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Buckling Analysis for Carbon and Glass Fibre Reinforced Hybrid Composite Stiffened Panels

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Abstract: Composite laminated structural panels are widely used in various industries such as aerospace and machinery because of their light weight, large specific stiffness, and strong fatigue resistance. As a typical engineering structure, the composite stiffened plate is designed to enhance the bearing capacity of the laminated plate. In this study, composite stiffened panels reinforced by carbon and/or E-glass fibres are modelled by finite element analysis (FEA) using Ansys. Nonlinear structural analysis is employed to find the critical buckling load. Three different skin layups, i.e., $[45°/-45°/90°/0°]_S$, $[90°/0°/90°/0°]_S$, and $[60°/-30°/90°/0°]_S$, are studied. For each ply angle combination, different ply material combinations are studied. The cost and weight of each combination formed by applying different ply materials to the skin and stiffeners are studied. The results show that hybrid reinforcement in the stiffened panels reduces costs and maintains high buckling loads. Carbon/epoxy composites as the outer layers also reduce costs and maintain acceptable buckling loads without compromising the overall performance. Customized composite designs in terms of cost and weight can be achieved while maintaining critical buckling loads.

Keywords: composite; hybrid; stiffened panel; buckling

1. Introduction

In recent years, the pursuit of lightweight and high-strength materials has led to significant advancements in the field of composite materials. Among these, hybrid composites, integrating diverse fibres such as carbon and glass, have emerged as promising candidates for structural applications [1]. One critical aspect of their performance is the buckling behaviour, especially in the context of stiffened panels. Stiffened panels play a crucial role in aerospace, automotive, and marine structures, where their ability to withstand compressive loads is of paramount importance [2]. Fu et al. [3] previously studied the impact characteristics of a reinforced sandwich of functionally graded porous materials with a hyperbolic shell with a concave-angled honeycomb auxetic core. The results showed that reinforced structures have significant advantages in impact energy absorption. This provides important reference and guidance for the optimal design and application of such structures.

Buckling failure in composite structures refers to the sudden, catastrophic collapse of a structure due to compressive loads exceeding the critical buckling load. Unlike homogeneous materials, composites exhibit complex failure modes, influenced by the interplay of various constituent materials. A buckle can be generally defined as a compression (or shear) failure in a feature (web or flange) or column that occurs in multiples of wavelengths over the whole length of the feature. When a panel is in the buckled state, it continues to carry shear load (usually a significantly greater load than the load at which the feature buckles) and the structure can be said to have residual strength in the post-buckled state. However, a buckled panel or web cannot continue to carry a compression load after it has buckled. Another type of failure related to buckling is crippling failure. A cripple is a failure, of a corner feature or compound shape that is not reversible upon the removal of the

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load. A crippling failure is usually considered an ultimate failure with no residual strength remaining after failure and occurs within a very local area rather than over a significant length [4].

The factors affecting the buckling of composites include material anisotropy, fibre–matrix interaction, geometric imperfections, and environmental effects [5]. Composite materials are anisotropic, meaning their properties vary with direction. The orientation of the fibres significantly affects the buckling behaviour. The interaction between reinforcing fibres and the matrix material influences how loads are transmitted and distributed within the composite. For a composite structure, any deviations from an idealized, perfectly straight structure can lead to localized stress concentrations, promoting buckling initiation. Additionally, exposure to environmental factors, such as moisture or temperature variations, can impact the composite's mechanical properties and contribute to buckling.

When designing a composite structure with buckling in consideration, the proper selection and arrangement of laminate layers play a crucial role in preventing or mitigating buckling. The fibre orientation and stacking sequence are key considerations. Understanding and applying appropriate boundary conditions are essential for accurate buckling predictions. The choice of support conditions significantly influences the critical buckling load.

The buckling of composite stiffened plates has been studied experimentally [6–8]. Most studies have considered axial compression loads [6,7]. Some studies have also considered shear loads [8]. Lanzi [6] conducted a numerical and experimental investigation into the post-buckling behaviour of composite stiffened panels. Orifici et al. [7] explored compression and post-buckling damage growth and collapse analysis of flat composite stiffened panels. Bai et al. [8] contributed to the field by studying the dynamic buckling behaviour of a J-stiffened composite panel under in-plane shear.

Numerical methods based on the finite element method [6–10] have been employed to predict the buckling of composite stiffened plates. Chen and Guedes Soares [9] focused on the reliability assessment of the post-buckling compressive strength of laminated composite plates and stiffened panels under axial compression. Guo et al. [10] delved into the buckling behaviour of stiffened laminated plates, providing valuable insights into their structural response.

Research has been performed for the optimisation of the buckling/postbuckling of stiffened composite panels [11–14]. Ye et al. [11] optimised the distribution and stacking sequence of sub-stiffeners to improve the critical buckling load without adding weight. Bisagni and Lanzi [12] developed an optimisation procedure based on a global approximation strategy and genetic algorithms. The structure response is given by a system of neural networks trained by means of FEA. Bacarreza et al. [13] presented a multilevel optimization including progressive failure analysis and robust design optimization for composite stiffened panels, in which the ultimate load that a post-buckled panel can bear is maximized for a chosen weight. This method is a novel robust multi-objective approach for structural sizing of composite stiffened panels at different design stages. Chu et al. [14] investigated the weight minimisation of stiffened panels simultaneously optimising sizing, layout, and topology under stress and buckling constraints. An effective topology optimisation parameterisation is presented using multiple level-set functions.

Hybrid composites comprising two or more types of fibre have received significant attention in engineering design because of the potential of achieving balanced properties. One common type of hybrid composite is the carbon and glass fibre reinforced hybrid composite. Previous research on this material suggested that the flexural strength could be improved via hybridisation [15,16]. The main reason is that glass fibre has higher strain-to-failure than carbon fibre, and consequently, the strain-to-failure is increased due to the inclusion of glass fibre [17]. Rajpurohit et al. [18] showed positive hybrid effects in tension and compression. Zhang et al. [19] showed the carbon/glass interlayer hybrid composite had improved low velocity impact performance. The existence of hybrid effect can be potentially useful for achieving a balanced cost and weight optimal composite material. It is shown carbon and glass fibre reinforced hybrid composites have been used in windsurf boards and wind turbine blades [20].

It is shown from the literature that little research has been performed on the effect of fibre hybridisation on the buckling of composites. Ranganathan and Mantena [21] investigated the effects of hybridisation on the buckling characteristics of flat pultruded glass-graphite/epoxy composite beams. It was shown that that buckling strengths improved with increase in graphite fibre content. Ragheb [22] investigated the effectiveness of utilizing hybridisation to improve the local buckling capacity of pultruded Fibre Reinforced Polymer (FRP) wide flange I-beams loaded in bending. Ahmed and Rajput [23] studied the buckling behaviour of interlayer hybrid I-shape composite panels composed of one natural and two synthetic unidirectional fabrics combined with epoxy resin. The results show that high buckling loads can be obtained by placing high-strength and high-stiffness material layers (Carbon/epoxy) on the top and bottom of I-shape beams. It was shown that significant increases in the local buckling load of the beam could be gained if the glass fibre mat laminates of the beam were replaced by carbon fibre ones, especially those located near the outer surface of the beam. No research has been performed on the effect of hybridisation on the buckling of complex composite stiffened panels. This study focuses on the buckling analysis of hybrid composite stiffened panels, exploring the effect of hybridisation on the buckling characteristics. Additionally, the cost and weight are considered. It is shown that fibre hybridisation can significantly reduce the cost.

2. Materials and Methods

2.1. Material Properties

In this study, hybrid composites are developed by reinforcing an epoxy matrix with unidirectional carbon fibre fabrics and unidirectional E-glass fibre fabrics. Epoxy resins are widely used in composites because of their high strength (tensile, compressive, and flexural), good chemical resistance, fatigue resistance, corrosion resistance, and electrical resistance [24]. Typical values of the properties of carbon and E-glass fibres and epoxy resin are given in Table 1 [25]. The detailed properties of carbon/epoxy and E-glass/epoxy composites are given in Table 2.

Table 1. Typical values of the properties of carbon and E-glass fibres and epoxy resin.

Material	Tensile Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm^3)	Cost ($/litre)
High strength carbon fibre	230	4900	1.8	151.2
E-glass fibre	72	3450	2.58	10.8
Epoxy	3.1	69.6	1.09	26.2

Table 2. Detailed properties of carbon/epoxy and E-glass/epoxy composites.

Property	Carbon/Epoxy	E-Glass/Epoxy
Longitudinal modulus (GPa)	150.59	37.55
Transverse modulus (GPa)	7.82	8.69
Longitudinal–transverse Poisson's ratio	0.235	0.250
Transverse–transverse Poisson's ratio	0.398	0.305
Longitudinal–transverse shear modulus (GPa)	3.21	3.24
Transversetransverse shear modulus (GPa)	2.80	3.33
Tensile strength (MPa)	3208.1	1474.8
Compressive strength (MPa)	1320.4	613.9

The density of the hybrid composite reinforced by carbon and glass fibres (ρ_c) can be derived based on the Rule of Mixtures (RoM) [26] as follows:

$$\rho_c = \left[\rho_{fc}V_{fc} + \rho_m\left(1 - V_{fc}\right)\right]f_c + \left[\rho_{fg}V_{fg} + \rho_m\left(1 - V_{fg}\right)\right]f_g \quad (1)$$

where ρ_{fc}, ρ_{fg}, and ρ_m are the densities of carbon fibre, glass fibre, and the matrix, respectively; V_{fc} and V_{fg} are the fibre volume fractions for carbon/epoxy and glass/epoxy plies, respectively; and f_c and f_g are the volume fractions of carbon/epoxy and glass/epoxy plies, respectively.

The material cost of the hybrid composite (C_c) is given by

$$C_c = \left[C_{fc}V_{fc} + C_m\left(1 - V_{fc}\right)\right]f_c + \left[C_{fg}V_{fg} + C_m\left(1 - V_{fg}\right)\right]f_g \quad (2)$$

where C_{fc}, C_{fg}, and C_m are the costs of carbon fibre, glass fibre, and the matrix, respectively.

2.2. FEA-Based Model

The composite panels in this study are modelled by FEA using Ansys. Composite materials are defined using Ansys ACP, and nonlinear structural analysis is employed for buckling analysis. The FEA-based modelling approach has been proven to be valid by previous studies [27,28].

A partially cylindrical composite shell containing four stiffeners similar to a previous study [29] is studied. The radius of curvature is 381 mm, the overall length/width is 356 mm, and the height of stiffeners is 33 mm. A shell FEA model is created using Ansys Workbench, as shown in Figure 1. The skin contains 8 plies and each stiffener contains 16 plies. The ply thickness is 0.125 mm for all plies.

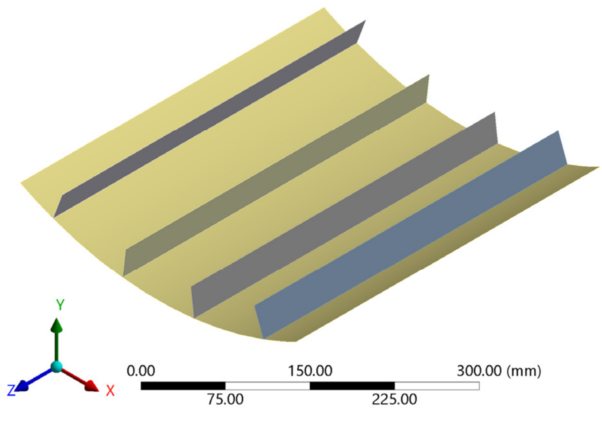

Figure 1. A partially cylindrical composite shell containing four stiffeners.

The layup for the stiffeners is fixed at $[[45°/-45°/90°/0°]_S]_2$, and three different ply angle layups, $[45°/-45°/90°/0°]_S$, $[90°/0°/90°/0°]_S$, and $[60°/-30°/90°/0°]_S$, are applied to the skin. For each ply angle layup combination, 12 different ply material combinations, as shown in Table 3, are applied to the skin and stiffeners, respectively. When hybrid layups are applied to the skin, the material of outer four layers is different from that of the inner four layers. Likewise, when hybrid layups are applied to the skin, the material of outer eight layers is different from that of the inner eight layers.

The composite panel is fixed at the bottom and subjected to an axial compressive load at the top, where from the top to bottom is in the positive z direction. The left and right edges of the composite panel are simply supported. The setting of the boundary conditions is shown in Table 4, where 1 represents being free, and 0 represents being constrained.

Table 3. Ply materials for each ply angle layup combination.

Ply Material Combination	Skin	Stiffeners
1	Carbon/epoxy	Carbon/epoxy
2	Carbon/epoxy	E-glass/epoxy
3	E-glass/epoxy	Carbon/epoxy
4	E-glass/epoxy	E-glass/epoxy
5	Carbon/epoxy	Hybrid (E-glass outer)
6	Carbon/epoxy	Hybrid (Carbon outer)
7	E-glass/epoxy	Hybrid (E-glass outer)
8	E-glass/epoxy	Hybrid (Carbon outer)
9	Hybrid (E-glass outer)	Carbon/epoxy
10	Hybrid (Carbon outer)	Carbon/epoxy
11	Hybrid (E-glass outer)	E-glass/epoxy
12	Hybrid (Carbon outer)	E-glass/epoxy

Table 4. The setting of curved stiffened plate boundary conditions.

Displacement Constraints	Top	Bottom	Left Side	Right Side
X	0	0	1	1
Y	0	0	0	0
Z	1	0	1	1

Nonlinear static analysis is conducted with progressively increasing loads to find the load levels at which the structure would fail.

3. Results

For all the ply material combinations given in Table 3, the critical buckling loads for all the skin ply angle layups are shown in Table 5. Similar trends are found for all the skin ply angle layups.

Table 5. Summary of critical buckling loads.

Ply Material Combination	Critical Buckling Load (kN)		
	$[45°/-45°/90°/0°]_S$	$[90°/0°/90°/0°]_S$	$[60°/-30°/90°/0°]_S$
1	30.14	36.80	32.74
2	30.06	36.26	32.04
3	14.34	17.06	15.23
4	13.85	16.35	14.84
5	30.04	36.64	32.50
6	30.10	36.73	32.72
7	13.77	16.73	14.87
8	14.09	17.00	14.99
9	17.96	18.56	19.15
10	26.56	33.08	28.85
11	18.23	19.43	18.69
12	24.63	31.89	26.67

Combinations 1 to 4 of the data in Table 5 are consistent with SudhirSastry's [29] previous research model parameters. It can be seen that under the three different skin ply angle layups, the results of each ply material combination of this study all show a buckling load from large to small, such as 1 > 2 > 3 > 4, in which the carbon/epoxy stiffened panel has the highest buckling load. This is consistent with the results of previous studies.

For skin ply angle layup $[45°/-45°/90°/0°]_S$, when both the skin and stiffeners are made of carbon/epoxy plies, the critical buckling load is 30,140 N, and the buckled shape is shown in Figure 2. The contours show the y displacement in mm. The maximum displacement is 5.50 mm.

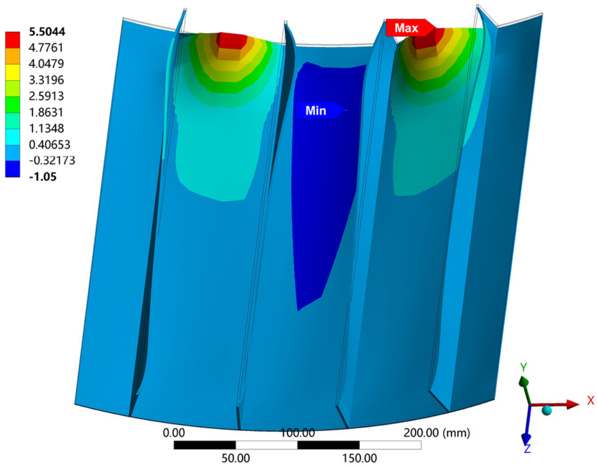

Figure 2. Buckled shape for carbon/epoxy skin and carbon/epoxy stiffeners for $[45°/-45°/90°/0°]_S$ skin.

When the skin is made of carbon/epoxy plies and the stiffeners are made of E-glass/epoxy plies, the critical buckling load is 30,060 N, and the buckled shape is shown in Figure 3. The contours show the y displacement in mm. The maximum displacement is 7.45 mm. Compared to all the carbon/epoxy composites, when the stiffeners are made of E-glass/epoxy composite, the critical buckling load only decreases slightly by 0.27%.

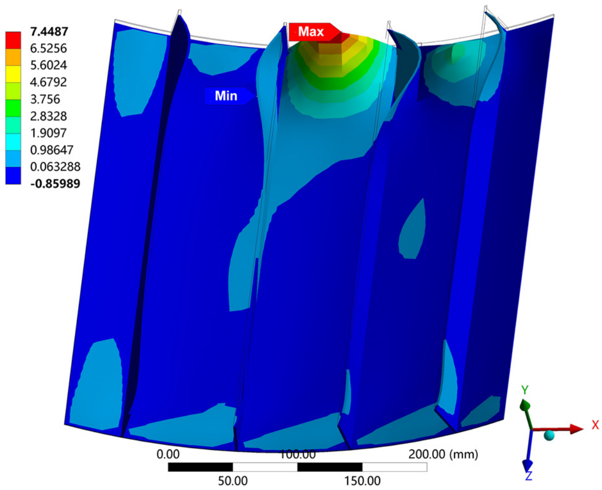

Figure 3. Buckled shape for carbon/epoxy skin and E-glass/epoxy stiffeners for $[45°/-45°/90°/0°]_S$ skin.

When the skin is made of E-glass/epoxy plies and the stiffeners are made of carbon/epoxy plies, the critical buckling load is 14,340 N, and the maximum displacement is 6.91 mm. When both the skin and stiffeners are made of E-glass/epoxy plies, the critical buckling load is 13,850 N, and the maximum displacement is 6.92 mm. The buckled shapes are similar to Figure 2. Compared to all the carbon/epoxy composites, the critical buckling load decreases significantly for both cases. The all E-glass/epoxy composite has the lowest critical buckling load. This is in agreement with previous research [29].

When the skin is made of carbon/epoxy plies and the stiffeners are made of hybrid plies with E-glass/epoxy plies as outer layers, the critical buckling load is 30,040 N, and the maximum displacement is 7.42 mm. The buckled shape is similar to that shown in Figure 2. When the stiffeners are made of hybrid plies with carbon/epoxy plies as the outer layers, the critical buckling load is 30,100 N, and the maximum displacement is 6.76 mm. The buckled shape is similar to Figure 3. It is seen that the critical buckling loads are similar for these two cases, and similar to that of the all carbon/epoxy composite.

When the skin is made of E-glass/epoxy plies and the stiffeners are made of hybrid plies with E-glass/epoxy plies as the outer layers, the critical buckling load is 13,770 N, and the maximum displacement is 5.51 mm. When the stiffeners are made of hybrid plies with carbon/epoxy plies as the outer layers, the critical buckling load is 14,090 N, and the maximum displacement is 5.58 mm. The buckled shapes are similar to Figure 2. It is seen that the critical buckling loads are similar for these two cases, and similar to that of the all E-glass/epoxy composite.

When the skin is made of hybrid plies with E-glass/epoxy plies as the outer layers, and the stiffeners are made of carbon/epoxy plies, the critical buckling load is 17,960 N, and the maximum displacement is 4.63 mm. When the skin is made of hybrid plies with carbon/epoxy plies as the outer layers, and the stiffeners are made of carbon/epoxy plies, the critical buckling load is 26,560 N, and the maximum displacement is 6.65 mm. The buckled shape is similar to that shown in Figure 2.

When the skin is made of hybrid plies with E-glass/epoxy plies as the outer layers, and the stiffeners are made of E-glass/epoxy plies, the critical buckling load is 18,230 N, and the maximum displacement is 5.00 mm; when the skin is made of hybrid plies with carbon/epoxy plies as the outer layers, and the stiffeners are made of E-glass/epoxy plies, the critical buckling load is 24,630 N, and the maximum displacement is 6.50 mm. The buckled shape is similar to that shown in Figure 2.

In summary, it is shown that the critical buckling load mostly depends on the layup of the skin. The all carbon/epoxy composite has the highest critical buckling load. When hybrid composites are used for the skin, carbon/epoxy plies should be placed as the outer layers. Compared to the all carbon/epoxy skin, the critical buckling load decreases slightly by about 12%.

When the layup of the skin is changed to $[90°/0°/90°/0°]_S$, the buckled shape becomes more complex. When the skin is made of hybrid plies with E-glass/epoxy plies as the outer layers, and the stiffeners are made of E-glass/epoxy plies, the buckled shape is of that shown in Figure 4.

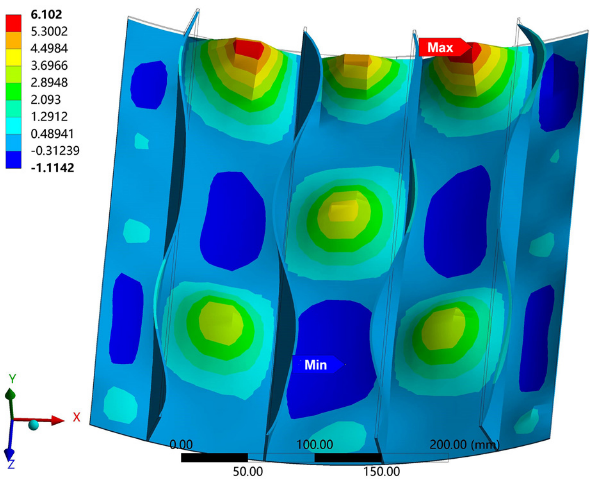

Figure 4. Buckled shape for hybrid skin with E-glass/epoxy plies as outer layers and E-glass/epoxy stiffeners for $[90°/0°/90°/0°]_S$ skin.

When the layup of the skin is changed to $[60°/-30°/90°/0°]_S$, similar buckled shapes compared to those of $[45°/-45°/90°/0°]_S$ are found.

It is shown that when the curved stiffened plate is made of carbon/epoxy, and the layups of the skin and the stiffeners are $[90°/0°/90°/0°]_s$ and $[[45°/-45°/0°/90°]_s]_2$, respectively, the highest critical buckling load is achieved, which is 36,800 N.

Using Equations (1) and (2), the overall cost and weight for each combination is calculated, as shown in Table 6.

Table 6. Overall cost and weight.

	Ply Material Combination	Cost ($)	Weight (g)
High critical buckling load	1	25.52	368.45
	2	16.57	396.96
	6	21.04	382.7
Middle critical buckling load	10	19.43	387.85
	12	10.48	416.36
Low critical buckling load	3	13.34	407.25
	4	4.39	435.77
	8	8.87	421.54

It is seen from Table 6 that the cost of the stiffened panel decreases with an increasing amount of glass fibre being used, but the weight increases. The hybridisation of stiffeners in stiffened plates can significantly cut costs while maintaining high critical buckling loads. Additionally, combinations 9, 10, and 1 can be interpreted as being generated by applying more carbon fibre to the skin of combination 3. An increase in the critical buckling load is observed with the increase in the carbon fibre content, which is consistent with previous research by Ranganathan et al. [21] on the effect of hybridisation with carbon fibres on the buckling behaviour of pultruded glass FRP flat plates. Notably, replacing the E-glass/epoxy layers of the skin with carbon/epoxy ones, especially those located near the outer surfaces of the skin, significantly improves the critical buckling load. This suggests that optimal improvements in the buckling load are observed when carbon fibre is positioned on the outer surfaces of the stiffened plate—a conclusion in line with Ragheb's research [22] on the effectiveness of hybridisation in improving the local buckling capacity of pultruded I-beams, where enhanced buckling loads were also recorded with the surface application of carbon layers.

When carbon fibre is partially replaced by glass fibre in an all the carbon curved composite stiffened plates, each 1% increase in weight corresponds to a cost reduction of $1.157. The integration of hybrid stiffeners in carbon stiffened plates proves to be a highly effective strategy, resulting in a notable 17.55% reduction in costs. Importantly, this cost optimisation is achieved while retaining robust buckling loads, exhibiting minimal decreases ranging from 0.06% to 0.73%.

Moreover, extending the hybridisation approach to the skin (carbon surface) yields even more substantial cost savings, with a reduction of 23.86%. Despite this, the buckling loads remain within acceptable limits, showcasing moderate decreases ranging from 10.11% to 11.89%. Consequently, the adoption of hybrid composites in stiffened plates emerges as an economically viable solution, ensuring not only significant cost efficiency but also maintaining satisfactory buckling performance. This approach provides valuable flexibility for design considerations, allowing for informed trade-offs in pursuit of optimal solutions.

Although the focus of this study is stiffened plates, the consistent findings across different structures suggest the general applicability of these conclusions. In this study, the introduction of hybridisation with carbon/epoxy being the outer layers can significantly reduce the cost while maintaining an acceptable buckling load, without undermining the overall high buckling performance.

4. Conclusions

A study on the effect of fibre hybridisation on the buckling of composite stiffened panels is presented in this paper. Various layups in terms of the ply angle and ply material are studied. It is shown that the hybridisation of stiffeners in stiffened plates can significantly cut costs while maintaining high critical buckling loads. The introduction of hybridisation with carbon/epoxy as the outer layers can significantly reduce the cost while maintaining an acceptable buckling load, without undermining the overall high buckling performance. Likewise, placing carbon/epoxy on the skin surface of stiffened panels can effectively increase buckling loads at a low cost. In addition, stiffeners are not the main load-bearing components of stiffened plate structures. Applying hybrid composites to stiffened plates allows for cost-effective solutions, offering flexibility in design trade-offs.

This paper focuses exclusively on modifying the skin layup of the stiffened plate in the composite material and the ply materials of both the skin and stiffeners to investigate their impact on the overall buckling. Notably, other influential variables affecting the stiffened plate of the composite materials, such as the load action mode, aspect ratio, thickness, height of stiffeners, and boundary conditions, are not examined in this study. Recognizing that these variables can significantly influence the overall buckling load of the plate, future research should broaden its scope to yield more comprehensive results beneficial for engineering design.

Moreover, it is important to note that post-buckling analysis is not addressed in this paper. When structural buckling occurs due to boundary constraints, tensile stress is generated on the middle surface. Consequently, the plate surface remains undamaged despite buckling and retains additional load-bearing capacity, constituting the post-buckling phenomenon. Given the substantial deflection observed during this phase, the post-buckling of the plate poses a geometrically nonlinear problem. To address this, future research could employ nonlinear stability theory to conduct a detailed analysis of the post-buckling problem. The complete deformation process, including the load–displacement path curve before and after instability, needs to be obtained. Conducting a comprehensive post-buckling analysis of the stiffened plate structure in subsequent research endeavours will contribute valuable data to enhance our understanding of its behaviour.

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