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Buckling of Thin-Walled Angle Column Made of Hybrid Laminate Under Axial Compression

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1. Introduction

Thin-walled laminate structures reinforced with fibers are commonly used in various industries, with a growing emphasis on environmental protection. Therefore, natural fibers like flax are increasingly utilized in composite production.

Natural fibers are characterized by their high availability and low price. Their mechanical properties are similar to synthetic fibers (in terms of strength to density ratio) [1, 2]. The production process for natural fibers is more economical than for synthetic, for example, they are characterized by less tool wear during their processing, which reduces production costs. In terms of environmental friendliness, the recycling process for natural fibers is simpler than for synthetic [3]. Natural fibers also have the advantage of being neutral to the human body, unlike glass fibers, which can cause skin irritation and lung disease. Nowadays, natural flax fibers are widely used in various industries, such as for car wipers, hockey sticks and door panels.

Due to the thin-walled geometry, it is particularly important to assess the stability of these structures and establish the effective operating range. The effective working range of thin-walled laminated structures consists of the following stages: pre-critical (only compression occurs in the walls of the structure), critical (buckling – occurs when an element loses its stability due to excessive load) and post-critical (the deflections due to bending increase, the consequence of further loading of the structure is its destruction) [4, 5]. This paper is focused on the buckling analysis. The aim of the analysis is to determine the load at which the buckling of the structure occurs – the bifurcation load.

Since natural fibers offer numerous benefits, it is essential to conduct a comprehensive analysis to enhance their utilization opportunities. Gliszczyński et al. [6] investigated (numerically and experimentally) the buckling and post-buckling behavior of flax-reinforced laminates and compared the critical load to the glass fibers reinforced polymer (GFRP). Various studies have explored the stability of laminate structures reinforced with different fibers: glass [7 – 8] and carbon [9 – 12], but research on flax-carbon hybrid laminates remains limited. Therefore, this study compared the flax, carbon, and hybrid laminates to identify the optimal structure in terms of strength, cost-effectiveness, and environmental impact.

The research analyzed an angle column under axial compression. The L-shaped composite columns were studied due to their widespread use in engineering design, where high strength parameters are required while keeping the weight of the structure as low as possible, including in the aerospace industry. Six column configurations were investigated based on the type of composite material used – flax, carbon and mixed. The finite element method with Abaqus software [13] was employed to solve the eigenproblem, and the results compared to evaluate the influence of material type on the bifurcation load value. This study lays the groundwork for further exploration into the post-buckling behavior of columns made from natural laminates.

2. Numerical model

The tested structure consisted of a thin-walled column (L-section profile), two deformable pads and two rigid plates (Fig. 1). The elastic pads were used to avoid the stress concentrations caused by contact between the plates and the profile surface (one for side). The investigated columns were simply supported on both sides. To achieve this, the non-deformable plates were used.

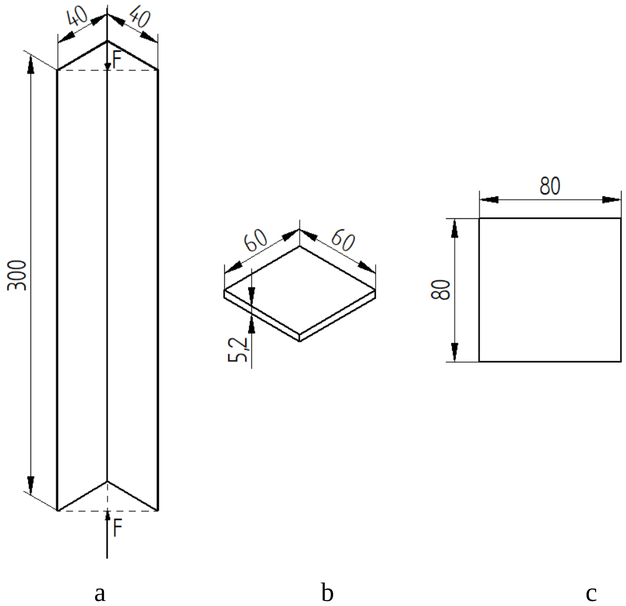


Fig. 1 Geometric diagram with dimensions: a – angle column, b – flexible pad, c – non-deformable plate

Six column configurations were analyzed. All samples had the same geometry and arrangement of layers [0/45/-60/90] s (the angles were measured from the vertical axis Z showed on the Fig. 2). The difference was that the material for individual layer was either flax or carbon laminate. Both laminates used (flax and carbon) have the same area-weight (grammage) of 150 g/m². Flax has a lower density than carbon fibers (1.5 g/cm³ for flax [14], 1.7 5-2 g/cm³ for carbon [15]), which, when using the same grammage, results in differences in wall thickness between the materials. The utilization of materials with the same grammage enables a direct comparison of strength properties relative to the weight of the structures being tested, which is crucial for the design of thin-walled engineering structures such as weight optimization in aerospace thin-walled structures. The total thickness of the profile varied depending on the configuration due to differing thickness values of individual flax and carbon layers. The configurations of the columns under analysis are detailed in Table 2. The mechanical properties of the materials used were adopted from the papers - [6, 16] for flax laminate, [17] for carbon laminate (Table 1). The structure of the material was modeled using *layup*-ply technique. The geometry of the samples used in the numerical studies corresponds to the physical samples for which experimental tests will be carried out in the future. The geometric dimensions of the samples were dictated by the specificity of the research in which local modes were analyzed. When testing sections, a change in the length (increase) and a change the flanges width (decrease) favors the appearance of global modes of buckling. Therefore, in our variant, short column with a length of 300 mm and a flange width of 40 mm were adopted. When analyzing local modes, an important factor is to check how close the adjacent buckling modes are to each other. The occurrence of two buckling modes close to each other in a compression test results in a jump from one mode to the other. For this reason, the numerical analysis was performed for the first three buckling modes.

The laminated column was discretized using eight-node shell elements with six degrees of freedom in each node (S8R). The profile was modeled using regular mesh with a single element size of 2 mm. The numerical model for plates was prepared using R3D4 shell elements with a linear shape function (six degrees of freedom in each node). For the elastic pad, an isotropic substitute material model was used with following parameters: Young's modulus $E = 40$ MPa, Poisson's ratio $\nu = 0.49$ [10]. To prepare the numerical model for the elastic pad, a solid elements C3D20R type were used. As a result of the discretization, the complete model consisted of 14684 elements and 50317 nodes. The boundary conditions of the numerical model and the types of finite elements used are presented Fig. 2.

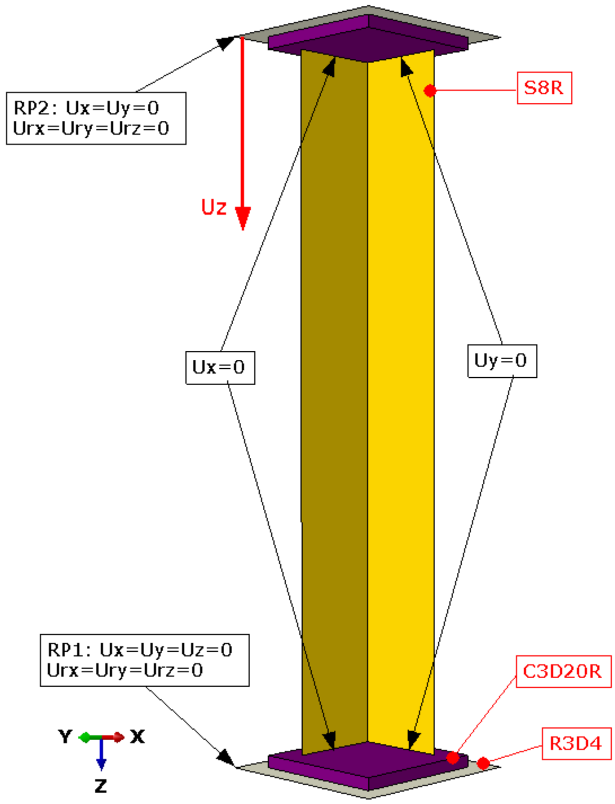


Fig. 2 Boundary conditions and used types of finite elements

A rigid *tie* connection was used between the plate surface and the pad surface. Between the edges of the profile and the surface of the elastic pad, a contact connection was defined in the normal and tangential directions, considering the friction coefficient. The bottom rigid plate was totally fixed, all degrees of freedom constrained (point RP1). The upper rigid plate was fixed with one degree of freedom, allowing displacement along the Z-axis (the column axis). The axial compression of the column was applied by moveing (unit load) the upper plate at point RP2.

3. Results of numerical analysis

The study determined the first three buckling modes for six different column configurations along with the corresponding bifurcation load values. Interestingly, the

Table 1

Mechanical characteristics for a single laminate ply [6, 16, 17]

Type of composite	Young's modulus along the fiber direction E_1, MPa	Young's module across the fiber direction E_2, MPa	Kirchhoff's modulus G_{12}, MPa	Poisson's ratio ν_{12}
Flax	31420	5580	2070	0.353
Carbon	104630	8159	3254	0.308

Table 2

Symbols for individual profile configurations

Symbol	Configuration	Wall thickness, mm
K1	[0/45/-60/90]s – all layers made from flax laminate	2.00
K2	[0/45/-60/90]s – all layers made from carbon laminate	1.36
K3	[0/45/-60/90]s – layers 0° made from carbon laminate, the rest from flax	1.84
K4	[0/45/-60/90]s – layers 45° made from carbon laminate, the rest from flax	1.84
K5	[0/45/-60/90]s – layers -60° made from carbon laminate, the rest from flax	1.84
K6	[0/45/-60/90]s – layers 90° made from carbon laminate, the rest from flax	1.84

same buckling modes were observed across all six configurations. The first mode exhibited a single half-wave at the center of the column height. The second mode featured two half-waves, one on each side of the profile. Similarly, the third mode featured three half-waves in the longitudinal direction: one at the center of the column and two symmetrically placed near the end sections. For the column made entirely of flax laminate, the bifurcation load value for the first mode was 1772.8 N. The highest load value for the first mode was achieved with the K4 configuration (45° carbon layers, the remaining layers flax). For the column made entirely of carbon laminate, the bifurcation load value for the first mode was 1532.9 N (lower than for flax laminate). For all modes, the lowest critical force value was obtained for the K6 configuration (90° carbon layers, the remaining layers flax). Fig. 3 presents a comparison of the load values for the first three buckling modes for the six configurations studied. Eigenmodes of the analyzed columns are illustrated in Fig. 4, while Table 3 presents the respective load values.

The increase in bifurcation loads for successive modes varied depending on the configuration. When considering the results for the flax laminate configuration (K1), the biggest variance was seen in comparison to the K3 configuration for the 3rd buckling mode – with the bifurcation load for K3 being 34.15% higher than K1.

The largest differences in load values for the different buckling modes were also noted for K3, with the smallest being 5.62% (for the first mode). The greatest difference compared to K1 for the first mode was found in configuration K4, at 27.96%. On the other hand, K4 showed the smallest disparities between load values for individual modes, with variances of 15.18% between the first and second modes, and 20.79% between the second and third modes. The higher critical load values observed for configurations with carbon layers at 0° (K3) and 45° (K4) in

Table 3

The values of bifurcation load for all columns

Configuration	Bifurcation load, N	Mode
K1	1772.8	1
K2	1532.9	
K3	1872.4	
K4	2268.5	
K5	1659.3	
K6	1355.7	
K1	2162.2	2
K2	1905.5	
K3	2583.0	
K4	2613.0	
K5	1988.1	
K6	1669.5	
K1	2794.0	3
K2	2515.4	
K3	3748.1	
K4	3156.1	
K5	2521.8	
K6	2182.1	

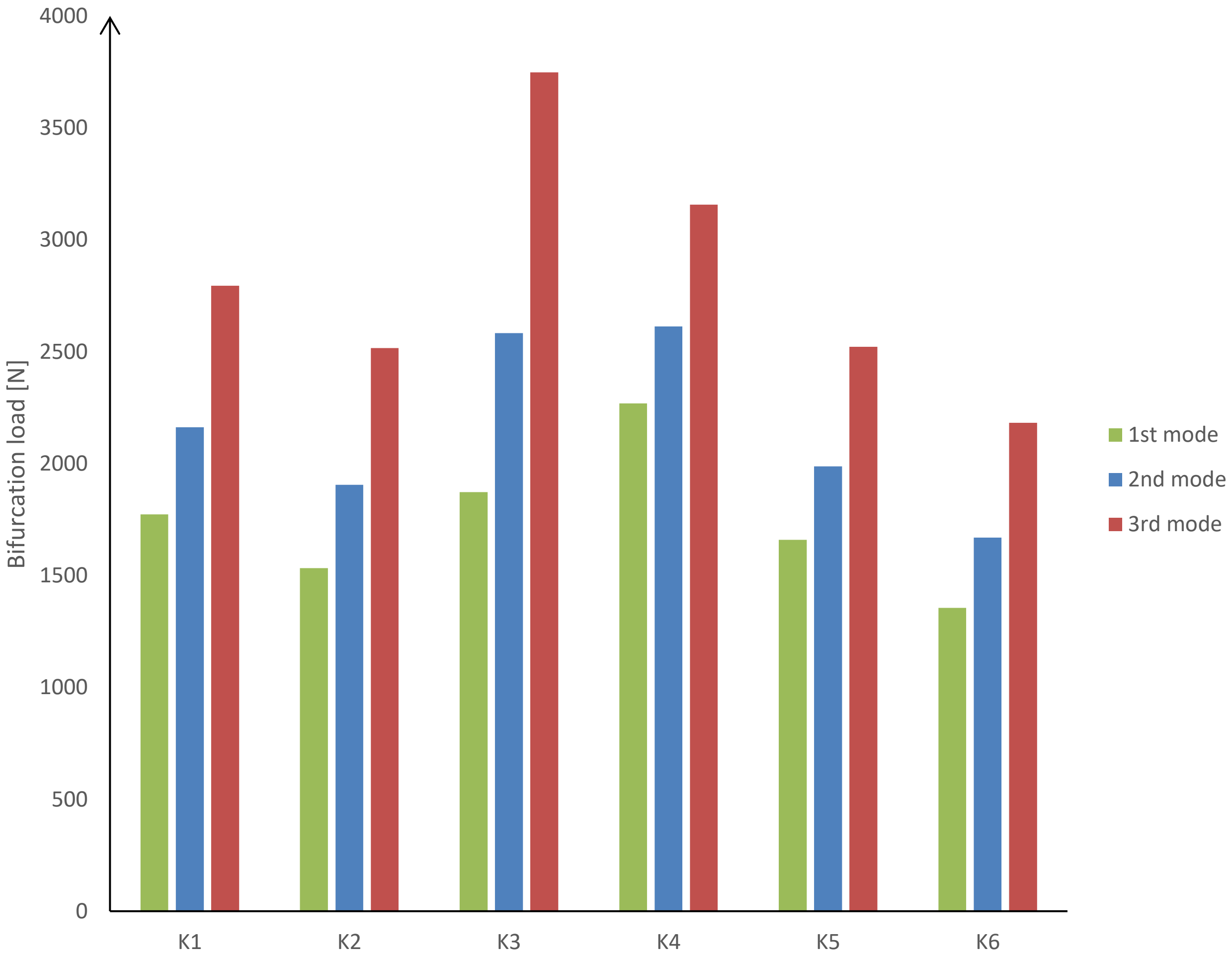


Fig. 3 The comparison of the bifurcation load values for the three modes of buckling for six column configurations

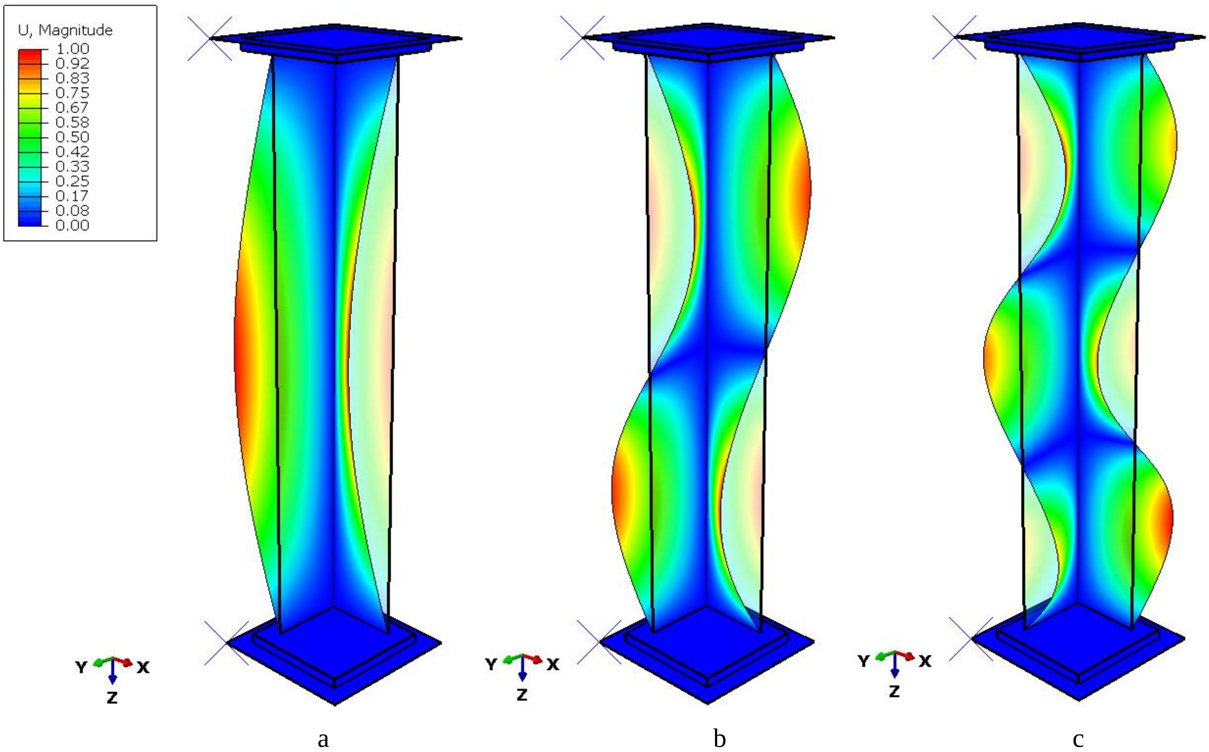


Fig. 4 The eigenmode of the analyzed column: a – the first buckling mode, b – the second buckling mode, c – the third buckling mode

to an all-flax laminate can be attributed to the superior stiffness of carbon fibers compared to natural fibers. Figure 5 illustrates the differences in the obtained bifurcation load results for each mode when compared to K1. Parameter *Error K_x/K1* is the relative error between configurations. The nature of the changes in load values varied depending on the configuration. The K2, K4 and K6 configurations showed a decrease in the bifurcation load difference for successive modes, while the opposite effect was seen for K3 and K5. These configurations exhibited an increase in load difference relative to K1 for successive buckling modes. However, the K2, K5 and K6 arrangements were less rigid than the flax configuration (K1). Whereas, the K3 and K4 configurations were characterized by greater stiffness than K1.

In order to further evaluate the impact of material changes on critical load values, four hybrid configurations (K3*-K6*) were studied using only a single carbon layer. The results were compared with hybrid configurations consisting of symmetrical pairs of carbon layers. For instance, the K3 configuration, with both carbon layers arranged at 0°, was compared with the K3* configuration, where only one carbon layer was positioned at 0° (with the remaining layers being flax fibers). It was observed that configurations

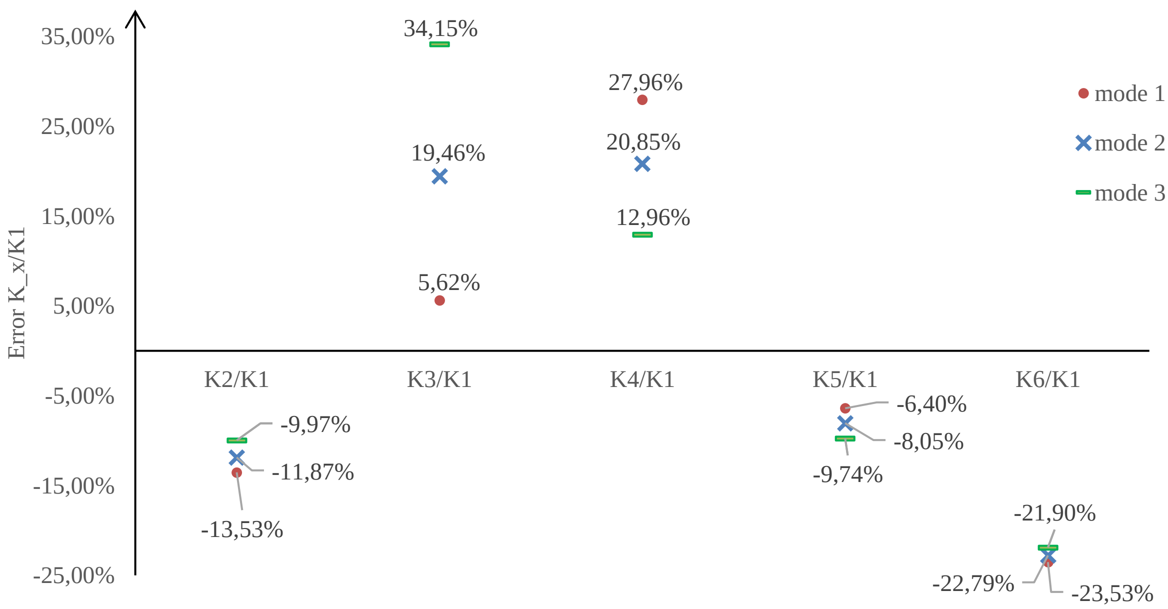
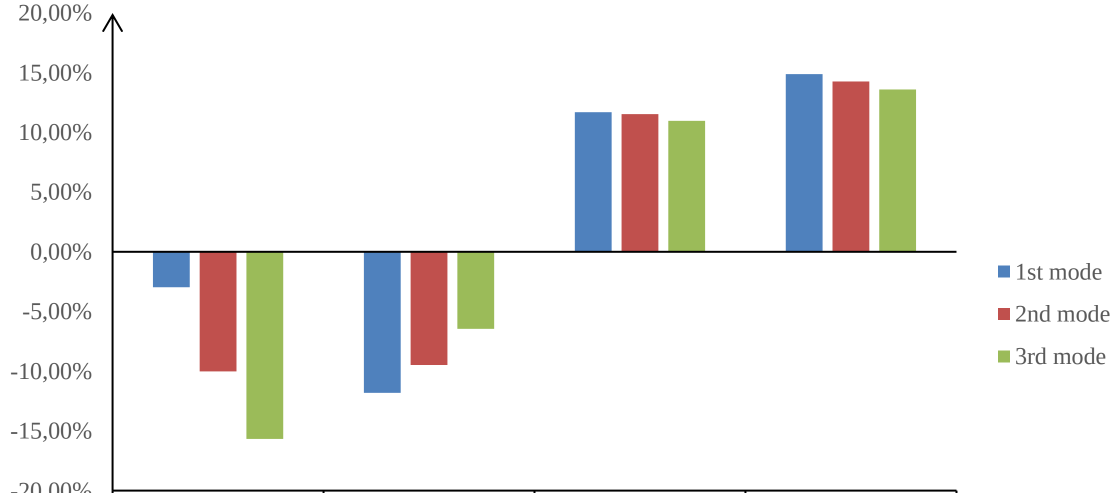


Fig. 5 Relative error for all configurations in relation to K1

with carbon layers at -60° and 90° benefited more from using a single layer rather than a pair of carbon layers. Conversely, when carbon layers with fibers at 0° or 45° angles were used, a single carbon layer resulted in a lower critical load value compared to a pair of corresponding carbon layers. The differences in bifurcation load values between hybrid configurations using a single carbon layer (K3*-K6*) and configurations with symmetrical carbon layers (K3-K6) are illustrated in Fig. 6. The study results indicate that flax laminates have a higher bifurcation load value compared to carbon laminates possibly due to the thicker wall of the natural laminate. Positive results can be achieved by incorporating individual carbon layers (K5*, K6*) into flax laminates. Composites with a balanced mix of flax and carbon layers exhibit a higher critical load value compared to laminates composed solely of flax or carbon. Even replacing a single ply in a flax laminate with a carbon ply can significantly enhance the critical load, thereby expanding the linear operating range of the composite. This is crucial as using natural fibers in composites is cost-effective and environmentally friendly. The next phase of the analysis will involve a nonlinear examination of thin-walled flax and hybrid laminates until structural failure, further exploring the stability of natural composites and increasing their potential applications.



	K3*	K4*	K5*	K6*
1st mode	-2,97%	-11,81%	11,70%	14,88%
2nd mode	-10,00%	-9,48%	11,52%	14,27%
3rd mode	-15,67%	-6,46%	10,97%	13,59%

Fig. 6 Comparison of critical load values for configurations with a single carbon layer (*) versus configurations with a pair of carbon layers

4. Conclusions

1. In comparison to carbon laminate, the flax laminate has higher bifurcation load values for the first three modes of buckling: approximately 14% higher for the first mode, 12% higher for the second mode, and 10% higher for the third mode. This difference may be attributed to the greater wall thickness of the bio-laminate.

2. Furthermore, modifying the individual layers of the material has a positive impact on the bifurcation load value. For instance, replacing flax layers with carbon layers (arranged at 0° and 45°) increases the critical load due to the higher stiffness of carbon layers.

3. An improvement in the critical load of the hybrid laminate is already apparent when one of the flax layers is replaced with a carbon layer. For structures utilizing carbon fibers positioned at -60° and 90°, a higher bifurcation load was achieved in laminates containing just one carbon layer as opposed to configurations with two carbon layers.

4. However, replacing flax layers (arranged at -60° and 90°) with carbon layers slightly reduces the bifurcation load values compared to an all-flax laminate.

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BUCKLING OF THIN-WALLED ANGLE COLUMN MADE OF HYBRID LAMINATE UNDER AXIAL COMPRESSION

S u m m a r y

This paper presents an investigation into the eigenproblem of angle columns manufactured using flax-carbon laminates. The first three eigenmodes and their corresponding critical load values for columns under axial compression were determined. The analysis covered six configurations with the same layer arrangement. The study also analyzed the impact of changing individual layer materials on bifurcation load values. A comparison was made showing differences in bifurcation load values for carbon and flax-carbon configurations compared to all-flax configurations for all three modes. The results suggest that replacing flax layers with carbon layers can extend the operational range of the system in the linear area. Additionally, the study explored the effect of using a single carbon layer versus a pair of carbon layers in hybrid configurations on critical load values. Results indicated that a higher bifurcation load value was obtained with a single carbon layer compared to a pair of symmetric carbon layers in selected configurations.

Keywords: buckling, thin-walled laminates, flax, carbon, hybrid laminate, natural material, numerical analysis.

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