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The Effect of Fiber Arrangement in the Bio-Laminate and Geometric Parameters on the Stability of Thin-Walled Angle Column under Axial Compression

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ABSTRACT

The aim of this study is to check how the change fiber configuration and geometric parameters affect the stability of a thin-walled angle column under compression. Buckling analysis of thin-walled structures made of bio-laminates was presented. Short angles with different configurations of reinforcing fibers and geometric parameters were studied. The laminate under analysis had a matrix made of epoxy resin reinforced with unidirectional flax fibers. The axially compressed structures were simply supported on both ends. Detailed numerical analyses were conducted by the finite element method using Abaqus software. The lowest two bifurcation loads and their corresponding eigenmodes were determined. Several configurations of unidirectional fiber arrangement with different width and length were tested. Results showed that the bio-laminate fiber configuration had a significant effect on the behavior of the compressed structure. Moreover, the change of geometrical parameters significantly influences the stability of the structure. In general, it was found that the bifurcation load decreased with the increase of the length of the L-profile column. However, increasing the flange width of the column resulted in a reduction of the bifurcation load (applies to a column with a length of 300 mm and longer). In paper the first stage of research is presented, which will be experimentally verified in subsequent studies.

Keywords: bio-laminates, flax, buckling analysis, L-profile, numerical case.

INTRODUCTION

In the era of global interest in fiber laminates, it is worth asking yourself whether their increased production will have a negative impact on the environment in which we live. An important aspect of the production of structures made of laminates should be not only to ensure high strength with low own weight of the element, but also the aspect of reducing energy consumption and the method of recycling such products. To meet these expectations, it is necessary to use materials that do not require external energy for their production and are not man-made, which will naturally decompose after use. These requirements are met by natural materials that can be easily used as a matrix in laminates. Natural fibers are cheap to produce, making them more economical and environmentally friendly than synthetic fibers [1]. Fibers of plant origin, such as coconut, linen, jute, hemp, sisal and bamboo, have desirable mechanical properties, which is why they are increasingly used in engineering structures [2–4]. Laminates reinforced with natural fibers are used in various industries, where they are used for the production of door panels, window posts or car trunk inserts, musical instruments, kayaks, hockey sticks, snowboards [5–7]. Interesting research is described in paper [8], where the authors looked for natural materials that can be used on the blades of a rotor to eliminate synthetic materials from production. The obtained results were compared with the glass-epoxy laminate, and a comparable mechanical performance was obtained.

In the world literature on natural composites, epoxy matrix laminates are the most common. Many studies have been carried out to assess the mechanical properties of such materials in various loading conditions, eg tensile or compression [9–11]. In paper [12] compressive mechanical testing is performed on continuous fiber flax/epoxy laminates. In experiment tested sample was made of unidirectional flax fiber. Except to epoxy resin as a matrix, sustainable polymers such as polylactic acid (PLA) are increasingly used. The authors of papers [13] presents the research on the mechanical properties of flax/PLA bio-laminates, which can potentially be used as bumper beams [14–15]. Knowing the parameters of natural materials, it is possible to build composite structures, thanks to which it will be possible to replace synthetic materials. One of the limitations in the use of natural composites is their absorption. Effect of water absorption on the mechanical properties of flax fiber reinforced epoxy composites is presented by Huner in paper [16]. An interesting aspect is the study of natural structures that will be subjected to a compressive load. The behavior of a flax/epoxy beam laminate under compression was studied in paper [17]. A three beam with different orientations of a bidirectional tape were investigated experimentally. Moreover, the critical load of the tested structure was determined analytically. The stability of a woven flax/epoxy laminate plate is considered in paper [18]. Numerical and experimental analyses were performed to determine the critical load of the structure. The effects of tape orientation, plate thickness and width on the compression behavior of the plate were investigated. In paper [19] authors examined the influence of the flax fiber arrangement in the epoxy laminate on the cracking of the entire structure. It was found that the volume fraction of the fiber has the greatest influence than the way of its arrangement. Moreover, it was emphasized that with proper preparation of the fabric it is possible to obtain a structure with high strength and stiffness. Ryzińska et al. [20] presents numerical calculations of the compression process of a composite reinforced with a fabric made of flax and jute fibers on epoxy resin. The data necessary for the numerical analysis in Ansys were calculated in the Digimat software. Channel sections with different number of layers were tested. The buckling forces obtained in the numerical analysis were compared to the experimental results presented in [21].

Due to the insufficient amount of scientific publications on the compression of structures made of natural materials (flax/epoxy laminate), it was necessary to present numerical studies on the stability in the compression process. A novelty in this work is the description of the behavior of an angle profile made of bio-laminates (flax/epoxy) in a critical state. In this paper a thin-walled structure made of 8 layers of flax / epoxy laminate is modeled. The available laminate material data [12] was used and the buckling numerical analysis under axial compression was performed. The finite element method was applied in the Abaqus environment, where several different configurations of the fiber arrangement were tested. Using the known method of modeling laminate [22–24], the influence of changing the structure parameters on the critical load was checked. The performed analysis will be a valuable hint to create real samples with given configurations of fiber arrangement. In the next step of the research, experimental research is planned.

MATERIALS AND METHODS

The numerical studies with the finite element method started with the validation of the available experimental results in [18], where a plate made of woven flax / bio epoxy material was tested. A rectangular sample with dimensions of 200 (100 active length)x40x1.5 mm made of laminate layers arranged in the 90° and 45° direction was subjected to a detailed analysis. The parameters of the material used are: Young's modulus in longitudinal direction – 5.968 GPa, Young's modulus in stiff direction – 5.392 GPa, Poisson's ratio – 0.396, shear modulus – 1.53 GPa. The tested plate was clamped on both sides, for which the first mode and the value of the critical load were determined.

A numerical model was created in the Abaqus environment with identical boundary conditions. Shell elements with 6 degrees of freedom at each node were used. The plate was mounted between two non-deformable plates, which were modelled with discrete rigid elements (Fig. 1). The critical loads and corresponding buckling modes were obtained. The first lowest buckling mode with one half-wave along the entire length of the plate was analyzed. The numerical results were compared with the experimental results reported in [18] and obtained a high agreement, with the relative error below 3 % (Table 1). This confirms that bio-laminates were correctly modelled in Abaqus software.

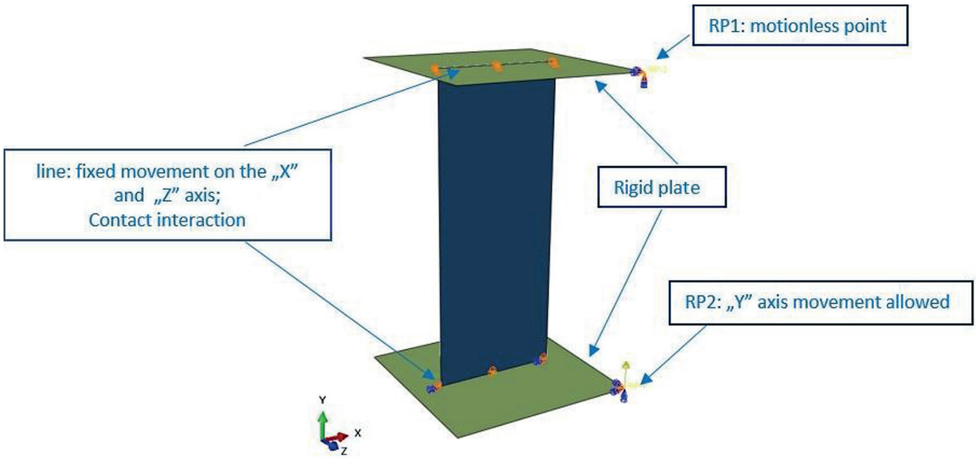

Fig. 1. The numerical model of tested structure

Table 1. Bifurcation load of a tested structure

Case	Experimental results [18]	FEM results	Error = $((P_{EXP}-P_{FEM})/P_{EXP})$*100%
Case 1 (orientation 90°)	80.32 N	81.68 N	-1.69 %
Case 2 (orientation 45°)	67.89 N	66.48 N	2.07 %

Table 2. All analyzed configurations of column with L profile

Configuration	Length (mm)	Width (mm)
C1 - [0/60/60/0]s	L1 – 200	W1 – 20
C2 - [60/0/60/0]s	L2 – 250	W2 – 30
C3- [0/-60/60/0]s	L3 – 300	W3 – 40
C4 - [-60/0/60/0]s	L4 – 350	W4 – 50
C5 - [-60/60/-60/0]s	L5 – 400	W5 – 60

After positive confirmation of the applied bio-laminate modeling technique, the study of the L profile column was started. The material data of the unidirectional flax-epoxy laminate (Young's modulus in longitudinal direction – 32 GPa, Young's modulus in stiff direction – 5.23 GPa, Poisson's ratio – 0.396, shear modulus – 1.66 GPa) from paper [12] was used and five configurations of

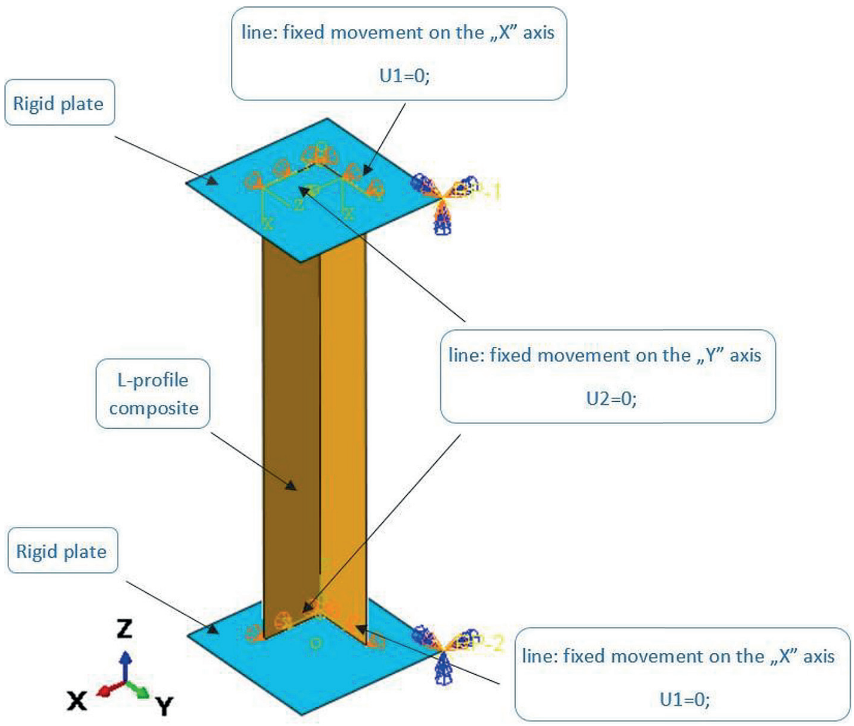

Fig. 2. The FE model of column with boundary conditions

fiber orientations were selected for testing (Table 2). In the early phase of the research, it was assumed that the thickness of the structures should be 2 mm. This is due to the conditions available in the laboratory and the high reproducibility of producing real thin-wall structures with the above-mentioned thickness. The prepreg's single ply had in all cases a thickness of 0.25 mm, which finally gave the sample thickness of 2 mm.

A FE model of a simply supported angle column was modeled using S8R shell elements having 6 degrees of freedom in each node. A regular mesh with an element size of 2 mm was used. The lay-up of laminate plies was prepared by the layup-ply technique. The tested column it was put between two non-deformable plates that were modeled using discrete rigid elements R3D4 with 6 degrees of freedom in each node. At the column/plate contact, the degrees of freedom perpendicular to the column surface were constrained. In each analyzed variant, identical boundary conditions were determined. The numerical model with boundary conditions is shown in Figure 2.

RESULTS OF NUMERICAL ANALYSIS

The numerical simulations consisting of solving an eigenproblem were performed. The minimum potential energy criterion was employed. Numerical results made it possible to determine the first and the second eigenmodes and the corresponding bifurcation loads value for each of the analyzed configurations. In all cases, the lowest buckling mode takes the form of a half-wave on each web of the angle section (Figure 3a). However, the second mode in each variant was characterized by the appearance of two half-waves on each side of the column (Figure 3b). All values of the bifurcation loads are summarized in Table 3.

The analysis of the obtained results was started in terms of how the change in the fibers arrangement configuration affects each length variants. At the lowest length and width (L1W1) between similar configurations C1 and C3, the relative error for the first mode was obtained at the level of 22%. When increasing the flange width, this error decreased until it reached about 6% for the width W5. The same situation was observed with the second mode. As a result of changing the angle of the fibers of one layer from +60 to -60, the C3 configuration was characterized by higher stiffness compared to the C1 configuration. Next, a similar results were obtained as before comparing similar C2 and C4 configurations, ie. the C4 system was characterized by 31% higher stiffness than C2 at the width W1. On the other hand, as the flange width increased, the difference in stiffness decreased to approx. 12%. Similar results were obtained for the first and the second mode. Comparing the C1 and C5 configurations with each other, it was found that for the C5W1 system

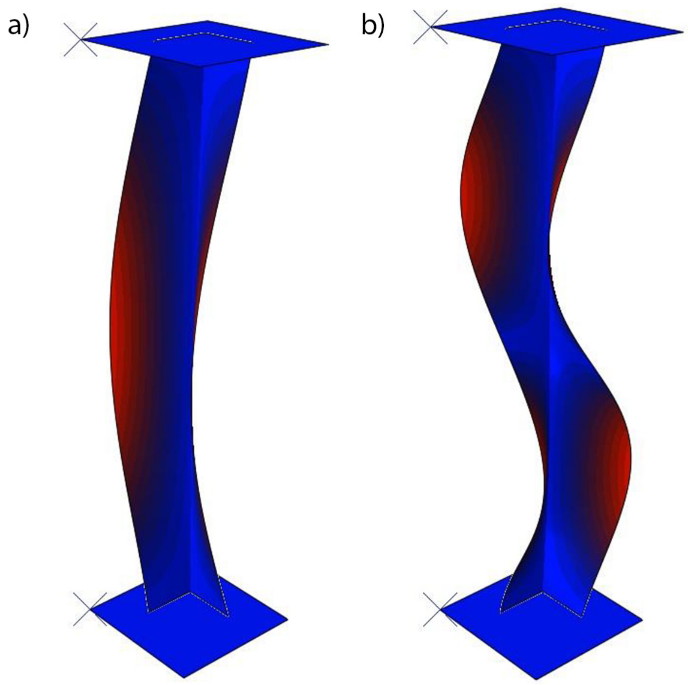

Fig. 3. The eigenmode of the analyzed angle column: (a) the first one; (b) the second one

Table 3. Bifurcation loads in N for thin-walled bio-laminated column

L1		W1	W2	W3	W4	W5
C1	Mode1	2052.7	1857.1	1833.3	1896.5	2013
	Mode2	2709.9	2732.5	2900.7	3115.2	3353.3
C2	Mode1	2150.9	1890.4	1819.1	1842	1916.4
	Mode2	2613.3	2513.1	2589.7	2717.2	2856.1
C3	Mode1	2504.2	2176.9	2060.1	2059.4	2132.6
	Mode2	3214.8	3092.7	3193.3	3389.7	3642.3
C4	Mode1	2823.5	2393.2	2196.9	2129.3	2137.9
	Mode2	3345.4	3041.4	2998.2	3063.9	3182.4
C5	Mode1	3709.9	3058.6	2619.9	2352.3	2190.2
	Mode2	4189.5	3436	3050.9	2857.7	2769.2
L2		W1	W2	W3	W4	W5
C1	Mode1	1895.9	1626.6	1521.6	1502.8	1532.9
	Mode2	2353.3	2221.7	2261.9	2366.7	2498.4
C2	Mode1	2014.1	1689.6	1545.4	1496.5	1500.5
	Mode2	2338.8	2108.2	2075	2121.7	2198.1
C3	Mode1	2347.5	1962.7	1771.7	1691.3	1676.6
	Mode2	2863.6	2587.6	2545.1	2607.1	2723.2
C4	Mode1	2676.8	2204.9	1945.1	1811.7	1752.1
	Mode2	3073.5	2647.8	2491.2	2459.3	2489.5
C5	Mode1	3525.3	2926.7	2469.1	2169.9	1972.9
	Mode2	4002.1	3215.5	2767.7	2512.8	2366.4
L3		W1	W2	W3	W4	W5
C1	Mode1	1802.5	1499	1350.4	1287.4	1272.9
	Mode2	2151	1929.8	1889.3	1926.5	1998.3
C2	Mode1	1930	1577.8	1394.4	1305.7	1270.6
	Mode2	2182.7	1878.9	1776	1764.8	1796.4
C3	Mode1	2247.6	1842.9	1613.8	1492.3	1434.2
	Mode2	2662	2301.6	2175.1	2159.8	2202.2
C4	Mode1	2576.3	2097.1	1805	1636.4	1540.9
	Mode2	2913.9	2424.4	2200.2	2107.6	2084
C5	Mode1	3369	2836.9	2379.1	2065.3	1850.5
	Mode2	3862.4	3085.7	2605.4	2315.6	2135.3
L4		W1	W2	W3	W4	W5
C1	Mode1	1738.5	1420.2	1246.1	1156.4	1115.2
	Mode2	2023.7	1748.2	1654.4	1645	1676.7
C2	Mode1	1870.1	1508.1	1302.1	1189.3	1130.1
	Mode2	2083.3	1736.8	1588.8	1537.1	1534.5
C3	Mode1	2174	1767.4	1517.2	1371.7	1288.5
	Mode2	2532.4	2123.9	1944.4	1879.3	1875.1
C4	Mode1	2496.9	2027.4	1718.1	1528.8	1411.8
	Mode2	2807.3	2285.1	2018.5	1885.8	1825.9
C5	Mode1	3227.9	2767.3	2318.1	1998.2	1773.5
	Mode2	3720.6	2999.4	2502.7	2191.7	1990.1
L5		W1	W2	W3	W4	W5
C1	Mode1	1689.7	1367.3	1177.5	1070.6	1012.1
	Mode2	1936.7	1627.6	1497.4	1454.8	1457.2
C2	Mode1	1822.5	1460.9	1241.1	1112.8	1037.9
	Mode2	2014	1642.6	1464.5	1384.1	1356
C3	Mode1	2114.2	1715.4	1453.4	1292.8	1193.7
	Mode2	2440.8	2005.7	1790.7	1691.8	1655.7
C4	Mode1	2428.7	1977.7	1659.8	1457.6	1326.8
	Mode2	2728.2	2191.7	1897.4	1737.4	1651.8
C5	Mode1	3095.3	2708.9	2272.7	1951.3	1721.1
	Mode2	3664.3	2936.2	2432.6	2108.2	1892.6

Table 4. The relative error for all cases

L1	W1	W2	W3	W4	W5
Error_C1C3 (%)					
Mode1	-22.00	-17.22	-12.37	-8.59	-5.94
Mode2	-18.63	-13.18	-10.09	-8.81	-8.62
Error_C2C4 (%)					
Mode1	-31.27	-26.60	-20.77	-15.60	-11.56
Mode2	-28.01	-21.02	-15.77	-12.76	-11.42
Error_C1C5 (%)					
Mode1	-80.73	-64.70	-42.91	-24.03	-8.80
Mode2	-54.60	-25.75	-5.18	8.27	17.42
L2	W1	W2	W3	W4	W5
Error_C1C3 (%)					
Mode1	-23.82	-20.66	-16.44	-12.54	-9.37
Mode2	-21.68	-16.47	-12.52	-10.16	-9.00
Error_C2C4 (%)					
Mode1	-32.90	-30.50	-25.86	-21.06	-16.77
Mode2	-31.41	-25.60	-20.06	-15.91	-13.26
Error_C1C5 (%)					
Mode1	-85.94	-79.93	-62.27	-44.39	-28.70
Mode2	-70.06	-44.73	-22.36	-6.17	5.28
L3	W1	W2	W3	W4	W5
Error_C1C3 (%)					
Mode1	-24.69	-22.94	-19.51	-15.92	-12.67
Mode2	-23.76	-19.27	-15.13	-12.11	-10.20
Error_C2C4 (%)					
Mode1	-33.49	-32.91	-29.45	-25.33	-21.27
Mode2	-33.50	-29.03	-23.89	-19.42	-16.01
Error_C1C5 (%)					
Mode1	-86.91	-89.25	-76.18	-60.42	-45.38
Mode2	-79.56	-59.90	-37.90	-20.20	-6.86
L4	W1	W2	W3	W4	W5
Error_C1C3 (%)					
Mode1	-25.05	-24.45	-21.76	-18.62	-15.54
Mode2	-25.14	-21.49	-17.53	-14.24	-11.83
Error_C2C4 (%)					
Mode1	-33.52	-34.43	-31.95	-28.55	-24.93
Mode2	-34.75	-31.57	-27.05	-22.69	-18.99
Error_C1C5 (%)					
Mode1	-85.67	-94.85	-86.03	-72.79	-59.03
Mode2	-83.85	-71.57	-51.28	-33.23	-18.69
L5	W1	W2	W3	W4	W5
Error_C1C3 (%)					
Mode1	-25.12	-25.46	-23.43	-20.75	-17.94
Mode2	-26.03	-23.23	-19.59	-16.29	-13.62
Error_C2C4 (%)					
Mode1	-33.26	-35.38	-33.74	-30.98	-27.84
Mode2	-35.46	-33.43	-29.56	-25.53	-21.81
Error_C1C5 (%)					
Mode1	-83.19	-98.12	-93.01	-82.26	-70.05
Mode2	-89.20	-80.40	-62.45	-44.91	-29.88

the first mode had a higher bifurcation load by 80%. The trend was the same for the first mode and with increasing flange width the difference decreased to 9%. In the case of the second mode, a slightly different phenomenon was observed, ie. for the width W1-W3, the C5 system had a higher bifurcation load, while for the W4–W5 width, the C1 system was obtained a higher bifurcation load.

For a small flange width (W1) but a different column length, no major changes in the percentages of the obtained loads were observed between the configurations C1–C3 and C2–C4. On the other hand, with the increase in the flange width, an increase in the relative error with the increase the column length was noticed for the same configurations. Thus, for the width W5, a threefold increase in error was obtained between the lengths L5 and L1. Similar relationships were noticed when comparing C1 and C5 configurations, where with a width of 20 mm, no significant change in the relative error was observed when the length was changed by 200 mm. However, with the greatest width 60 mm, a nine-fold increase in the relative error for the longest column, compared to the shortest, was noticed. Detailed values of the relative error are presented in Table 4, where the relative errors were calculated: error_C1C3 = ((F_C1 – F_C3)/F_C1)·100%; error_C2C4 = ((F_C2 – F_C4)/F_C2)·100%; error_C1C5 = ((F_C1 – F_C5)/F_C1)·100%.

All the analyzed configurations showed that with increase of the column length, its stiffness and the bifurcation load decreased for the two eigenmodes. Moreover, it was observed that with the increase of the flange width, the C1–C4 configurations additionally obtained smaller bifurcation loads, and the system showed a decrease in stiffness with the increase of the flange width. Such a property was determined for both the first and second eigenmodes. However, in the case of the C5 configuration, the additional change in the flange width did not significantly affect the obtained relative errors for the first eigenmode (Figure 4a). Much greater differences were obtained for the second eigenmode (Figure 4b), which were at a similar level as those observed for the C1–C4 configurations.

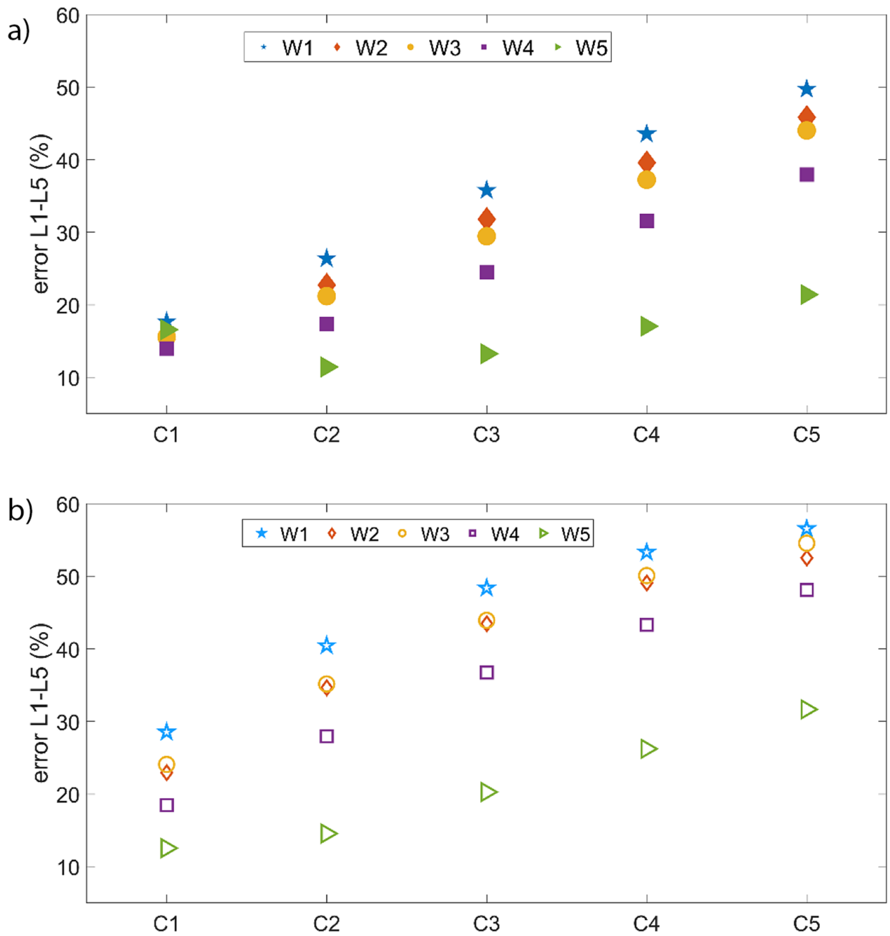

Fig. 4. Relative error between the extreme lengths of the L1–L5 column at different widths and different configurations of fiber arrangement: (a) the first mode ; (b) the second mode. Parameter error_L1–L5 = ((F_L1 – F_L5)/F_L1)*100 %

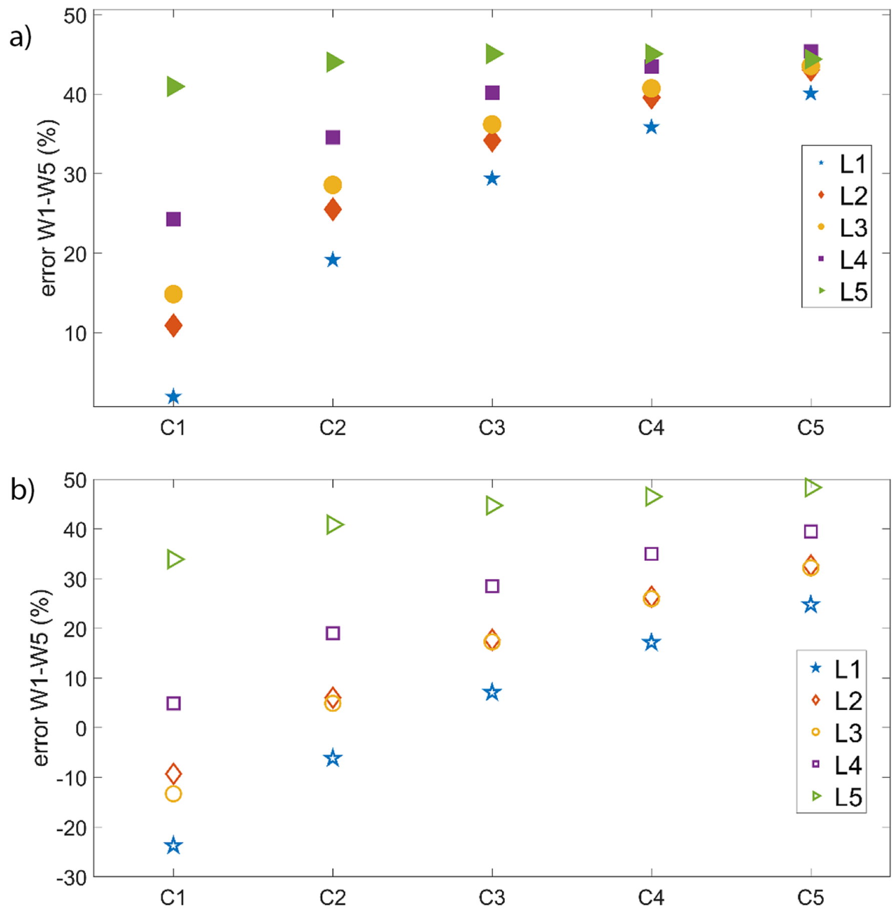

Fig. 5. Relative error between the extreme widths of W1–W5 at different column length and different configuration of the fibers arrangement: (a) the first mode ; (b) the second mode. Parameter error_W1–W5 = ((F_W1 – F_W5)/F_W1)*100 %

With the longest length of column 400 mm, a constant increase in the first bifurcation load by approx. 42% was observed with the change of the flange width for all analyzed C1–C5 variants. In the case of the shortest column, it was found that the obtained bifurcation loads significantly depend on the change in the flange width and the C1–C5 configurations. This applies to both the first and the second eigenmode. The smallest effect of width (up to 10%) was determined for the C1 and C2 configurations, while the largest change in bifurcation load (up to 40%) was observed for the C5 configuration. The effect of the change in width in all analyzed variants is shown in Figure 5. Moreover, for the longest column (L5) it was found that the values of the parameter: error_W1–W5 did not change significantly when changing the configuration. In contrast to the shortest column with a length of 200 mm (L1), where a difference of over 40% was obtained between the C1–C5 configuration. A similar effect was observed for the first and second mode.

CONCLUSIONS

The stability of a thin-walled bio-laminate angle under axial compression was analyzed numerically. Numerical simulations were performed by the finite element method in the Abaqus environment. The first and second local eigenmodes of the structure were analyzed. Five different configurations of unidirectional prepreg fibers were tested. Additionally, the influence of changes in the flanges width and changes in the length of the column on the stability of the system were checked. A column with a flanges width of 20 mm to 60 mm was tested. The analyzed beam length ranged from 200 mm to 400 mm.

Detailed numerical analyses have shown that the short bio-laminate angles under compression are sensitive to the angle of reinforcing fiber arrangement. It was found for all cases that the value of the lowest bifurcation load decreased with the increase of the flange width. In the second eigenmode, a similar phenomenon was observed only for column longer than 250 mm. For shorter columns, the change in width does not significantly affect the obtained values of the second eigenmode in C1–C4 configurations. However, it is significant in the C5 configuration. The columns showed the highest stiffness for the shortest length, while the bifurcation load decreased with the increase of the column length. This applies to both the first and the second eigenvalue. In addition, columns with a smaller flange width showed a smaller effect on the change in column length (11–30%). On the other hand, at the widest walls, this effect was observed at the level of 49–57% for the C1 configuration. It is worth mentioning that the C5 configuration showed the smallest value difference with the change of length, i.e. the difference between L1–L5 at constant width did not change significantly (only a few %) with increasing flange width.

Comparing similar C1 and C3 configurations, an increase in stiffness by 20–25% (L1–L5) was observed for the lowest flange width. As the width increased, the relative error between the obtained eigenvalues decreased. The change in the length of the column slightly (up to 5%) affects the obtained differences. However comparing similar C2 and C4 configurations, it was found that the C4 configuration has a stiffness of about 30% higher for the W1 width than the C2 configuration. With the change in width, the difference decreased and for W5 it is 11–27% (L1–L5). The C5 configuration showed the highest stiffness of all tested systems. Compared to the C1 system, the lowest bifurcation load value increased by 80–87% at the W1 width. Changing the flange width while changing the column length significantly influences the obtained differences in eigenvalues. At the lowest length L1, with the decrease in width, the load values were closer to each other and a difference of 9% was obtained. However, for a length of 400 mm and a width of 60 mm, the difference was 70%.

Considering the results, it can be concluded that the laminate fiber arrangement has a significant impact on the characteristics of the L-profile column. The results of this study will serve as a basis for further research in which a nonlinear range will be investigated. Further studies will also involve conducting experiments on real biolaminate angle columns.

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