INVESTIGATIONS INTO THE STABILITY OF THIN-WALLED COMPOSITE STRUCTURES WITH TOP-HAT CROSS-SECTIONS

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Abstract: This paper presents a study of compressed thin-walled composite columns with an open cross-section. The tested specimens with a top-hat cross-section were made of CFRP material. Two arrangements of composite layers [0/-45/45/90]s and [90/0/90/0]s were compared. The paper focuses on the buckling phenomenon and the determination of the critical loads of the structure. It includes both numerical analyses using the finite element method (FEM) and validation on real specimens made using the autoclave technique. A comparison is made between the results obtained by both methods. The critical forces of the real specimens were determined using the P-wc3 approximation method. Both the evaluation of the buckling shape and the values of the critical forces showed a significant correlation between the experimental and numerical tests. This paper also compares the tested lay-ups.

Key words: buckling, post-buckling equilibrium paths, critical loads, thin-walled composite structures, finite element method, experimental tests

1. INTRODUCTION

Thin-walled structures are widely used in many industries such as civil engineering, automotive industry, aviation and aerospace. Many responsible components, for example, pads in sports, structural components for aircraft and helicopters [1, 2] and vehicle components [3] are made from these structures. Among these, structures made of composite materials are particularly important.

The use of thin-walled structures introduces the possibility of structural buckling. However, it is important to note that local buckling of a structure may not necessarily result in a loss of load-carrying capacity. Many structures show the ability to carry loads further in the post-buckling state. Nevertheless, for the safety design and subsequent behaviour of the structure, it is very important to determine the critical load and the behaviour in the post-buckling state.

Some of the first investigators dealing with the phenomenon of elastic stability were Koiter and Hutchinson [4], Byskov [5], Thompson and Hunt [6] and Goltermann and Mollman [7, 8]. Although the beginning of research into the phenomenon of buckling of structures dates to the 18th century, the subject is still relevant and further work is needed to design structures more and more confidently. This is confirmed, for example, by the fact that scientists such as Kubiak [9], Dębski [10] and Różyło [11] are continuously working on this topic. Many papers in recent years have been devoted to the study of the stability and buckling of structures constructed from various types of composites [12–16]. In addition, some of them deal precisely with columns with open cross-sections, which highlights the novelty and currency of the studied topic [10, 17, 18].

Due to the rapid evolution of computer hardware and engineering software, an increasing range of engineering problems may be solved using numerical simulations. Within these, finite element method (FEM) calculations are currently leading. These are used, for example, for thermal, modal and strength analyses. Numerical analysis also allows the determination of critical loads, which cause buckling of the structure. Critical loads may also be established through experimental investigations. Some of the approximation methods used to determine critical forces are the Koiter method [19, 20], P-wc2 and P-wc3 [21]. The use of the P-wc3 method, which is rarely used in the literature [21, 22, 23], brings a novelty to the paper and allows to expand the overall state of knowledge on the subject. The aforementioned methods are based on the post-buckling equilibrium paths recorded during experimental testing, which represents the dependence of the load on the deflection of the specimen.

In this study, the buckling tests were carried out using the numerical analysis in the Abaqus software and experimental tests on a universal testing machine. The interdisciplinary approach of the research made it possible to compare the results obtained from the computer simulations with the real samples. The influence of composite lay-up on the stability of the structure was also investigated. The presented research extends the state of knowledge regarding the stability and determination of critical loads of thin-walled composite columns with open cross-sections.

The research performed in this paper (on composite structures with top-hat sections) is a prelude to the research from project No. 2021/41/B/ST8/00148, National Science Centre (Poland), on composite profiles with closed sections.

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2. OBJECT OF RESEARCH

The object of the study was thin-walled open-section columns made of CFRP (carbon fiber reinforced polymer) composite material. They had a top-hat cross-section of 60 mm × 30 mm × 15 mm and a height of 200 mm. A numerical model of the specimen with the marked dimensions is shown in Fig. 1. The test specimens consisted of eight laminate layers with a thickness of 0.105 mm per layer. The presented research focuses on the comparison of two lay-ups W1 – [0/-45/45/90]s and W2 – [90/0/90/0]s. Three samples from each layer arrangement were used in the experimental part of the study. These were made as long columns using the autoclave method and then cut to a dimension of 200 mm. In the numerical part of the study, the real specimens were represented by numerical models.

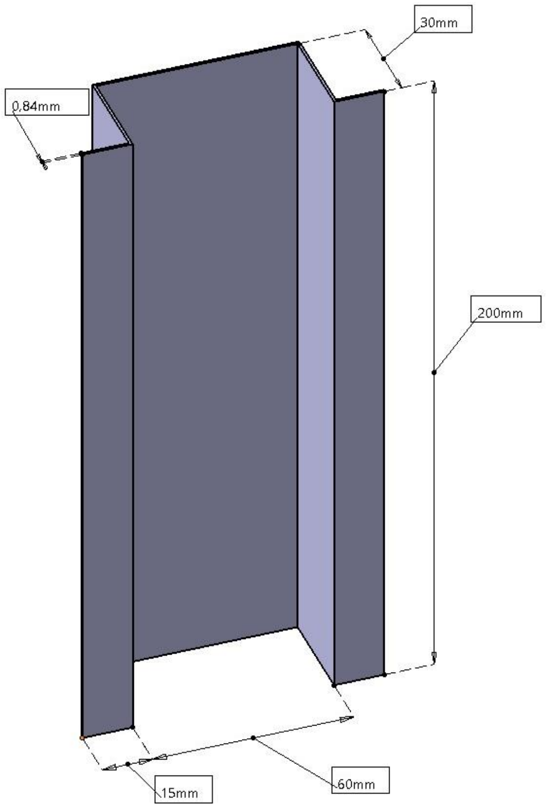

Fig. 1. Numerical model of the specimen with marked dimensions

The properties of the CFRP composite material were determined in compliance with ISO standards. The mechanical properties for a single laminate layer are shown in Tab. 1, where E_1 is Young's modulus in the fibre alignment direction, E_2 is Young's modulus in the direction perpendicular to the fibres, v_{12} is Poisson's ratio in the surface of the layer and G_{12} is Kirchoff's modulus in the surface of the layer.

Tab. 1. Mechanical properties of a single layer of CFRP material [24]

Symbol	Value	Unit
E_1	143,528.5	MPa
E_2	5,826.3	MPa
v_{12}	0.36	–
G_{12}	3,845.5	MPa

3. NUMERICAL STUDIES

Numerical analysis was carried out using the FEM in the Abaqus software. The paper is devoted entirely to the issue of linear buckling of structures. The linear stability analysis of the structure was conducted using a minimum potential energy criterion. The scope of the study included modelling the actual specimens and boundary conditions, discretising the models and solving the eigenproblem to determine the critical loads and buckling form of the columns.

The specimen models were made directly in Abaqus software using the lay-up ply modelling method. The layers were arranged in two configurations, W1 and W2, as described earlier, and the orthotropic properties were assigned to them as shown in Tab. 1. When discretising the models, shell-type finite elements with reduced integration and 4 nodes (S4R) were used. These are elements with 6 degrees of freedom at each node. The discretisation was performed using linear finite elements.

During the test, the models were placed between two non-deformable plates to represent the boundary conditions in the experimental test more precisely. The discretisation of the plates was performed using R3D4 elements. One of the plates (the bottom one) was completely restrained by removing the possibility of movement in each direction ($U_x = 0$, $U_y = 0$, $U_z = 0$, $UR_x = 0$, $UR_y = 0$, $UR_z = 0$). The other plate (the top one) was allowed to move along the height of the column, and the other movements were blocked ($U_x = 0$, $U_y = 0$, $UR_x = 0$, $UR_y = 0$, $UR_z = 0$). A compressive load was applied to the reference point on the top plate. The reference point is connected to the entire, non-deformable plate and move with all plate providing uniform load distribution. Contact interactions in the normal ('Hard' Contact) and tangential (frictional with friction coefficient = 1) directions were applied between the plates and the test columns. An overview of the whole model after discretisation, including the plates and the boundary conditions marked, is shown in Fig. 2. The whole model consisted of 2,153 nodes, 1,200 S4R elements and 800 R3D4 elements.

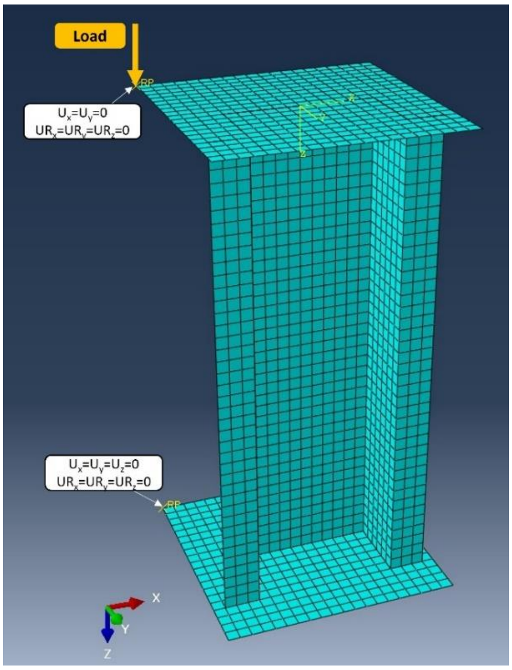

Fig. 2. Discrete model with boundary conditions

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4. EXPERIMENTAL RESEARCH

The compression of the specimens was carried out on a Zwick Z100 universal testing machine. Room temperature was prevailing during the tests. The specimens were placed between two non-deformable, non-rotatable fixed plates. The lower one was fixed while the upper one compressed the specimens at a rate of 1 mm/min. The compression of the specimens was continued until the forces were about 30%–40% higher than the critical loads predicted by the numerical tests. This allowed a clear observation of the shape of the local buckling in the specimens. No signs of specimen failure were observed during or after the tests. During the test, pads made of soft material were placed between the specimens and the machine plates. These reduced the effect of non-ideal cutting of the specimen cross-sections on the uniformity of profile loading. The specimens were positioned precisely using special centring for the screw in the machine plate inserts. A general view of the test stand is shown in Fig. 3.

A laser sensor was used during the test to measure the deflection value at the point of maximum half-wave displacement. By plotting the deflection against the load, it was possible to approximate the value of the critical load in the experimental study. After a preliminary analysis of three approximation methods – the Koiter method, P-w_c^2 and P-w_c^3, it was decided to use the P-w_c^3 method due to the smallest discrepancies in critical loads between the various samples of a single configuration. The use of deflection instead of strain increment was possible due to the proportionality of these values [25]. The P-w_c^3 method allows the critical force to be determined using a post-buckling equilibrium path for values of strain (or deflection due to proportionality) raised to the cube. The portion of the diagram occurring beyond the region of inflection is approximated by a straight line. The intersection of this straight line with the vertical axis of the coordinate system determines the approximate value of the critical load. In this method, it is important to properly select the range of data that are approximated. The correlation coefficient R^2 should take values not <0.95 [23]. R^2 is the correlation coefficient indicating the matching quality between the approximation curve and the selected section of the experimental curve.

Fig. 3. A general view of the test stand

a) b)

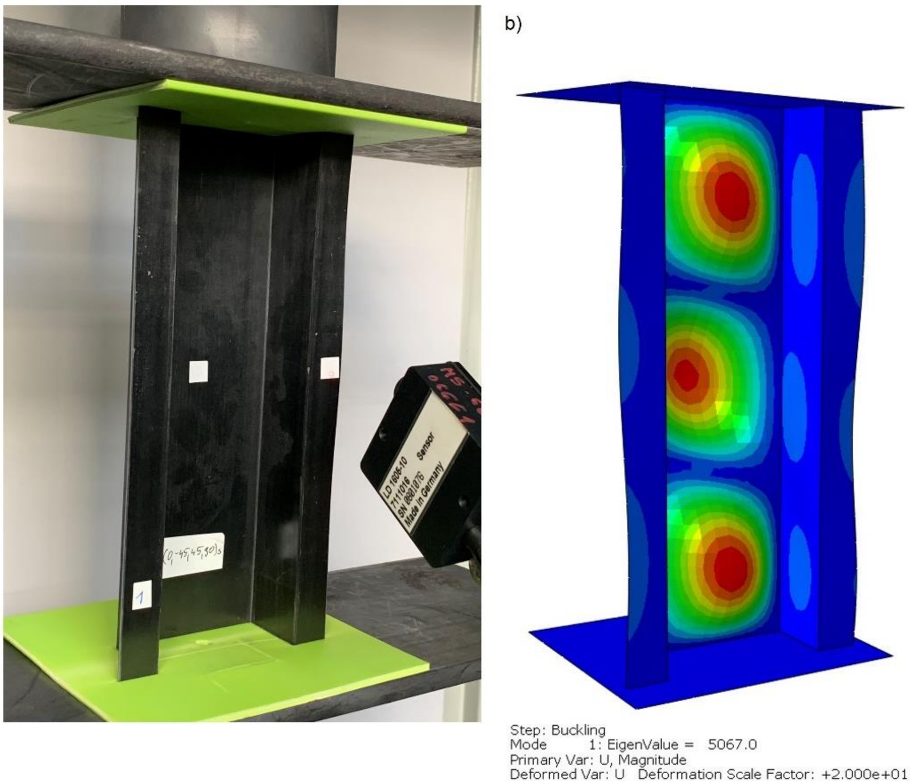

Fig. 4. Comparison of W1 configuration results: **(a)** experimental studies and **(b)** numerical analysis

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5. RESULTS

The performed tests allowed verification of the similarity of critical loads determined by approximation methods through experimental tests and values obtained by numerical simulations. In addition, it was also possible to compare the shape of the local buckling occurring in real specimens and numerical models.

Both numerical and experimental studies have shown an identical arrangement of half-waves for the individual composite configurations. For the first one (W1 – [0/-45/45/90]s), three half-waves are visible, as shown in Fig. 4. For the experimental sample, the half-waves are best visible on the side shelf of the profile. For the W2 – [90/0/90/0]s configuration, five half-waves are observed, which are visible on both the numerical model and the actual sample (Fig. 5.) Similarly to the W1 configuration, the best visibility of the half-waves is at the same area of the column.

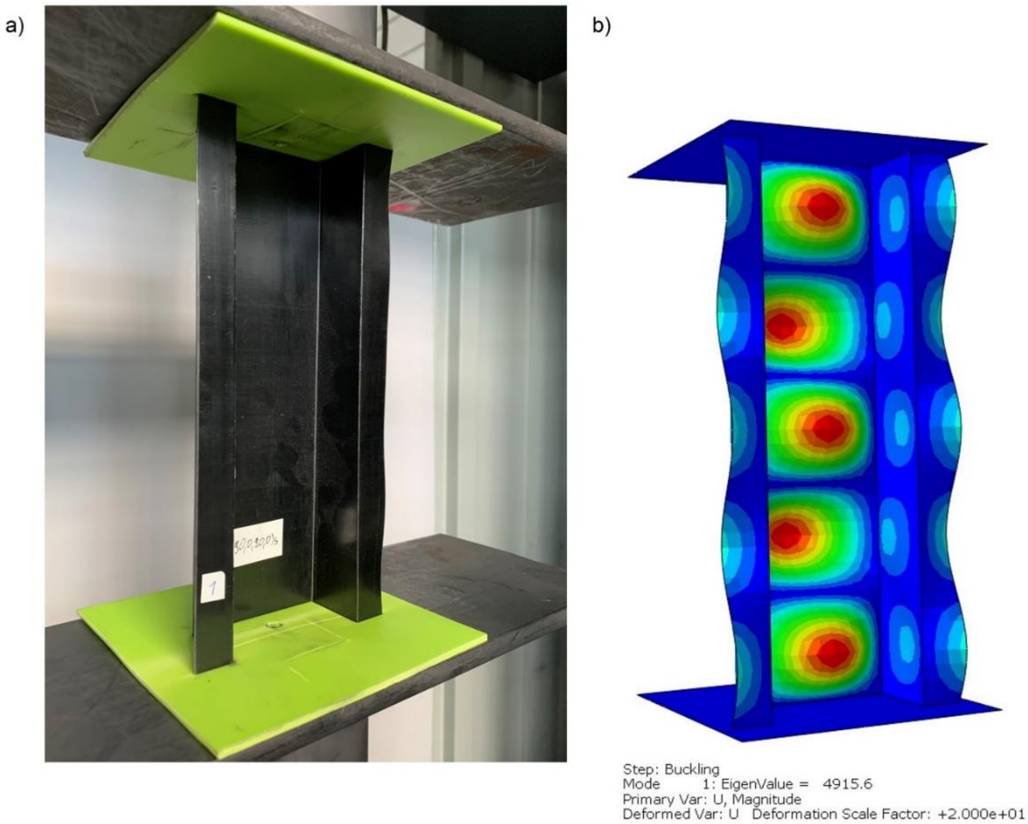

Fig. 5. Comparison of W2 configuration results: **(a)** experimental studies and **(b)** numerical analysis

The critical loads obtained from numerical and experimental studies also showed similar values. The average value of the critical load P_{cr_E} approximated by the P-w_c^3 method for the W1 configuration was 5,224.7 N and for the W2 configuration was 4,387.1 N. In both cases, the standard deviation of the results obtained for the individual experimental samples was not >4%. The corresponding graphs used to approximate the critical force values are shown in Figs. 6 and 7 for the W1 and W2 configurations, respectively.

The critical load values achieved from the numerical simulations P_{cr_N} were 5,067.0 N for the W1 configuration and 4,915.6 N for the W2 configuration. The percentage error between the average values obtained from the experimental tests and the values from the numerical simulations was calculated according to the following Eq. (1):

$$\delta P_{cr} = \frac{|P_{cr\_E} - P_{cr\_N}|}{P_{cr\_E}} \times 100\% \tag{1}$$

where P_{cr_E} is the average of the values approximated from the experimental tests and P_{cr_N} is the value obtained using FEM. A smaller error rate of only 3.0% was obtained for the composite in the W1 configuration, while for the W2 configuration, it was 12.0%. The data discussed are shown in Tab. 2.

Tab. 2. Comparison of critical force values for experimental and numerical studies

Configuration	P-w_c^3 P_{cr_E} [N]	FEM P_{cr_N} [N]	δP_{cr} [%]
W1 – [0/-45/45/90]s	5,224.7	5,067.0	3.0
W2 – [90/0/90/0]s	4,387.1	4,915.6	12.0

FEM, finite element method

For both experimental and numerical studies, the W1 configuration has a higher critical load value. However, this effect is more noticeable in the experimental studies, where the difference is about 837.6 N (>19% of the force value of W2). For the numerical analysis, the difference is only 151.4 N (about 3% of the force value of W2).

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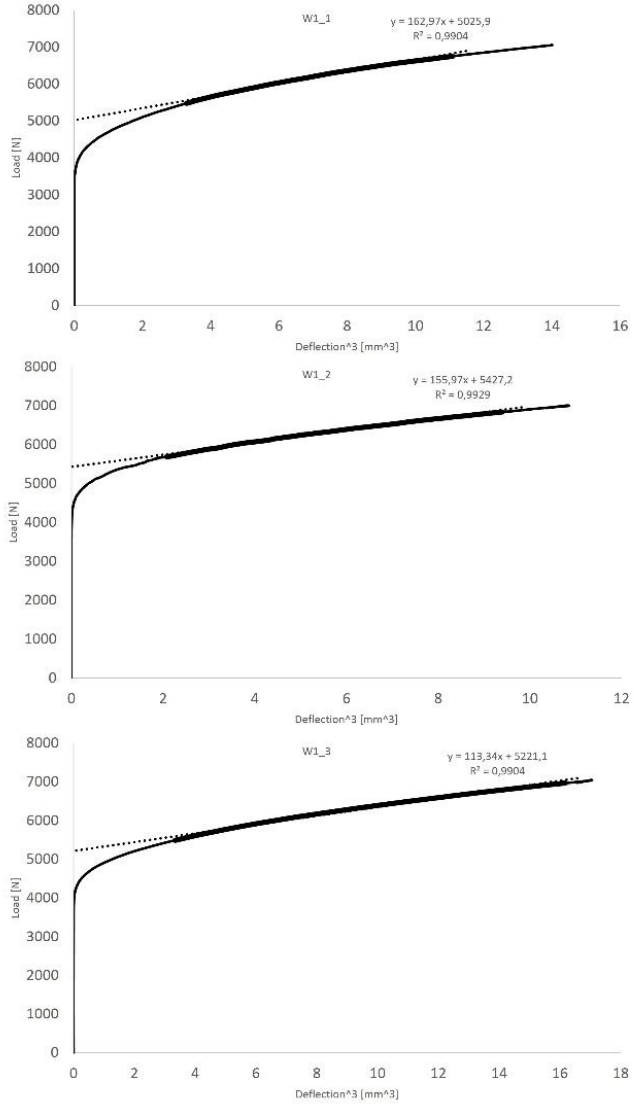

Fig. 6. Post-buckling equilibrium paths – configuration W1

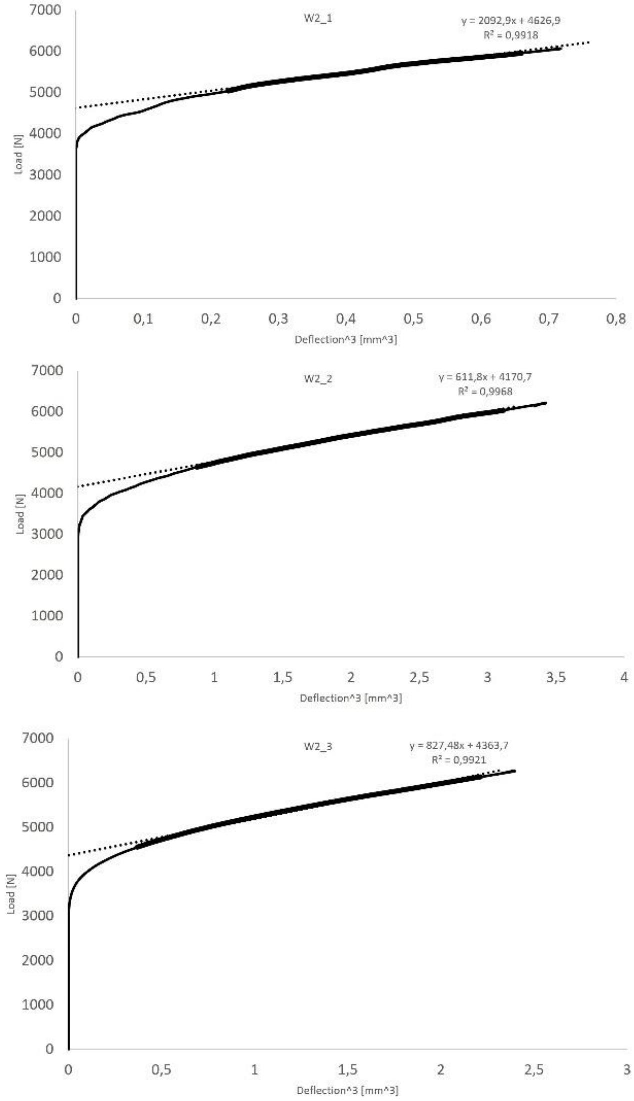

Fig. 7. Post-buckling equilibrium paths – configuration W2

6. CONCLUSIONS

The study carried out compares the critical state behaviour of composite columns with top-hat cross-sections in real conditions and numerical simulation. They show similar visual characteristics and identical half-wave quantities in experimental tests and FEM simulations. The critical load values obtained using the P-w_c^3 approximation method are similar to those derived using numerical calculations. The difference between the methods does not exceed 12%.

The study also allowed the comparison of two composite layer configurations W1 – [0/-45/45/90]s and W2 – [90/0/90/0]s. Both methods (P-w_c^3 approximation and eigenproblem solution using FEM) consistently show higher critical load values occurring for the W1 configuration.

Future studies of non-linear state behaviour and failure of structure analysis are planned. The acoustic emission method and microscopic observation will be used in this study.

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