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EXPERIMENTAL INVESTIGATION OF POST-BUCKLING BEHAVIOR OF COMPOSITE COLUMN WITH TOP-HAT CROSS-SECTION

EKSPERYMENTALNO-NUMERYCZNE BADANIA POKRYTYCZNYCH ZACHOWAŃ KOMPOZYTOWYCH KOLUMN O PRZEKROJU OMEGOWYM*

The object of this study is a thin-walled beam made of carbon-epoxy composite with open cross-section. The material used was a composite of epoxy matrix reinforced with carbon fiber (system HexPly M12, Hexcel). The M12 system is used above all in aircraft structures. It exhibits high fatigue durability and good maintenance properties at relatively low specific gravity. The research was lead as the FEM numerical analyses and experimental tests in buckling and post-buckling state, as well. In the conducted research in order to evaluate the effort ratio of the composite the Tsai-Wu tensor criterion was exploited. The numerical tool used was the ABAQUS software.

Keywords: *numerical modeling, thin-walled structures, FEM analysis, composite materials, experimental testing.*

Przedmiotem badań jest cienkościenna belka wykonana z kompozytu węglowo-epoksydowego o przekroju otwartym. Zastosowanym materiałem był kompozyt o osnowie żywicy epoksydowej wzmacniany włóknami węglowymi systemu HexPly M12 (Hexcel). System M12 wykorzystywany jest w przede wszystkim w strukturach lotniczych i charakteryzuje się wysoką trwałością zmęczeniową oraz dobrymi właściwościami eksploatacyjnymi, przy stosunkowo niskim ciężarze własnym. Badania prowadzono w zakresie obliczeń numerycznych z wykorzystaniem MES oraz badań eksperymentalnych w stanie krytycznym i pokrytycznym. W prowadzonych badaniach do oceny stopnia wytężenia kompozytu wykorzystano kryterium tensorowe Tsai-Wu. Zastosowanym narzędziem numerycznym był program ABAQUS.

Słowa kluczowe: *modelowanie numeryczne, cienkościenne struktury, analiza MES, materiały kompozytowe, badania eksperymentalne.*

1. Introduction

Thin-walled structures belong to a category of load-carrying structures that have wide field of applications in contemporary engineering. An example of their applications can be aircraft structures, for which high stiffness and strength demands under maintenance loads are formulated together with a tendency to minimize the mass of the structure. One of the basic questions connected to the design of thin-walled structures is a problem of stability loss, as well as load-carrying capacity of the system elements. Recently in the design of thin-walled load-carrying structures an increase in number of applications of modern constructional materials – composites in comparison to traditional structural materials could be noticed. Widely used group of materials are polymeric composites reinforced with glass, carbon or kevlar fibres. Application of these materials yields from advantageous ratio of their strength to mass and a resistance to unfavourable working conditions. A lot of papers concerning questions of stability, as well as load-carrying capacity of thin-walled structures is available [3, 11-14,16, 19, 25]. However, a large majority of them applies to classical structural materials, having isotropic properties. Over a span of a few recent years many articles describing properties of fibrous composites – the laminates were published, but they considered mainly theoretical models. There is still a lack of comprehensive information on experimental tests on layered composites reinforced with fibres. This inspired the author of this article to undertake a study in this subject area.

In this work, results of experimental tests on thin-walled composite columns of top-hat cross-section subjected to compressive load were presented. The obtained research results allow to verify the results given by FE models, as well as by author's own analytical-numerical (A-N) method based on the Koiter theory [10]. The experiments covered also determination of material properties, used later in worked out numerical models. Such approach allowed more credible comparison of the prepared composite profiles behaviour with numerical models, being usually only models of ideal structures.

2. Subject of research

The subject of the research were thin-walled columns of top-hat cross-sections made of M12/35%/UD134/AS7/300 Hexcel's "HexPly" unidirectional carbon-epoxy composite prepreg tape. Its matrix was made of epoxy resin (mass density: 1.24 g/cm^3; T_g: 128ºC; R_m: 64 MPa; v: 0.4; E: 5.1 GPa), whereas the reinforcement was AS7J12K carbon fibers (mass density: 2.5 g/cm^3; R_m: 4830 MPa; v: 0.269; E: 241 GPa). Nominal volume fraction of reinforcing fibres in the composite was ca 60 %. The composites were produced with autoclaving technique in the Department of Material Engineering at the Lublin University of Technology [5, 6, 15]. The laminate texture was composed of 8 plies of equal thickness of 0.131 mm sequenced symmetrically $[0,90]_{2s}$. The dimensions of the thin-walled column, as well as the composite layout are presented in Fig. 1.

The columns were produced with autoclaving technique with the use of vacuum packet, prepared in a special mould mapping the shape and the dimensions of the composite profiles. The prepared hermetic packet, providing stable sub-atmospheric pressure of ca -0.1 MPa was subjected to polymerization process in a laboratory-autoclave, where an overpressure of 0.4 MPa was kept in order to provide required holding down. In case of the carbon-epoxy composite a temperature
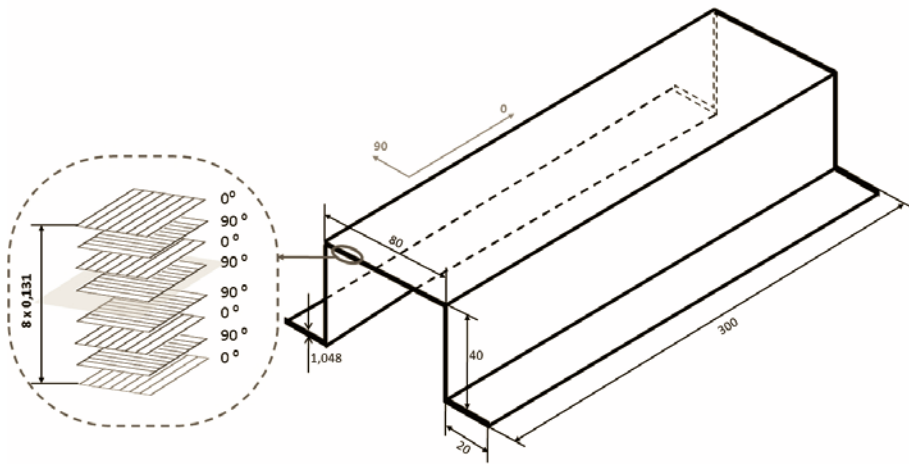
Fig.1. Dimensions of the analysed column and plies layup

of material heating of 135 °C was kept for 2 hours, what enabled finishing of the prepreg polymerization process. In order to eliminate disadvantageous phenomena usually emerging during the composite production process (excessive increase of thermal stresses inside the material and restraining of proper relaxation of initial and thermal stresses) a precise heating and cooling rate of 0.033 K/s was applied.

For the purpose of laminate texture quality check non-destructive testing (NDT) methods were used together with optical microscopy and computer-assisted micro-tomography. Each produced profile underwent thorough quality control in respect of flaw existence, such as porosity or delamination. Thus, every wall of the top-hat profile was examined with ultrasonic echo method using a phased array technique [9]. This testing was performed with OmniScan MXU-M ultrasonic defectoscope equipped with Olympus 5L64 A12 head and having wegde-type SA12-OL delay. The following test parameters were used: frequency 5 MHz, wave-propagation velocity 3100 m/s and amplification of 68 dB. In the conducted research for the purpose of quality control of the produced laminates an A-scan imaging (converted real-time amplitude plot), as well as a C-scan (a real-time collection of B-scan images coming from many converters). The imaging method used enabled simultaneous determination of a flaw's depth (A-scan), as well as its location depth and the flaw's width in any given direction (C-scan). The above mentioned procedure allows to localize delaminations or clusters of pores inside the composite
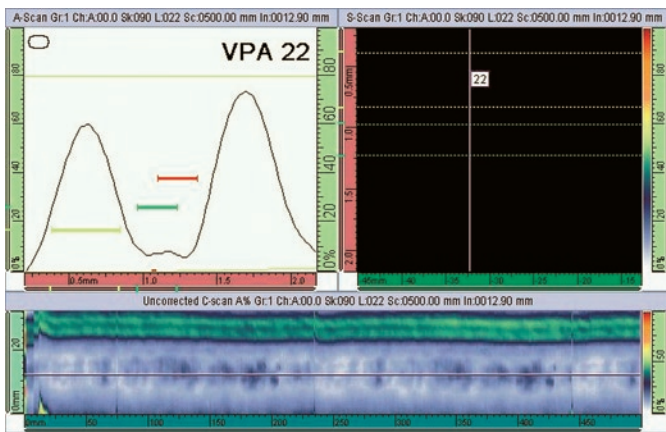
body [7, 18]. The performed quality control of the produced profiles did not reveal any discontinuities in them. An uniform level of reflection of the entrance and of the echo from the bottom (A-scan), as well as uniform C-scan image was obtained. The B-scan was eliminated by decreasing the observation range down to values exceeding the B-scan usability (thin-walled elements) to the advantage of the C-scan module precision. The results of the measurements are given in Fig. 2.

Moreover, for the purpose of the laminate quality control microstructural testing with optical microscopy (NikonMA200, Japan) was employed. It based on computer image analysis (Image Pro Plus, NIS-Elements) and computer-assisted micro-tomography (SkyScan 1174 micro-tomograph). In particular, a quality of the profile's fillet radii was checked, as in these regions are especially prone to inter-layer discontinuities in the form of delamination. Texture inspection and non-destructive testing confirmed very good quality of the composite columns, especially in respect of material discontinuities (internal porosity, delamination). Application of autoclaving composite production technique enabled receiving structures having high mechanical characteristics confirmed by performed strength tests and minimal porosity amount <1%, as well as provided repeatability of the composite fabrication process.

In order to determine mechanical properties of the produced laminates strength testing was performed in accordance with ISO standards. The experiments were done at room temperature (RT) with Zwick's Z100/SN3A universal testing machine, having the accuracy class of 1. To the prepared composite samples (columns) VISHAY's EA-13-24022-120 strain gauges were sticked. They were connected to the MGCplus (Hottinger) measurement system in order to measure the columns' deformations. A loading bar velocity was 2 mm/min. Experimentally determined basic mechanical characteristics of the carbon-epoxy composite were subsequently collected in Table 1. The

Table 1. Mechanical characteristics of carbon-epoxy composite

Tensile strength F_{TU} [MPa]		Young modulus in tension E_T [GPa]		Poisson ratio v		Shear strength F_{SU} [MPa]	Shear modulus G [GPa]	Compressive strength F_{CU} [MPa]	
0°	90°	0°	90°	0°	90°	±45°	±45°	0°	90°
1867.2	25.97	130.71	6.36	0.32	0.02	100.15	4.18	1531	214

Fig. 2. Quality assessment of composite profiles with the use of non-destructive ultrasonic methods (NDT)

received values were exploited in the definition of material model in Finite Elements numerical calculations.

3. Numerical calculations

Discretisation of the thin-walled column model was based on 4-noded reduced integration shell elements (S4R) in the Abaqus and 8-noded elements (Shell99) in the Ansys software. Both types of finite elements had 6 degrees of freedom at each node. They were thin-walled plane-stress shell elements, in which the strain state was defined on the basis of displacements. On the other hand, the bending-state strains were described by angular displacements. A *Layup-Ply* technique was employed for the purpose of the symmetrical $[0,90,0,90]_s$ laminate modelling – Fig. 3.

Boundary conditions of the numerical model representing articulated support of the column's ends were defined by restraining the kinematic degrees of freedom of the nodes belonging to the borders of the

first and the last cross-section. The load was applied to the model as uniformly distributed concentrated forces at the top-end of the column – Fig. 3.
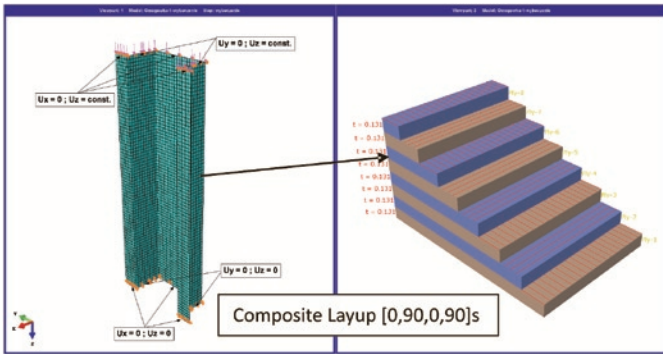

Fig.3.   Discrete model of composite column

Fig.4.   Test stand outfit: self-aligning grips, composite column and laser sensor

The properties of composite material were described by definition of orthotropic material in plane stress state, what allowed to describe the laminate properties in particular directions, according to fibres' arrangement [23] – Table 1. The numerical calculations within the framework of FE were performed in two stages. The linear stability problem (critical state) was solved by finding critical load and buckling mode, as well. Verification of the obtained results was performed with the A-N method [11], based on the Koiter's general asymptotic theory of conservative systems stability [10]. The post-critical calculations were performed as non-linear static analysis of the structure with initiated imperfections having a dimension of 0.05 of the top-hat profile wall thickness, corresponding to the first instability mode of the column. The post-critical analysis taking into account geometrically non-linear problem in Abaqus [1] was done with incremental-iterative Newton-Raphson method, whereas the post-critical equilibrium path was tracked with the Arc-length procedure (the Ricks Method) in the Ansys program [2]. The range of the numerical calculations covered also an attempt to estimate a probability of the composite damage occurence in post-critical state according to the Tsai-Wu criterion [26]. This needed determination of additional material characteristics, such as: F_{TU} – tensile strength along fibres (0º-direction) and in the perpendicular 90º-direction, as well, F_{CU} – compressive strength in both directions and F_{SU} – shear strength of the ±45º-interface. These characteristics were obtained from the performed experiments, see Table 1.

4. Experiments

Stand tests of the top-hat cross-section columns in compression were done with the Zwick Z100/SN3A 1-accuracy class universal testing machine of the 100 kN load range. For this purpose the machine was equipped with intentionally designed and fabricated grips providing that a column was loaded axially – Fig. 4. The grips were set coaxially by fixing them to the machine's loading pins. The ball-and-socket joint enabled free rotations of the grips. Small imperfections of the composite columns ends, as well as possibility to occur local effects in boundary sections of the columns were compensated with thin soft-plastic pads. Before each test the loading system was loaded up to 15 % of the expected critical load in order to provide best alignment of the column placed between the grips. Next, the grip retainers were removed and the column was completely unloaded. On the sample's surface, in a point of the biggest deflection of the composite profile web (the middle wall) two strain gauges were sticked along the 0º-direction on bo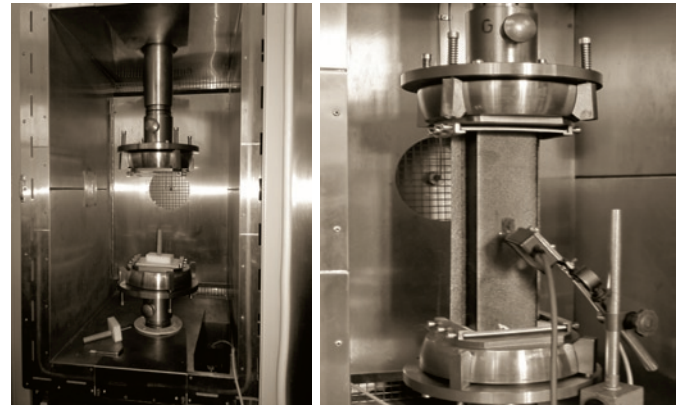th sides of the column. In addition, the deflection was measured with the OptoNCDT 1605 laser sensor at the point of the biggest deflections of the profile web or its arm (the side wall).

During the tests the following variables were registered: the time, the compressive force, the displacement of the cross-bar, the web deflection (with the laser sensor) and the strains (with gauges). The sampling frequency of all parameters was 1 Hz. The experiments were lead in standard conditions at 23 ºC and at a steady cross-bar velocity equal 1 mm/min. The tests were continued until the load reached double critical force. The tests covered registration of the subcritical, critical and post-critical state. However, during the tests no symptoms of the structure failure were perceived.

In the conducted experiments for the purpose of critical forces' estimation the following methods were used [8, 20, 21, 22, 24, 27, 28]:

- a) the vertical-tangent line method (the mean-strains method) – denoted as K1,
- b) the method of straight lines intersection in the plot of mean strains – denoted as K2,
- c) the P-w^2 method – denoted as K3,
- d) the inflexion-point method – denoted as K4,
- e) the Tereszowski method – denoted as K5,
- f) the Koiter method – denoted as K6.

The experimental tests were conducted on 3 specimens with 3 measurements for each of them.

5. Results

The critical state analysis of the compressed thin-walled column showed a local mode of stability loss, manifesting itself by taking a shape of 4 half-waves by all walls of the profile – Fig. 5. For every numerical tool employed in simulations (FEM, A-N method) a qualitative, as well as a quantitative agreement of the computational results was obtained.
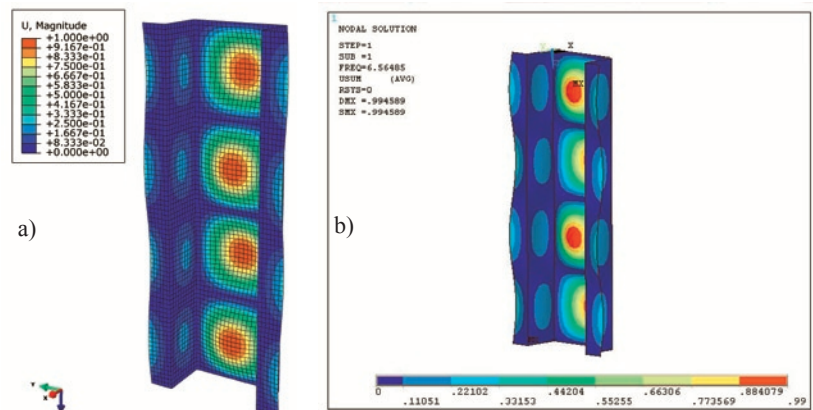

Fig.5. First buckling mode of composite column: a) Abaqus results; b) Ansys results

Table 2. *Critical load values for the firs buckling mode*

Computational tool	Abaqus (FEM)	Ansys (FEM)	Analytical-numerical method (A-N)
Critical force [N]	$P_{CR/Ab} = 6655$ [N]	$P_{CR/As} = 6565$ [N]	$P_{CR} = 6629$ [N]
Number of half-waves	4	4	4

The values of critical forces obtained with particular methods were collected in Table 2. Experimental results for the critical state were given below in a form of force vs testing method plots, obtained from all measurements performed with any particular method, together with confidence interval – Fig. 6. Non-linear computations enabled deformation mode analysis of the structure in post-critical state, up to a laminate's failure load, determined with the Tsai-Wu criterion. The failure load value for the laminate material was accepted as the one corresponding to a failure parameter equal to 1 (on the scale of 0 to 1). The failure force values determined this way with the Abaqus and the Ansys programs were $P_{f/Ab} = 18.6$ kN and $P_{f/An} = 17.1$ kN, respectively. One can notice, that these values equal to 280% or 260% of the respective critical force $P_{CR/Ab}$ or $P_{CR/An}$. Zones in models, in which critical value of the failure parameter was reached indicate hazardous regions of the real composite structure. This means, the regions where the risk of damage of some plies is high. The post-critical deformation form with Tsai-Wu criterion maps for the upper surface of the external laminate layer obtained with the Abaqus and the Ansys programs at failure load are shown in Fig. 7.

Figure 8 presents a comparison of post-critical force-displacement equilibrium paths for the node experiencing maximal defor-
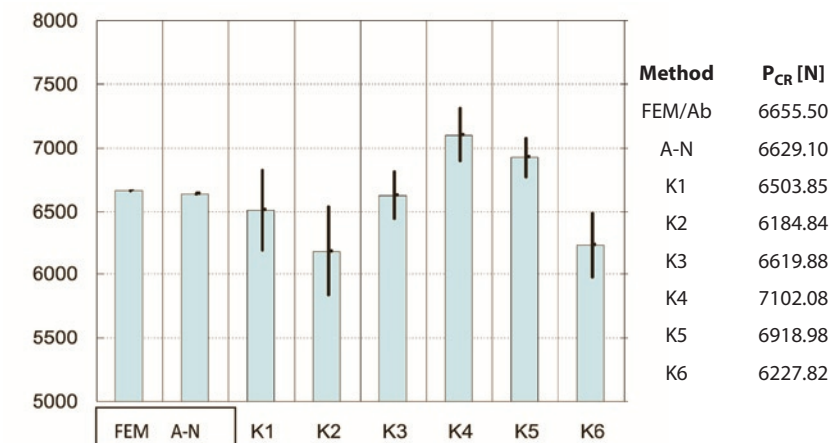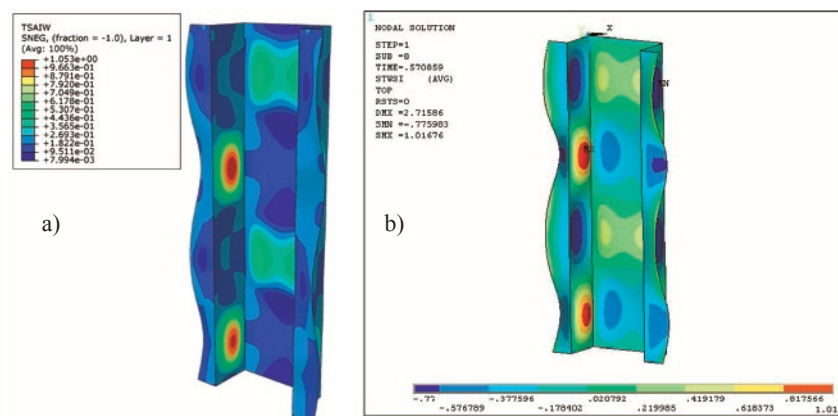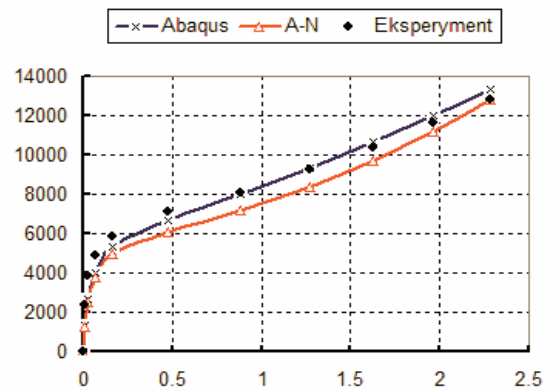

Fig.8. *Post-critical force-displacement equilibrium paths*

mation amplitude of the wider wall of the top-hat profile. The plot displays the results obtained with different research methods: FEM (Abaqus), analytical-numerical (A-N) method, as well as experimental outcomes.

6. Conclusions

The paper presents studies on critical, as well as post-critical state of thin-walled composite columns subjected to axial compression. The performed analysis prooved qualitative and quantitative agreement of the research results made with different methods. Analysis of the curves shown in Fig. 8 reveals good agreement of computational results with those of experiments, both in subcritical and post-critical range. This confirms the adequacy of the worked out numerical models. The accepted methods of critical load determination, based on experiments (Fig. 6) allowed to estimate the range of experimental value of the critical force $P_{CR} = 6184 \div 7102$ N with maximal difference among the used methods equal to 13 %. The critical load value determined with computational methods: FEM (the Abaqus, the Ansys) and analytical-numerical (A-N) method were located in the middle of the obtained range – Table 2. In the post-critical range almost identical force-displacement equilibrium paths in case of FEM and experiment were obtained. Only the A-N method gave slightly different results (ca 10 %), but the nature of the curve was the same.

The obtained results give wide possibilities of observation and analysis of deformation states, as well as effort levels up to the failure. This enabled the identification of damage-prone zones in the laminate and the determination of the failure load level in relation to the critical load. The analysis of the post-cricital equilibrium path allows to assess the structure's stiffness after the loss of stability in the context of applied ply sequence. Thus, the obtained results delivered a lot of important information useful in the process of forming and optimization of the composite texture in the context of its maintenance loading conditions.

Method	P_{CR} [N]
FEM/Ab	6655.50
A-N	6629.10
K1	6503.85
K2	6184.84
K3	6619.88
K4	7102.08
K5	6918.98
K6	6227.82

Fig.6. *Comparison of critical forces' values PCR [N] determined with different methods*

Fig.7. *Post-critical deformation: a) Tsai-Wu – Abaqus; b) Tsai-Wu – Ansys*

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