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Buckling of Compressed Thin-Walled Composite Structures with Closed Sections

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ABSTRACT

The purpose of the study was to conduct an experimental-numerical analysis of the critical state (buckling) of thin-walled composite structures with a square cross-section. The subject of the study was thin-walled composite structures, which were made of CFRP – carbon epoxy composite. The structures were characterized by a closed square cross-sectional shape. In the research paper, stability tests of axially compressed thin-walled struts were performed in order to determine the critical state of the structures. Experimental tests were carried out on a universal testing machine, using a system for optical measurement of deformation of structures. Numerical simulations were carried out using the finite element method (FEM). The research made it possible to evaluate the work of the structure in the buckling state from a qualitative as well as quantitative point of view. During the study, the buckling form and the corresponding critical load were determined – which quantitatively and qualitatively showed high agreement for both experimental testing and numerical simulation. The novelty of the present paper was the use of several interdisciplinary research methods (testing machine, optical deformation measurement system and numerical simulations) in order to determine the critical state of thin-walled composite structures with closed sections.

Keywords: buckling, closed-section profiles, experimental studies, FEM.

INTRODUCTION

Thin-walled (load-carrying) columns produced of composite materials represent a special group of structures that have special strength properties [1-3]. These structures occur in the form of thin-walled struts with open [4-6], and closed sections [7-9]. Usually such structures are made of GFRP [8-10] and CFRP-type composite material [11-13]. These structures, especially those with closed sections, are designed to carry a load, especially a compressive load, after achieving the phenomenon commonly known as buckling [13-15]. The following phenomenon is characterized by a sudden change in the deformations form of the column under axial compressive loading conditions [16-18]. The buckling phenomenon has been and continues to be of interest to many researchers [19-21]. In most cases, the composite columns are able to carry the axial compressive force after losing stability (buckling) [22-24]. Thin-walled composite structures are capable of carrying up to several times the critical load value [23]. By using an appropriate arrangement of laminate layers, it is possible to achieve higher critical forces as well as damage forces [23, 25-27]. In the area of science dealing with the stability of thin-walled composite structures, the correct ability to determine critical forces – using experimental approximation methods – is significant [28, 29]. The commonly used approximation methods have been presented in scientific papers on the literature of the subject [18, 28]. For numerical simulations using the FEM, the buckling is determined by solving a linear eigenproblem [23, 30]. The above makes it possible to both determine the critical load and buckling form of a thin-walled structure. This paper focuses exclusively on the correct determination of the critical state of thin-walled composite struts made of CFRP, for which material properties have been determined experimentally and published in papers [31, 32]. Experimental studies were performed using a universal testing machine (UTM) and an Aramis optical system [17, 33, 34], with parallel numerical simulations performed in Abaqus® software [35]. The novelty of the paper is primarily the simultaneous use of several independent test methods (universal testing machine, Aramis system, FEM numerical simulations) to evaluate the stability of compressed thin-walled struts - with closed cross-section. The scope of the research included the analysis of the buckling state of thin-walled composite structures. The further direction of the research will include a detailed analysis of the behavior of the structure, in the post-buckling state - taking into account the phenomenon of damage to the composite material. The main aim of the study was to determine the values of critical forces and the corresponding buckling modes for both experimental studies using one of the approximation methods [29] and numerical simulations. In the case of experimental studies, the approximation method of intersection of straight lines was used to determine critical loads, based on load-displacement/shortening characteristics, while in the case of numerical simulation, linear structural stability analysis was used. The study was prepared based on research conducted under the National Science Centre (Poland) – number of the project: 2021/41/B/ST8/00148.

THE SUBJECT OF THE STUDY

The subject of study was thin-walled struts, made of carbon-epoxy (CFRP) composite (using autoclave technique) with a laminate lay-up arrangement $[0°/45°/-45°/90°]_s$. The test specimens were marked as follows: A1_1, A1_2 and A1_3. All composite structures were manufactured from a special (unidirectional) prepreg tape CYCOM 985-42%-HS-135-305. The 985 resin system was characterised by the volume proportion of the material was 42% resin, while the fibres used were high strength with a fibre weight of 135 g/m^2 (base strip width of 305 mm). All structures were autoclave-cured at 177 °C and 0.6 MPa overpressure. The composite structures were manufactured

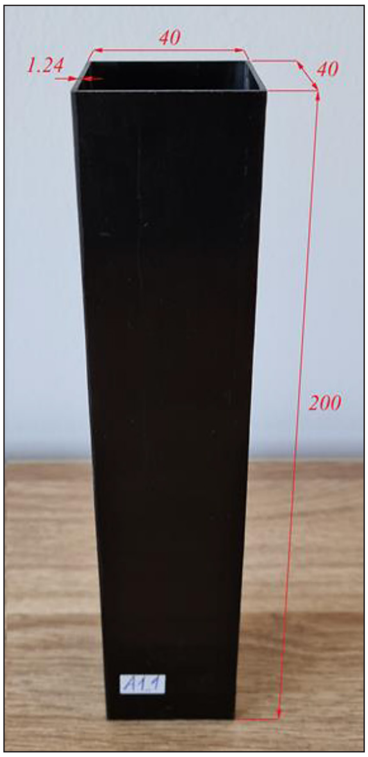


Fig. 1. Test specimen

Table 1. Material properties of the CFRP material – average values (standard deviation)

Mechanical properties		Strength properties	
Young's modulus e_1 [MPa]	103014.11 (2145.73)	Tensile strength f_{tu} (0°) [MPa]	1277.41 (56.23)
Young's modulus e_2 [MPa]	7361.45 (307.97)	Compressive strength f_{cu} (0°) [MPa]	572.44 (46.20)
Poisson's ratio v_{12} [-]	0.37 (0.17)	Tensile strength f_{tu} (90°) [MPa]	31.46 (9.64)
Kirchhoff modulus g_{12} [MPa]	4040.53 (167.35)	Compressive strength f_{cu} (90°) [MPa]	104.04 (7.34)
–	–	Shear strength f_{su} (45°) [MPa]	134.48 (2.71)

with a very high level of care (accuracy as well as repeatability of the manufacturing process were maintained). Figure 1 shows an example of composite profile for experimental testing.

The material parameters of the material were determined (on the basis of the ISO standards) [36]. The procedure for determining material parameters is presented in the publication [31]. The properties of the CFRP material are shown in the Table 1 [31, 32].

The plan for the research work on the manufactured specimens, consisted of the preparation of an experimental test stand for testing the loss of stability (buckling) of the structure, as well as the development of the author's numerical model - allowing faithful representation of the experimental tests. As part of the experimental tests, equilibrium paths were determined, from which the values of critical loads were successively determined, as well as the forms of buckling of the structure were registered. In numerical simulations, by solving a linear eigenproblem, the critical state was determined – which in turn was compared with experimental results. For numerical simulation, the Abaqus® program based on the finite element method was used.

EXPERIMENTAL STUDIES

The experimental testing of the critical state was performed using a Zwick Z100 universal testing machine [23, 35]. The tests were performed under conditions of constant traverse speed of 1 mm/min. The study dealt with the determination of buckling loads [18, 28]. For this purpose, the method of intersection of straight lines was used, based on experimental load-displacement (shortening) curves [29]. The method involves approximating using straight lines (a linear function) the two effective ranges of the experimental characteristics (curve) – the part of the curve before the change in its "stiffness", where the characteristic bend occurs, and the part of the curve after the change in "stiffness". The intersection point of the straight lines (which represent the approximation functions) dropped on the vertical axis within the load-displacement curve represents the approximate value of the critical load. The determinant that represents the correct approximation of the experimental curve using the given approximating functions is the correlation coefficient R^2. In general the R_2 coefficient means the correlation coefficient, which is a strongly generalized term. In practice, with respect to the research being conducted, the R^2 coefficient is strictly concerned with trend lines. A trend line equation is a formula which finds the line that best fits the data points. The R-squared value measures the reliability of the trend line – as the R^2 value is closer to 1, the better the trend line fits the data. This coefficient should be maintained at a minimum level $R^2 \geq 0.95$ [18]. If the correlation coefficient for the approximation procedure used is higher, the more favorable the result becomes. The process of determining the critical force value [29] initially comes down to solving the system of equations shown below (1):

$$\begin{cases} A_1x + B_1y + C_1 = 0 \\ A_2x + B_2y + C_2 = 0 \end{cases} \tag{1}$$

where: A_1 and A_2 denote the values of the (directional) coefficients of the straight lines at x;
B_1 and B_2 denote the values of the coefficients at y;
C_1 and C_2 denote the (numerical) values that determine the free expression of the linear function.

In order to determine the point of intersection, the notation resulting from equation (1) must be transformed to different form (2):

$$\begin{cases} A_1x + B_1y = -C_1 \\ A_2x + B_2y = -C_2 \end{cases} \tag{2}$$

The resulting first-degree equations system with two unknowns, can be solved by the method known as determinants of matrices (3-5):

$$W = \begin{bmatrix} A_1 & B_1 \\ A_2 & B_2 \end{bmatrix} = A_1 \cdot B_2 - A_2 \cdot B_1 \tag{3}$$

$$W_x = \begin{bmatrix} -C_1 & B_1 \\ -C_2 & B_2 \end{bmatrix} = (-C_1) \cdot B_2 - (-C_2) \cdot B_1 \tag{4}$$

$$W_y = \begin{bmatrix} A_1 & -C_1 \\ A_2 & -C_2 \end{bmatrix} = A_1 \cdot (-C_2) - A_2 \cdot (-C_1) \tag{5}$$

In the case that the aforementioned lines are not parallel ($W \neq 0$), the system of equations (is marked) has exactly one solution (6):

$$\begin{cases} x = \dfrac{W_x}{W} \\ y = \dfrac{W_y}{W} \end{cases} \tag{6}$$

where: x and y constitute the coordinates of the intersection point of the straight lines.

The critical point, determined in the above mentioned method (with x and y coordinates), according to equation (6), determines the critical force value. The above-presented procedure for determining approximate values of critical loads (as presented in more detail in the papers [28, 29]) was applied to all specimens. A graphical representation of the critical (buckling) load determination method is shown in Figure 2.

In the experimental study, both the universal testing machine and the Aramis 2D optical structural deformation measurement system were used [37, 38]. During the experimental investigations, the load applied to the composite strut and the displacement of the crosshead was registered in real time - which allowed the determination of the previously described critical load values. The test specimens for experimental testing were placed in the central part (in the center) of the testing machine heads having flat working surfaces parallel to each other, thus realizing the axial compression process of the structure. In addition, the use of the Aramis 2D system made it possible to register the deformation of the structure, using the digital image correlation (DIC) method. The test stand is presented in Figure 3.

Furthermore, a special red mat – which provided the background of the actual experimental

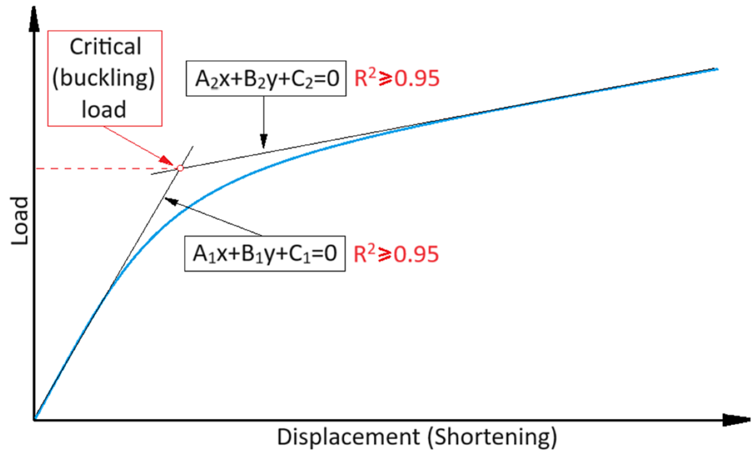


Fig. 2. Determination of critical load

a) b)

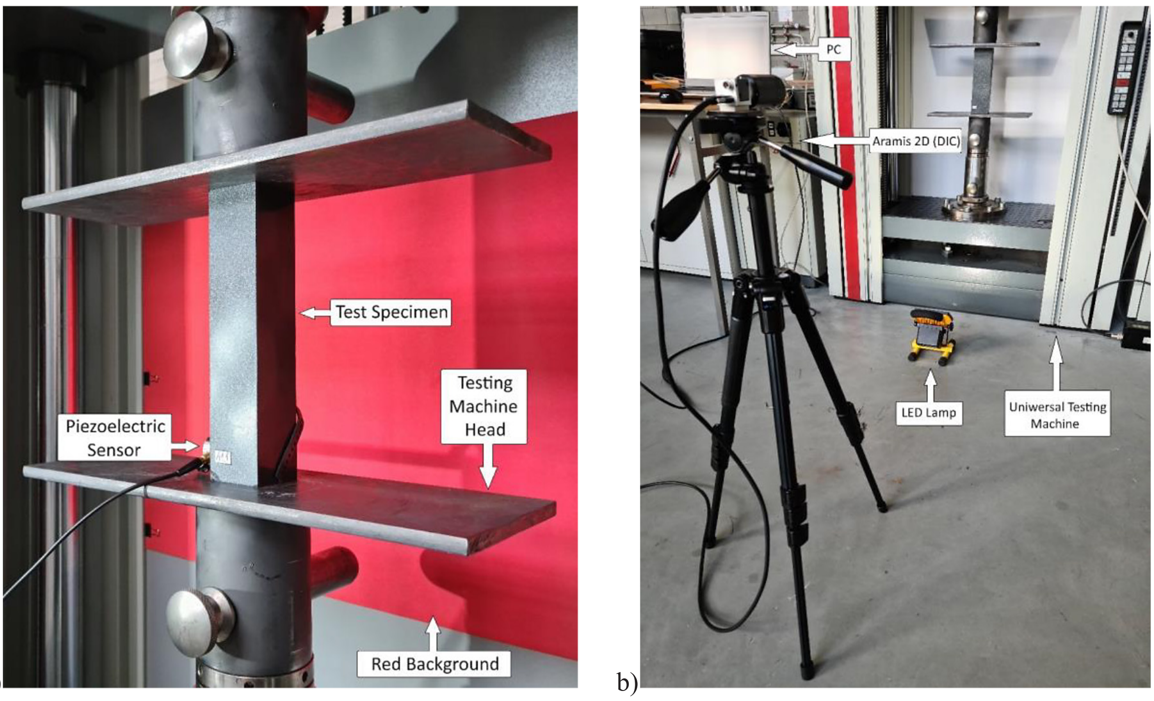


Fig. 3. Experimental test stand: a) experimental test heads with specimen, b) general view of the test stand - Zwick Z100 testing machine with Aramis 2D system

specimens - was used in the experimental studies. The aforementioned red mat, made it possible to correctly record the deformation of the column using the Aramis 2D (optical deformation measurement) – where there were no reflection effects, in close vicinity of the test specimen area.The above approach made it possible to eliminate any negative optical effects as part of the registration of the deformation of the structure, where the red background absorbed any brightness resulting from the use of the aforementioned optical system.

NUMERICAL SIMULATIONS

Finite element method simulations were conducted using the Abaqus. The prepared numerical model enables the simulation of the phenomenon of structural stability – with particular emphasis on the buckling phase of the column, on the basis of the solution of a linear eigenproblem. The above, made it possible to determine the buckling (mode) form and the corresponding critical force [23]. The relationship that enables the determination of the buckling load is shown in equation (7) [23]:

$$\left(K_0^{NM} + \lambda_i K_\Delta^{NM}\right) v_i^M = 0 \tag{7}$$

where: K_0^{NM} signifies the structural stiffness matrix (corresponding to the base state, which includes the effects of the preloads P^N);
K_Δ^{NM} signifies the differential (initial) stress as well as load stiffness matrix caused by the incremental loading pattern (Q^N);
λ_i signifies the eigenvalues;
v_i^M denote the buckling mode shapes – eigenvectors (v_i^M are normalized vectors - so that the maximum component of the displacement is 1.0);
^{M} and ^{N} refer to degrees of freedom (M and N of the developed model);
$_i$ refers to the $_i$th buckling form (mode). Furthermore, the critical loads represent then $P^N + \lambda_i Q^N$.

A detailed description of the linear solution of the eigenproblem is presented in the paper [39], where relation (7) is presented in a slightly different form.

The numerical model included both a composite specimen and plates that reflected the flat surfaces of the test machine heads. The composite specimen consisted of 8 layers $[0°/45°/-45°/90°]_s$ and was modeled using the LayUp Ply technique, where a discrete model of the structure was defined using Continuum Shell elements (SC8R – 8-node finite elements with 3 translational degrees of freedom – at each node). In the case of elements that constitute non-deformable plates, shell elements of type R3D4 were used (having 4 nodes per finite element and 6 degrees of freedom – at each node – 3 translational/3 rotational). The mesh density for the composite structure was 2 mm while for the non-deformable panels it was 2.5 mm. The total number of finite elements (FE) assigned to the system under study, i.e. the composite specimen and two non-deformable plate structures (representing the top and bottom support), was 10320 (9200 SC8R-type FE and 1120 R3D4-type elements) and 19802 computational nodes. Contact relations were used between the plates and the composite structure, taking into account contact interactions [40, 41] in the normal as well as tangential directions (with a friction 0.2). Boundary conditions were assigned to reference points (RPs) coupled to non-deformable plates, where in the case of the bottom plate, all degrees of freedom were blocked, while the top plate had only the ability to move according to the direction of the Z-axis (in order to simulate the compression phenomenon). A unit load (in the form of a concentrated force) was applied to the top plate. The above approach, in the case of the conducted analysis of the eigenproblem (Linear Perturbation - Buckle), allowed to determine the critical forcevalue and the form of buckling of the structure corresponding to this load. The numerical model used an orthotropic Lamina-type material model, the properties of which were the same as the material parameters determined experimentally and presented in the previously presented Table 1. The numerical model is presented in Figure 4.

RESEARCH RESULTS

In the framework of the tests, results were obtained enabling the determination of the buckling state. In the case of experimental studies, the critical forces values were determined using the (approximation) method of intersection of straight lines, as well as the form of buckling of the structure corresponding to the critical force was registered. The experimentally determined values of critical loads are presented in Figure 5.

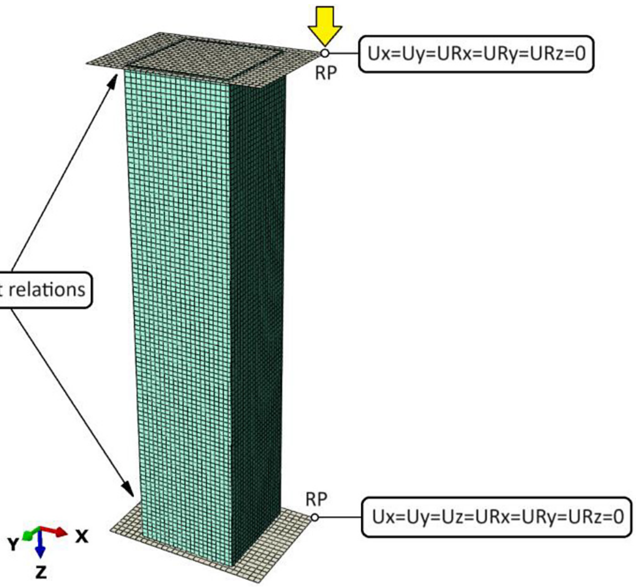
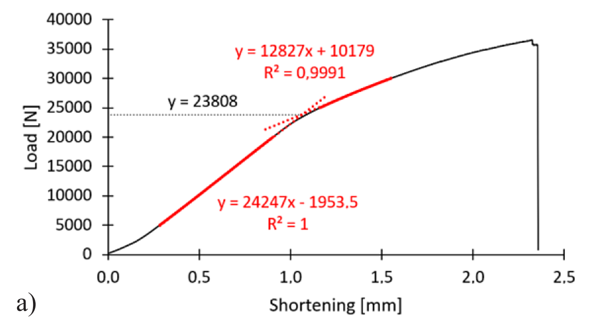
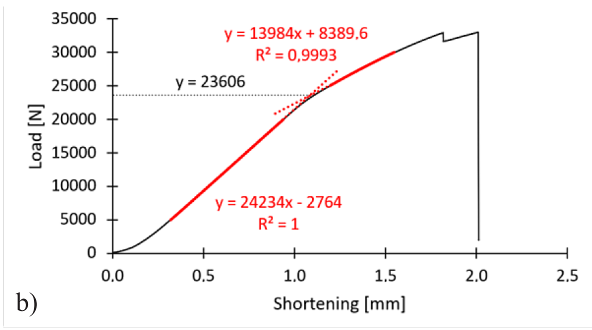


Fig. 4. Graphical presentation of the numerical model





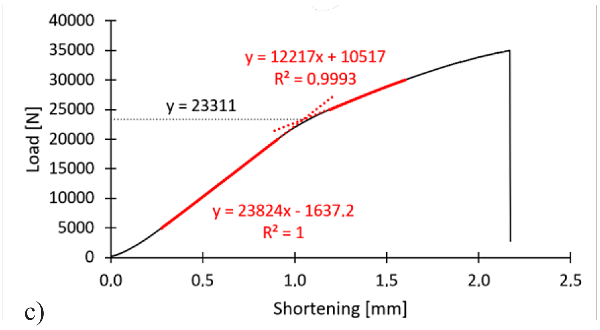
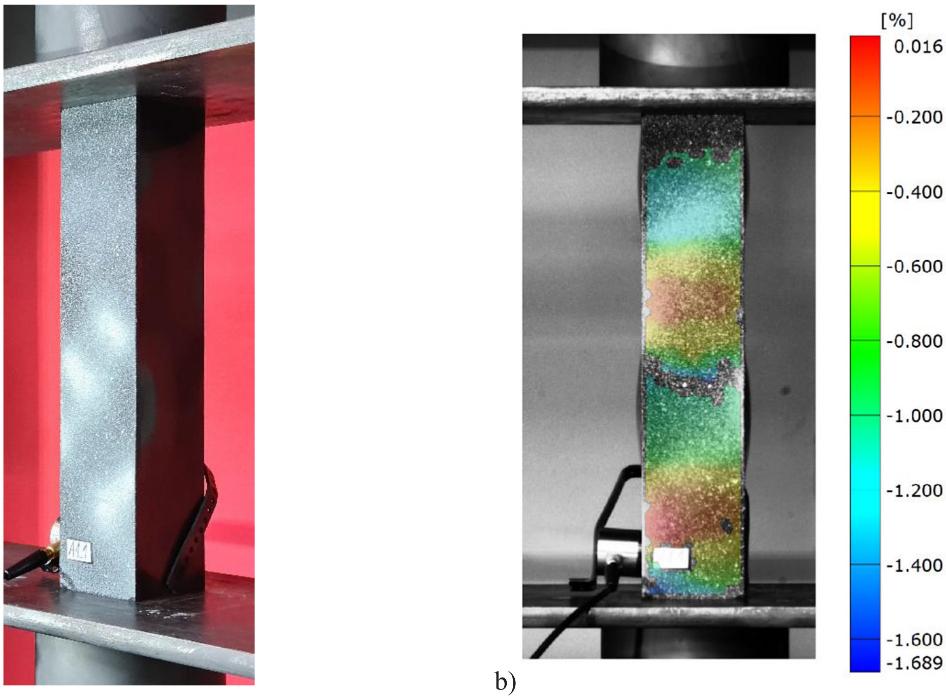


Fig. 5. Experimentally determined critical load: a) specimen A1_1, b) specimen A1_2, c) specimen A1_3

For the actual experimental specimens, the determined critical load values were, respectively: A1_1 – 23808 N, A1_2 – 23606 N and A1_3 – 23311 N. With reference to the study, the average value of the experimentally determined critical load P_{cr} = 23575 N was specified.

Regarding the experimental studies, the form of buckling was registered, among other things, using an optical system for measuring the deformation of structures - Aramis 2D (two-dimensional version). Through the use of special settings of the Aramis 2D system and the application of a special median filter as part of the visualization of the results, it was possible to capture a graphical representation of the buckling of the actual structure. The above, made it possible to capture the form of buckling of the structure when the critical force is reached. The experimentally registered form of buckling is shown in Figure 6.

In the case of the tested structure with a lay-up $[0°/45°/-45°/90°]_s$ the buckling form of the strut was registered, in which 4 half-waves were observed – in the longitudinal direction of the column.



a) b)

Fig. 6. Loss of structural stability (Buckling) - experimental studies

Simultaneously conducted FEM simulations made it possible to define both the value of the critical force and the buckling mode corresponding to this load. The above was obtained by solving a linear eigenvalue problem. The obtained buckling mode for the composite strut and the critical force value are shown in Figure 7.

Regarding the numerical simulations, similar results were obtained as in the experimental tests. The critical forcevalue was 24501 N, while the form of buckling was the same as the one obtained at the stage of experimental testing - where 4 half-waves were also registered in the longitudinal direction of the structure. The critical load obtained using the numerical simulation was 1.04 times higher than the average value of the critical load obtained from the experimental studies. The slight difference between the critical load values represents the high agreement of the FE model, correctly validated by the experimental findings.

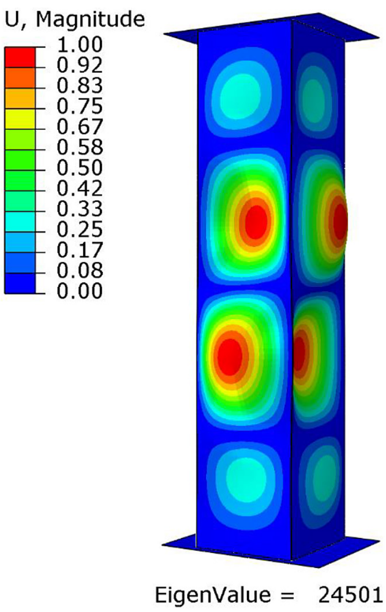


Fig. 7. Loss of structural stability (buckling) - numerical studies

Further research direction will include stability analysis of already manufactured composite structures, under the project from the National Science Centre (project number 2021/41/B/ST8/00148) for other lay-ups of composite material. Moreover, other cross-sectional shapes of composite columns will be analyzed, as well as research will be carried out in terms of the load carrying capacity (failure) of the structures, using interdisciplinary experimental research techniques and advanced numerical models – taking into account the phenomenon of failure.

CONCLUSIONS

The research presented in the present paper is a preliminary study on the stability problem of thin-walled composite struts with closed sections. In the course of the research, the problem of buckling of structures made of CFRP-composite was analyzed. The measurable effect of the tests was the determination of the values of buckling loads and the buckling form in the case of actual structures and in the case of a numerical model. It was observed that:

- it is possible to determine the approximate value of the critical load using the experimental approximation method of intersection of straight lines, based on the load-displacement characteristics (shortening of the structure);
- it is possible to qualitatively assess the form of buckling using the Aramis 2D (DIC), validated by FEM simulation results;
- it is possible to develop a numerical model, using FEM, allowing to faithfully reproduce both the experimentally obtained form of buckling and to obtain an approximate value of the buckling load.

Based on the axial compression tests of thin-walled composite structures, it was determined that there was a slight discrepancy in the critical load, between the experimental tests and the FEM simulation. The buckling load obtained in the numerical simulation was only 1.04 times higher than the average value of the critical load obtained in the experimental tests. Qualitatively, the number of half-waves of the column equal to 4 was the same for experimental testing and FEM simulation. The above demonstrates the high quality of the developed numerical model. Further research will be an expansion of the current investigations both in the context of stability, but especially in the context of failure of thin-walled struts made of CFRP materials with closed sections. Further research will make use of additional testing apparatus, such as the acoustic emission method and digital microscope [5, 42, 43] in order to conduct further studies of the stability and load carrying capacity of the structure [44, 45].

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REFERENCES

1. Rozylo, P.; Debski. H. Effect of eccentric loading on the stability and load-carrying capacity of thin-walled composite profiles with top-hat section. Compos. Struct. 2020; 245: 112388.
2. Rozylo, P.; Falkowicz, K.; Wysmulski, P.; Debski, H.; Pasnik, J.; Kral, J. Experimental-Numerical Failure Analysis of Thin-Walled Composite Columns Using Advanced Damage Models. Materials 2021; 14: 1506. https://doi.org/10.3390/ma14061506.
3. Fascetti, A.; Feo, L.; Nistic, N.; Penna, R. Web-flange behavior of pultruded GFRP I beams: A lattice model for the interpretation of experimental results. Compos. B Eng. 2016; 100: 257–269.
4. Gliszczynski, A.; Kubiak, T. Progressive failure analysis of thin-walled composite columns subjected to uniaxial compression. Compos. Struct. 2017; 169: 52–61.
5. Debski, H., Samborski, S., Rozylo, P., Wysmulski, P. Stability and load-carrying capacity of thin-walled FRP composite Z-profiles under eccentric compression. Materials, 2020, 13(13), 2956.
6. Rozylo, P. Failure phenomenon of compressed thin-walled composite columns with top-hat cross-section for three laminate lay-ups. Composite Structures, 304, (2023), 116381.
7. Kim, N-I., Shin D.K., Park, Y-S. Coupled stability analysis of thin-walled composite beams with closed cross-section. Thin-Walled Structures, 48, (2010), 581–596.
8. Urbaniak M., Swiniarski J., Czapski P., Kubiak T. Experimental investigations of thin-walled GFRP beams subjected to pure bending. Thin-Walled Structures, 107, (2016), 397–404.
9. Drozdziel M., Podolak P., Czapski P., Zgorniak P., Jakubczak P. Failure analysis of GFRP columns subjected to axial compression manufactured under various curing-process conditions. Composite Structures, 262, (2021), 113342.
10. Czapski P., Kubiak T. Numerical and experimental investigations of the post-buckling behaviour of square cross-section composite tubes. Composite Structures, 132, (2015), 1160–1167.
11. Rozylo P., Debski H. The Influence of Composite Lay-Up on the Stability of a Structure with Closed Section. Advances in Science and Technology Research Journal 2022, 16(1), 260–265.
12. Czajka B., Rozylo P. The Influence of Composite Lay-Up and the Shape of the Closed Section on the Stability of the Structure. Advances in Science and Technology Research Journal 2022, 16(2), 216–224.
13. Taraghi P., Zirakian T., Karampour H. Parametric study on buckling stability of CFRP-strengthened

cylindrical shells subjected to uniform external pressure. Thin–Walled Structures, 161, (2021), 107411.

14. Bazant Z.P., Cedolin L. Stability of structures. elastic, inelastic, fracture and damage theories. UK: Oxford University Press; 2010.
15. Singer J., Arbocz J., Weller T. Buckling experiments. Experimental methods in buckling of thin-walled structure. Basic concepts, columns, beams, and plates, vol. 1. New York: John Wiley & Sons Inc.; 1998 (vol. 2: 2002).
16. Banat, D., Mania, R.J. Failure assessment of thin-walled FML profiles during buckling and postbuckling response. Compos Part B Eng 2017;112:278–89.
17. Rozylo, P., Falkowicz, K. Stability and failure analysis of compressed thin-walled composite structures with central cut-out, using three advanced independent damage models. Compos. Struct., 2021;273:114298.
18. Rozylo, P., Teter, A., Debski, H., Wysmulski, P., Falkowicz, K. Experimental an numerical study of buckling of composite profiles with open cross section under axial compression. Appl Compos Mater 2017;24:1251–64.
19. Li, Z.M., Qiao, P. Buckling and postbuckling behavior of shear deformable anisotropic laminated beams with initial geometric imperfections subjected to axial compression. Eng Struct. 2015;85:277–92.
20. Ragheb Wael F. Local buckling analysis of pultruded FRP structural shapes subjected to eccentric compression. Thin-Walled Struct. 2010;48:709–17.
21. Turvey GJ, Zhang Y. A computational and experimental analysis of the buckling, postbuckling and initial failure of pultruded GRP columns. Compos, Struct. 2006;84:1527–37.
22. Rozylo, P.,Debski, H. Stability and load-carrying capacity of short composite Z-profiles under eccentric compression, Thin-Walled Struct., 157, (2020), 107019.
23. Rozylo P., Debski, H. Failure study of compressed thin-walled composite columns with top-hat cross-section. Thin-Walled Structures, 180, (2022), 109869.
24. Li, W., Cai, H., Li, C., Wang, K., Fang, L. Progressive failure of laminated composites with a hole under compressive loading based on micro-mechanics, Adv. Compos. Mater. 23 (2014) 477–490.
25. Zhang, H., Yang, D., Ding, H., Wang, H., Xu, Q., Ma, Y., Bi, Y. Effect of Z-pin insertion angles on low-velocity impact mechanical response and damage mechanism of CFRP laminates with different layups. Composites: Part A, 150, (2021), 106593.
26. Qiu, C., Han, Y., Shanmugam, L., Zhao, Y., Dong, S., Du, S., Yang, J. A deep learning-based composite design strategy for efficient selection of material and layup sequences from a given database. Composites Science and Technology, 230, (2022), 109154.
27. Hu, Y., Zhang, Y., Fu, X., Hao, G., Jiang, W. Mechanical properties of Ti/CF/PMR polyimide fiber metal laminates with various layup configurations. Composite Structures, 229, (2019), 111408.
28. Paszkiewicz, M., Kubiak, T. Selected problems concerning determination of the buckling load of channel section beams and columns, Thin-Walled Struct. 93 (2015) 112–121.
29. Kamarudin, M.N.B.; Ali, J.S.M.; Aabid, A.; Ibrahim, Y.E. Buckling Analysis of a Thin-Walled Structure Using Finite Element and Design of Experiments Methods. Aerospace, 2022, 9, 541.
30. Kubiak, T. Static and Dynamic Buckling of Thin-Walled Plate Structures. Springer, 2013.
31. Rozylo, P., Smagowski, W., Pasnik, J. Experimental Research in the Aspect of Determining the Mechanical and Strength Properties of the Composite Material Made of Carbon-Epoxy Composite. Advances in Science and Technology Research Journal, 2023, 17(2), 232–246.
32. Rozylo, P. Determined Material Properties within the framework of the NCN project (OPUS) No. 2021/41/B/ST8/00148. Dataset. DOI: 10.5281/zenodo.7606942, DOI: 10.18150/V6VJET.
33. Kubiak, T., Samborski, S., Teter, A. Experimental investigation of failure process in compressed channel-section GFRP laminate columns assisted with the acoustic emission method. Compos. Struct. 133, (2015), 921–929.
34. Gliszczynski, A., Kubiak, T. Progressive failure analysis of thin-walled composite columns subjected to uniaxial compression. Compos. Struct. 169, (2017), 52–61.
35. Rozylo, P. Stability and failure of compressed thin-walled composite columns using experimental tests and advanced numerical damage models. Int. J. Numer. Methods. Eng., 2021;122:5076–99.
36. Ramkumar, R., Rajaram, K., Saravanan, P., Venkatesh, R., Saranya, K., Jenaris, D.S. Determination of mechanical properties of CFRP composite reinforced with Abaca and Kenaf fibres. Mater. Today: Proc. 2022; 62: 5311–5316.
37. Holmes, J., Sommacal, S., Das, R., Stachurski, Z., Compstion, P. Digital image and volume correlation for deformation and damage characterisation of fibre-reinforced composites: A review. Composite Structures, 315, (2023), 116994.
38. Nowak, M., Maj, M. Determination of coupled mechanical and thermal fields using 2D digital image correlation and infrared thermography: Numerical

procedures and results. Archives of Civil and Mechanical Engineering, 18, 2018, 630-644.

39. Kubiak, T. Static and Dynamic Buckling of Thin-Walled Plate Structures. Springer, 2013.
40. Grzejda, R.Fe-modelling of a contact layer between elements joined in preloaded bolted connections for the operational condition. Advances in Science and Technology Research Journal, 2014, 8(24), 19–23.
41. Grzejda, R. Determination of Bolt Forces and Normal Contact Pressure Between Elements in the System with Many Bolts for its Assembly Conditions. Adv. Sci. Technol. Res. J. 2019; 13(1):116–121.
42. Rozylo, P. Failure analysis of beam composite elements subjected to three-point bending using advanced numerical damage models. Acta Mechanica et Automatica, 2023, 17(1), 133-144.
43. Falkowicz, K., Ferdynus, M., Rozylo, P. Experimental and numerical analysis of stability and failure of compressed composite plates. Composite Structures, 261, 2021, 113657.
44. Rozylo, P. Experimental-numerical test of open section composite columns stability subjected to axial compression. Archives of Materials Science and Engineering, 2017, 84(2), 58–64.
45. Rozylo, P., Debski, H., Kral, J. Buckling and limit states of composite profiles with top-hat channel section subjected to axial compression. AIP Conference Proceedings, 2018, 1922, 080001.