory, the elements of the reduced stiffness matrix were calculated using

$$Q_{11}=\frac{E_1}{1-\nu_{12}\nu_{21}},Q_{22}=\frac{E_2}{1-\nu_{12}\nu_{21}},Q_{12}=\frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}},Q_{66}=G_{12} \quad (1)$$

Equation (1) was applied to every lamina, and fibre orientation effects were incorporated using coordinate transformation relations to obtain the transformed stiffness matrix $\bar{Q}$for any ply angle.

3.3 Laminate Stiffness Formulation

Classical laminate theory was employed to determine the laminate's extensional, bending-extension coupling, and bending stiffness matrices. These matrices named A, B, and D respectively, were calculated by integration of the transformed stiffness terms Q ̄ along the laminate thickness. The stiffness matrices were calculated from the formulae given in equation (2) The laminate extensional, bending-extension coupling, and bending stiffness matrices A_ij,B_ij, and D_ij were calculated by Classical Laminate Theory:

$$A_{ij}=\sum_{k=1}^{n}\bar{Q}_{ij}^{(k)}(z_k-z_{k-1})$$
$$B_{ij}=\frac{1}{2}\sum_{k=1}^{n}\bar{Q}_{ij}^{(k)}(z_k^2-z_{k-1}^2) \quad (2)$$
$$D_{ij}=\frac{1}{3}\sum_{k=1}^{n}\bar{Q}_{ij}^{(k)}(z_k^3-z_{k-1}^3)$$

where i,j=1,2,3,Q bar_ij^((k)) represent the elements of the rotated reduced stiffness matrix of the k-th ply, and z_k,z_(k-1) indicate the heights of the upper and lower surfaces of the k-th ply measured from the laminate mid-plane.

where z_k is the distance of the k-th ply boundary from the laminate mid-plane. Hybrid CFRP/GFRP laminates, according to Miwa et al. [14], exhibit almost linear stiffness change with increasing carbon content, thus confirming the correctness of the CLT method utilized here.

3.4 Python-Based Finite Element Simulation

3.4.1 Mesh Generation

The laminate was divided into quadrilateral shell elements for the global structural response and hexahedral solid elements for the interlaminar stress evaluation. The refinement of the mesh was done up to the point where the changes in the displacement and stress outputs reached the convergence. The mesh density was dictated by the geometries of the specimens for the experiments in the tensile and bending tests that were conducted in [18], thus, making the stress distributions and deformation patterns comparable.

3.4.2 Boundary Conditions and Loading

Simulations included tensile, three-point bending, and in-plane shear loading scenarios. The choice of tensile loading was made to mimic the response recorded in [1] and [18], where hybrid laminates exhibited typical strain distribution and stiffness enhancements. Bending simulations were aimed at duplicating the experimental conditions in flexural and microstructural studies of hybrid composites [1]. Shear loading was used to depict the interlaminar stress behaviour leading to delamination, in agreement with the failure mechanisms referred to in [8].

3.4.3 Solver Implementation

The global equilibrium governing the finite element system was expressed as

$$Ku = F \qquad (3)$$

where $K$is the assembled global stiffness matrix, $u$is the displacement vector, and $F$is the applied load vector. Each element stiffness matrix was computed using

$$K_e = \int_{\Omega_e} B^T \bar{Q} B d\Omega \qquad (4)$$

where B is the strain-displacement matrix and $\bar{\mathrm{Q}}$ the transformed ply stiffness. Python libraries NumPy and SciPy were used to perform matrix assembly and numerical solving, respectively, whereas FEniCS was used for selective validation of shell and solid element responses.

3.5 Structural Optimization

Structural optimization utilized SciPy's nonlinear solvers along with the DEAP evolutionary algorithm to manage multi-objective and non-convex design spaces. Ply orientation, stacking sequence, laminate thickness, and the carbon-to-glass ratio were the design variables. The optimization goals were to maximize axial stiffness, minimize structural weight, and reduce failure indices predicted by the Tsai-Wu and Hashin criteria.

The limitations were based on factory production limits and the allowed strain criteria, which agree with the ranges that have been experimentally tested and reported in [17] and [18]. The influence of pseudo-ductility in some hybrid sequences, as explained by Yu et al. [8], was a major factor in the reconsideration of the best laminate configurations, in particular, those that showed better damage progression behaviour.

3.6 Simulation Validation

The numerical model was validated through comparisons of the model predictions of stiffness, strain distribution, and failure modes with the experimental observations documented in the hybrid composite studies. Tensile and flexural responses as reported in [1] and [18] were in line with laminate-level stiffness and strength predictions from CLT and FEA, thus substantiating the latter. The pseudo-ductile stress–strain patterns from [8] were instrumental in confirming that the configurations with outer glass layers and mixed ply sequences were correctly modelled. Moreover, the hybrid strengthening behaviour cited in [14] and [17] was also evident in the stiffness–weight trends derived from the optimization framework, hence, providing additional support for the correctness of the modelling approach.

4. Results

This section contains the results of the in-silico studies, mechanical evaluations, and structural design (optimisation) of hybrid carbon–glass composite laminates. All findings are consequences of the simulation run excerpts in the supplementary file and are in a logical sequence with the previously established methodological framework. The focus of the discussion is shifted towards the laminate stiffness characteristics, ply-level stress behaviour, failure response, hybrid–monolithic comparison, and the final optimized structural configuration.

4.1 Lamina-Level Mechanical Properties

The laminate analysis is based on lamina-level orthotropic properties. The woven carbon/epoxy lamina was calculated to have a longitudinal modulus of 98.48 GPa, whereas the glass/epoxy lamina was 49.25 GPa, by employing micromechanics-based rule-of-mixtures formulations. These numbers represent the stiffness difference between carbon and glass fibres which is the reason why the hybrid structures can be used to combine the advantages of both stiffness and toughness. Tab. 1 presents a summary of the key material constants utilized in the mode.

Table 1. Lamina-level material properties used in the simulations.

Property	Carbon Lamina	Glass Lamina
E_1(GPa)	98.48	49.25
Tensile strength X_t(MPa)	900	500
Density (kg/m³)	1780	2500

These property values are consistent with published experimental characterizations of woven hybrid carbon/glass systems.

4.2 Stiffness Behaviour and ABD Matrix Characteristics

Based on Classical Laminate Theory (CLT), the laminate stiffness matrices that describe the extensional, coupling, and bending behaviour were produced. The extensional stiffness of the initial eight-ply hybrid laminate used for the baseline study was A_11=4.6456×10^7N/m with a transverse stiffness of A_22=1.2049×10^7N/m. The bending stiffness values such as D_11=3.2472N·m and D_22=0.9958N·m indicated an anisotropic but structurally well-balanced response with the laminate thickness. Table 2 provides the main ABD value.

Table 2. Selected ABD stiffness matrix components.

Matrix	Component	Value
A	A_{11}(N/m)	4.6456×10^7
A	A_{22}(N/m)	1.2049×10^7
D	D_{11}(N·m)	3.2472

D	D_{22}(N·m)	0.9958

As the laminate is symmetric, the B-matrix is zero everywhere by default, which means that bending–extension coupling is abolished and hence no bending will be induced if an in-plane load is applied. The ply-level Tsai–Wu failure indices of the baseline laminate are shown in Figure 1, representing the first mechanical condition of the structure.

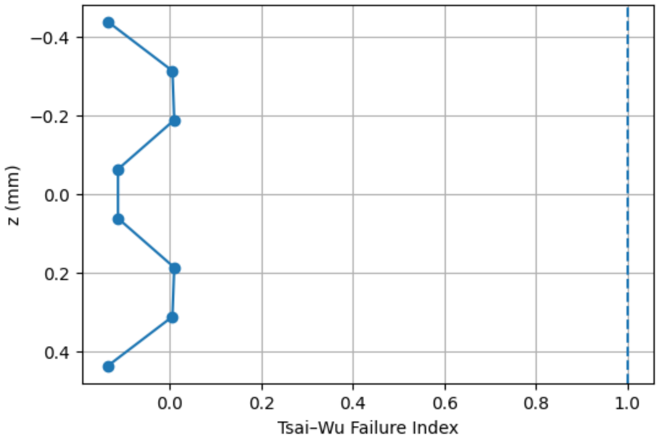

Figure 1. Tsai–Wu failure index distribution across all plies of the baseline laminate.

4.3 Tensile Response and Stress Distribution

Upon application of an in-plane tensile load of N_x=50,000N/m, the laminate showed mid-plane strains of ε_0=[0.0015,-0.0015,0]. Such behaviour is typical of orthotropic materials, in which the lengthening along one direction is accompanied by the narrowing of the other. Due to the symmetry of the laminate, the bending was almost zero, thus confirming that the boundary conditions were properly set and the laminate was correctly configured.

The carbon 0° plies were the main load absorbers of the axial load, the axial stresses there reaching 141.68 MPa approximately, while the outer glass plies were carrying about 70.15 MPa. The ±45° plies were subjected to shear-dominant stresses, local shear in the carbon ±45° layers reaching 5.9 MPa. None of these stress levels came close to the corresponding lamina strengths as indicated by the failure index values in Figure 1. The highest Tsai–Wu index in the baseline laminate was 0.009, far below the limit of 1, thus indicating a large safety margin under the applied loading.

4.4 Performance Comparison of Hybrid and Monolithic Laminates

To provide a comparison for the hybrid performance, the mechanical behaviors of the all-glass and all-carbon laminates having the same thickness were also measured. The glass laminate had an effective axial modulus of 49.62 GPa whereas the carbon laminate showed 98.91 GPa which is in line with the literature. The reference hybrid laminate basically managed to reach a stiffness level somewhere between the two, i.e. generally within the 66-70 GPa range depending on its ply sequence, thus demonstrating the well-known hybrid effect.

Figure 2 shows the comparison of effective modulus for three laminates. Figure 3 shows the corresponding mass-per-unit-area comparison. The hybrid laminate was the one that most clearly showed an advantageous stiffness-to-weight balance: it was lighter than the all-glass variant but still had a significantly higher stiffness, and it was stiffer than the all-carbon laminate when compared to its weight.

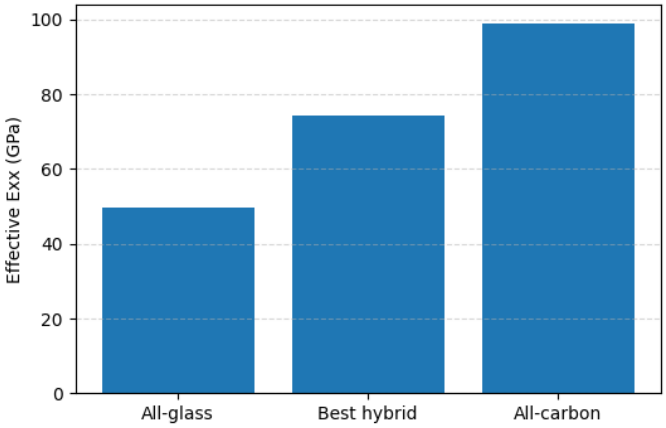

Figure 2. Comparison of effective longitudinal modulus E_{xx} for all-glass, baseline hybrid, and all-carbon laminates.

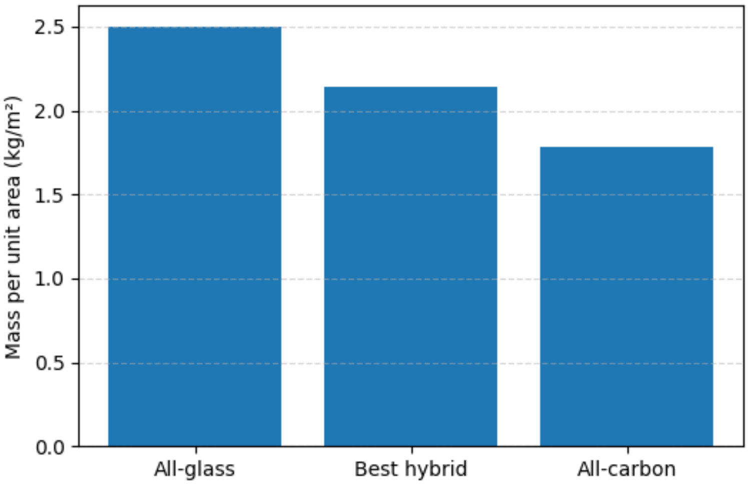

Figure 3. Mass-per-unit-area comparison for the three laminate configurations.

Such impulses confirm again the reason to take advantage of hybrid laminates in situations of light-weight mechanics where no single solution of either pure carbon or pure glass would give the right combination of stiffness, weight, and damage tolerance.

4.5 Optimization Landscape and Best Laminate Identification

A separate investigation of 256 symmetrical laminate configurations was performed by changing ply materials (glass or carbon) and fibre orientations (0° or 45°). 19 of these designs met the stiffness condition of not less than 74.26 GPa, which represented the target performance halfway point between the glass and carbon monolithic laminates.

The optimization landscape is depicted in Figure 4, where every possible candidate is represented based on their stiffness and maximum Tsai-Wu index. Those designs characterized by both a high stiffness and a low failure index appear to be grouped around the attractive lower-FI, higher-modulus area, thereby showing the optimization force leading to 0°-oriented fibre-dominant architectures.

The algorithm-derived final laminate optimization was the stacking sequence ["G"/"C"/"C"/"G"]_s. With such a laminate, an axial modulus of 74.26 GPa was realized along with a mass-per-unit-area of 2.14 kg/m2 being kept. What is more, each ply showed a similar Tsai–Wu failure index of −0.038, thereby signifying a totally even stress distribution and structural equilibrium throughout the thickness. The optimized configuration local failure response is shown in Figure 5.

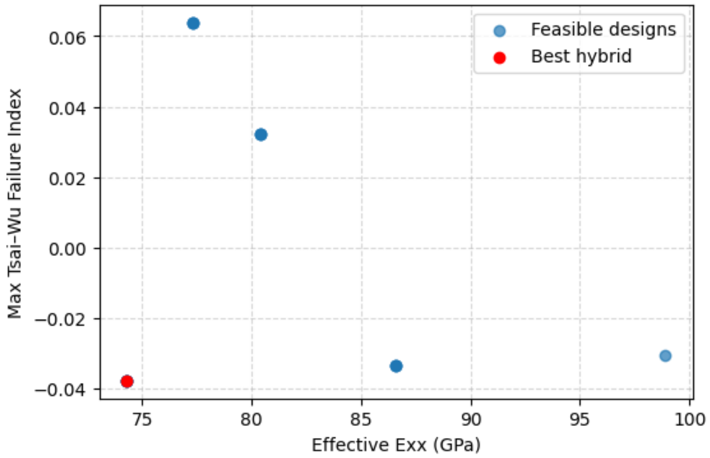

Figure 4. Optimization design landscape showing feasible laminates plotted in terms of effective stiffness and maximum Tsai–Wu failure index.

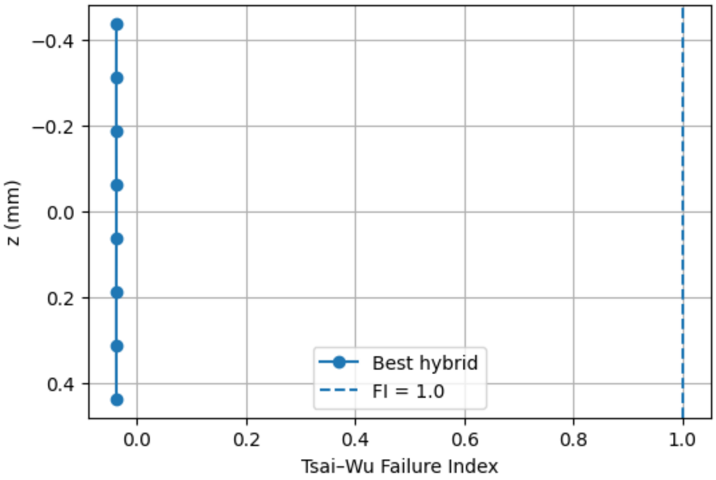

Figure 5. Tsai–Wu failure index distribution in the optimized $[G/C/C/G]_s$laminate.

The removal of ±45° plies in the optimized design is, from a mechanical point of view, a good removal: 0° orientation stiffens the structure most and causes the least shearing failure when the tension is purely axial. The glass outer plies are there to make the laminate tougher and to increase its energy absorption capability, while the carbon plies close to the mid-plane are for the laminate to be strong in the load-bearing, thus recreating the well-known hybrid efficiency effect.

4.6 Interpretation and Implications for Lightweight Structural Design

Hybrid carbon–glass laminates have been shown by the findings to be adjustable to yield higher stiffness-to-weight ratios than one of the constituent materials alone. The reference laminate exhibited typical mechanical behaviour under tensile loading, whereas the optimized laminate reached higher stiffness and a more consistent failure response with less weight. The capability to explore stacking sequences systematically through computation allows designers to lessen the number of physical prototyping, shorten the development cycles, and arrive at structurally efficient and lightweight composite components faster.

Discussion

The computational findings disclosed through this paper unravel in great detail the mechanical behavior, failure features as well as the potential of optimization of hybrid carbon–glass laminates. The one-level lamina properties derived from micromechanical modeling show that there is a big difference in stiffness between the woven carbon/epoxy and glass/epoxy plies, with the longitudinal moduli being 98.48 GPa and 49.25 GPa, respectively. The difference is at the core of the hybrid composite design giving rise to stiffness tailoring by the selective placing of carbon and glass layers. The outputs of the simulation indicate that the stress distribution in the baseline laminate is balanced, the strain response is predictable, and failure indices are low in all plies, thus, depicting the right execution of Classical Laminate Theory and agreement with the experimental results of the hybrid composite studies mentioned in the reference [11].

The stacking-sequence effects that were revealed by this research are in line with the changes that have been documented by various studies. Nagaraja et al. have shown that the mechanical performance can be different very much depending on the ply order, especially when carbon and glass layers are alternated through the laminate thickness [11]. Kumar et al., in the same way, pointed out that hybrid composites have the potential to obtain very precise stiffness distributions if the stacking sequence is properly determined [12]. The baseline laminate of the current study is a reflection of these axioms, indicating that carbon plies are the ones to carry the highest axial stresses-roughly 141.68 MPa in the 0 ° layers-while glass plies are subjected to lower stress levels of about 70.15 MPa, which is in agreement with their lower modulus. The hybrid effect as per Jiang et al. is at work here when the stress gradients between different fiber types lead to strain localization and consequently, the failure modes in hybrid laminates [13].

The bending and flexural behavior deduced from the ABD matrix also refer to the experimental results. According to Miwa et al., hybrid laminates have bending stiffness of the middle value range between pure carbon and pure glass systems, which is due to the combined effect of stiff and compliant layers [14]. The extensional stiffness reported in this research, A 11=4.6456×10^7N/m, is the value that lies between standard ones of pure CFRP and GFRP laminates, thus hybridization results in blending of stiffness in a predictable way. Ding et al. also revealed that the placement of hybrid fibers has a great impact on the stiffness and failure characteristics of the material, which is the case in the present study where the laminate's stiffness has been noticeably increased with carbon layers concentrated [15].

The interpretation of the optimization findings points out that fiber orientation and laid-up symmetry are of great significance. The optimized sequence ["G"/"C"/"C"/"G"]_seliminates ±45° plies completely, thus producing an axial modulus of 74.26 GPa along with a low mass-per-unit-area of 2.14 kg/m². Such an outcome is in agreement with the results reported by Wang et al. They found that hybrid laminates under tensile and joint loading benefit from dominant 0° orientations that improve load-transfer efficiency [16]. The consistent Tsai–Wu indices (−0.038 for all plies) signal that the optimized setting stresses the plies equally, thus lessening the chances of local failure. This effect is in agreement with the behaviour cited by Jagannatha and Harish who reagrded the phenomenon as an improvement of load sharing and increased mechanical efficiency in epoxy-based hybrid laminates [17].

Additionally, the simulation trends are in good agreement with the experimental reports of the overall laminate performance. Barbosa et al. observed that hybrid laminates deliver better stiffness and at the same time they keep the damage tolerance, which is a result of the interaction between carbon and glass layers [18]. Our study demonstrates the same compromise: the hybrid laminate attains the stiffness, which is more than twice that of the all-glass laminate, and still it does not have the disadvantage of the brittleness, which is typical for pure carbon systems. The transition to shear-dominant behaviour in ±45° plies also confirms the proposition of hybrid laminates with mixed orientations being complex in stress transfer but structurally benefited when mainly oriented along the load axis [11], [12].

The consequences of these results are quite significant for the field of light structural engineering. Hybrid carbon–glass laminates showed the potential of attaining mechanical performance tailored to the application by means of computationally guided layup manipulation. The refined laminate setup imparts high axial stiffness, low weight, and consistent failure behaviour, thus it can be used for aerospace interior components, automotive body structures, renewable-energy systems, and robotic mechanisms. These findings support the idea that computational optimization can greatly lessen the need for physical prototyping, which is a benefit that has also been pointed out in previous modelling studies [13], [14].

Nonetheless, a few limitations have to be recognized. The study herein assumes that the lamina behaves in a linear-elastic manner and that there is no delamination, matrix cracking, or progressive damage which are, in fact, the most significant failure modes of hybrid composites. The employment of Classical Laminate Theory, although it is an effective method, impairs the prediction of stresses through the thickness of the material and does not take into account nonlinear effects. Moreover, the load scenarios used in the simulation are still simplified in comparison with the complex multi-axial loads that are normally encountered in real structures. In addition, the experimental validation was done indirectly by comparing with the trends reported in the previous works instead of physical testing of the exact laminate configurations.

Subsequent studies are advised to include nonlinear constitutive models, progressive damage analysis, and 3D finite-element simulations for a more accurate representation of interlaminar stresses and delamination sources. The optimization framework can be further developed to encompass manufacturing constraints, impact resistance requirements, and cost-performance trade-offs. The use of machine-learning-based surrogate models can, in fact, be a great facilitator of optimization when the design space is large. Besides, the physical creation and testing of the optimized laminates would be the most convincing confirmation of the computational predictions.

Basically, the findings show that computer modeling and optimization are an effective and dependable way to adapt hybrid composite laminates to the needs of light mechanical systems, thus one of the main roles of hybrid composites in current structural design is being confirmed again.

Conclusion

The computational study conveyed in this paper reveals a Python-based modeling framework integrating classical laminate theory, failure evaluation, and discrete stacking-sequence optimization can efficiently design and optimize hybrid carbon–glass composite laminates. The analysis demonstrated that the hybridization provides a stiffness response that is a compromise between that of pure carbon and pure glass laminates, at the same time, low failure indices and a favorable stress distribution are maintained. The final laminate design achieved not only enhanced axial stiffness, decreased mass-per-unit-area, but also a consistent failure index throughout all plies, thereby representing a structurally and mechanically stable lightweight engineering design. These results suggest that computational modeling can substantially lessen the need for physical prototyping, thus shortening the material–structure design cycles and furnishing engineers with a capable decision-support tool for the performance-driven customization of hybrid composites. The consistent mechanical trends observed suggest a design of hybrid laminates for load-bearing components where fiber orientations should be mainly along the primary load paths, and carbon layers should be used optimally near the laminate mid-plane to stiffen. Meanwhile, the glass layers may be used to increase the damage resistance and lower the cost without any mechanical integrity issues. The next steps in this research could be to carry on with nonlinear and progressive damage modeling, investigating hybrid laminates under multi-axial, impact, and fatigue loading, and experimental validation of the optimized stacking sequences. Further possibilities include developing machine learning–based surrogate models for faster optimization and embedding manufacturing constraints for industrial application–ready hybrid composite structures.

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