A RESEARCH ON NONLINEAR STABILITY AND FAILURE OF THIN-WALLED COMPOSITE COLUMNS WITH OPEN CROSS-SECTION

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Keywords: composite structures, thin-walled columns, finite element analysis, damage of composite material.

Abstract

In the paper a numerical and experimental analysis of post-critical state of a thin-walled channel-section simply supported beam under axial compression. The beam was made of carbon-epoxy symmetrical composite prepared with a pre-preg technology using 8 layers of unidirectional band. 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 post-buckling and limit states, as well. Experimental studies were conducted to confirm results obtained from numerical calculations, which was performed using the ABAQUS software.

1. Introduction

Polymeric composites – the laminates are currently one of the most developing materials group applied in contemporary thin-walled structures. This yields from an advantageous set of physical-chemical and mechanical properties, particularly high strength in relation to low mass density of the composite material [1,2]. From a wide group of laminates mainly those having epoxy matrix reinforced with glass, carbon or kevlar fibres find applications. One of the most advanced processes for manufacturing composite materials is the autoclave method [3,4]. Composite elements manufactured by the autoclave method meet all the criteria for primary structures [3]. Composite materials manufactured by the autoclave method exhibit favorable characteristics that cannot be obtained with other manufacturing processes. These characteristics include, among others, high mechanical properties, high quality of both composites and surfaces, repeatability and complete control of the manufacturing process (the process is automated), complete control of the detail in the hardening process (temperature, pressure) and minimal porosity (<1%). These features determine the application of polymer composites as load-bearing elements in thin aerospace or automotive structures, subjected to complex load conditions. An important issue in the design of thin-walled composite structures is a problem of loss of structure stability, specifically search for solutions to increase the critical load and stiffness in the nearly-critical stages, with minimal increase in weight of the entire system. One of the protecting methods of thin-walled structure against loss of stability is the use of profiles with a complex cross-sectional shapes as well as various reinforcements.

The paper deals with experimental testing of thin-walled composite columns under compression monitored with an Acoustic Emission system. The columns were made of eight-layer carbon-epoxy laminate with channel cross-section. The laminate structures were formed with the autoclaving technique. Strength properties of the composites were determined experimentally in accordance with the appropriate ISO standards. The structures were compressed axially through articulated support up to the moment of failure. The obtained research results allow to verify the results given by FE models, using the ABAQUS software. 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. Object of research

The object of the research was the thin-walled beam made of carbon-epoxy composite formed into a channel cross-section with the following dimensions: 80x40x1.048 mm (the cross-section) and L=300 mm (the length). The composite had epoxy matrix having the following characteristics: mass density: 1.24 g/cm3; curing temperature: 128^{o}C; tensile strength: 64 MPa; Poisson ratio: 0.4; Young modulus in tension: 5.1 GPa. For reinforcement the AS7J12K carbon fibres were used with mass density: 2.5 g/cm3; tensile strength: 4830 MPa; Poisson ratio: 0.269; Young modulus in tension: 241 GPa. Nominal volume fraction of the reinforcement was approximately equals 60%. The composites were produced with autoclaving technique in the Department of Material Engineering at the Lublin University of Technology. The laminate texture was composed of 8 plies of equal thickness of 0.131 mm sequenced symmetrically $[0/90/0/90]_s$. The physical model of thin-walled column, as well as the composite layout are presented in Figure 1.

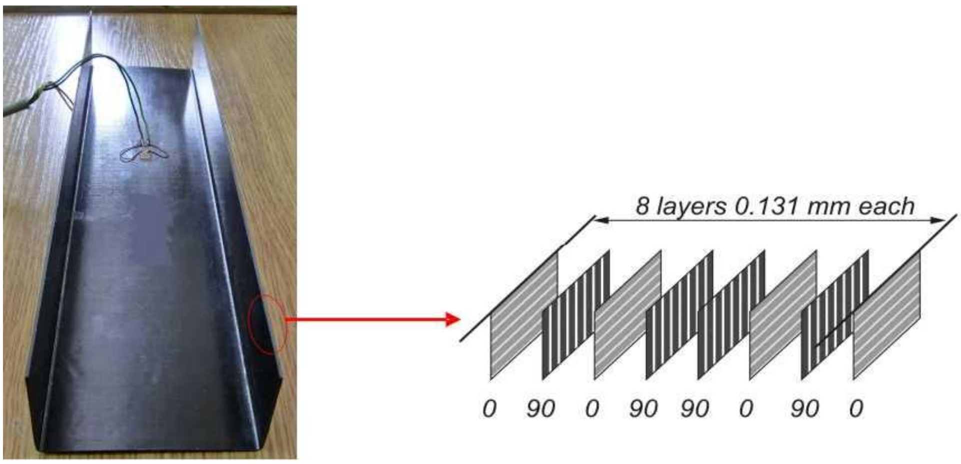

Figure 1. Physical model of the analysed column and plies layup.

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 of material heating of 135 ^{o}C was kept for 2 hours, what enabled finishing of the pre-preg 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.

3. Experimental investigation

The experimental tests were conducted on axially compressed thin-walled composite columns with top-hat cross-section. Stand tests were done with the Zwick Z100/SN3A 1-accuracy class universal testing machine of the 100 kN load range. Any imperfections of the columns'ends, able to cause unwanted boundary effects, were compensated by specially prepared soft-plastic pads. On the specimen's internal and external surfaces in the vicinity of the biggest web's deflection area Vishay's electrical strain gauges were sticked along the loading direction. The two CEA-06-125UW-350 series gauges had a constant k=2.135±0.5 % and electrical resistance of 350 Ω±0.3 % (Figure 1). In addition the deflections were measured with the optoNCDT 1605 laser dilatometer. All the measurement elements were plugged to the MGCplus system (Hottinger). During the tests the indications of all sensors were registered with a frequency of 1 Hz. All tests were conducted in standard conditions, at 23 ^{o}C with constant velocity of the cross-bar equal to 2 mm/min. During the whole compression process the Vallen's "AMSY-5" Acoustic Emission (AE) acquisition system was collecting the elastic wave propagation data. These signals contained information on defect initiation and propagation within the composite columns, even though the damage was not visible nor could be heard. The piezoelectric sensor registered the motion of the specimen's surface as a result of damage processes. The signal was next multiplied and registered by the "AMSY-5" AE equipment. Thanks to this, the load – deflection curve could be enriched with additional data, such as the number of AE counts. The test stand in the course of measurements is shown in Figure 2.

Figure 2. The test stand with a composite sample.

4. Numerical analysis

The finite element method (software package ABAQUS) was employed to analyse the post-buckling behaviour of the thin-walled composite columns. The scope of the calculations covered critical state analysis – linear calculations with the *eigenbuckling analysis* option, enabling determination of critical loads with corresponding buckling modes. The non-linear static analysis was employed to analyse the post-critical behaviour of the structures. In numerical analysis the initial geometrical imperfections were assumed to exist. The amplitude of imperfection equaled 0.1 of the profile's wall thickness; the shape of imperfection corresponded to the first buckling mode. The post-critical analysis, taking into account a geometrically non-linear problem, was performed in ABAQUS with the incremental-iterative Newton-Raphson method [5,6,7]. 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 [8]. 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). In the process of structure discretization the 8-node shell elements (type S8R) with quadratic shape function and reduced integration having 6 degrees of freedom in each node were used [9]. A numerical model with of the channel section composite columns is presented in Figure 3. The boundary conditions were defined as reproducing of articulated support of both ends of profile.

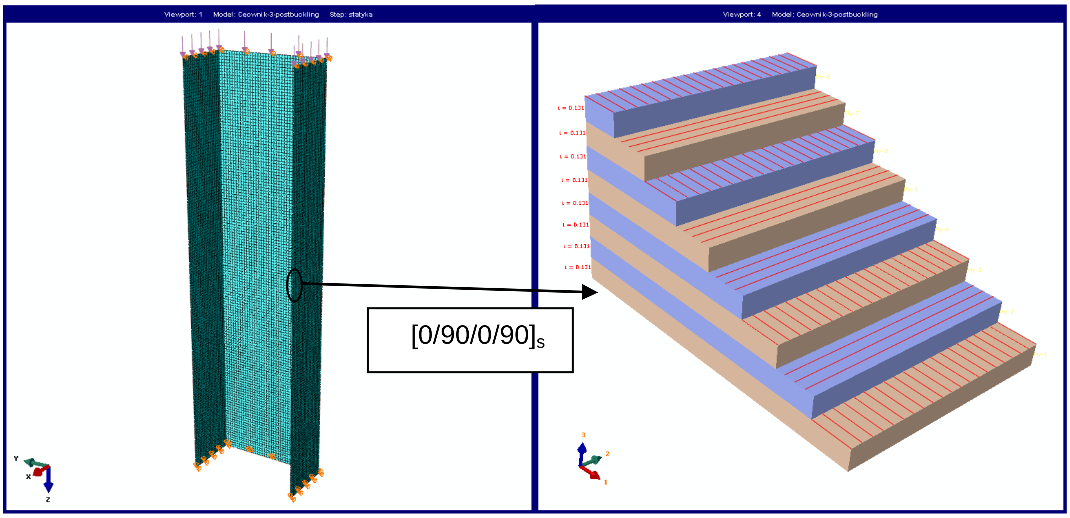

Figure 3. Discrete model of composite column and plies layup.

For the used composite material, the following mechanical characteristics were accepted in calculations: Young's modulus: $E_1 = 130.71$ GPa, $E_2 = 6.36$ GPa, Kirchhoff's modulus: $G_{12} = 4.18$ GPa, Poisson's ratio: $\nu_{12} = 0.32$. An orthotropic material model was defined. A two-dimensional theory was used to analyse the composite laminates for stresses (i.e. the classical laminated plate theory (CLPT)) [10]. The ply sequences were defined using a *Layup-Ply* technique.

5. Results and discussion

The tests allowed to examine forms of deformation and to measure the required test parameters until a moment of failure. During loading, the forms of structure stability loss were more and more advanced and they corresponded to the lowest buckling mode. The loss of load-carrying capacity of the examined channel section columns occurred once the limit load was reached, without any previous signs of local material damage. The damage process was rapid, from short material cracking to a complete loss of load-carrying capacity of the column. Figure 4 shows the recorded image of the structure at advanced post-critical state and moment of failure. Based on the results obtained with the testing machine, post-critical equilibrium paths P-ε (load-strain) were determined, which were then compared with the results obtained by the acoustic emission method. The results with regard to structural load made it possible to compare the post-critical equilibrium path and the recorded acoustic emission signals - real-time energy (Figure 5).

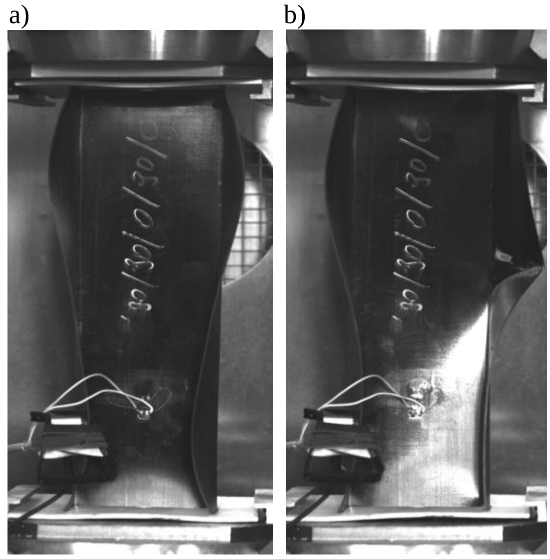

Figure 4. Experimental tests of channel section columns: a) post-critical state, b) failure moment.

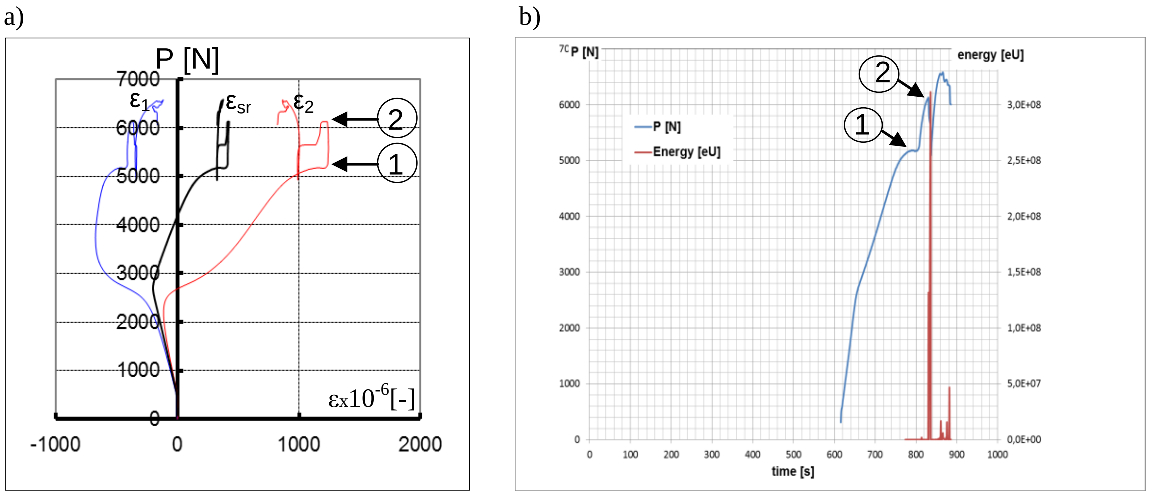

Figure 5. Experimental results: a) testing machine *P*-*ε*, b) acoustic emission signal energy.

Figure 5a shows strain curves for the channel section profile web in the place of maximum deflections, where resistance extensometers were fixed on both ends. An analysis of the post-critical equilibrium path *P*-*ε* demonstrates that the path has a local break-point denoted by 1 and 2. As can be seen from the curves representing the acoustic emission results (Figure 5b), this points are also the places where an increase in acoustic emission signal was observed. The signals were assumed to be the first signs of failure in certain areas of the first layer of the composite material. The value of load corresponding to the observed post-critical equilibrium path break-point number 1 was set to be the value of failure initiation load $P_{f(1)\text{-}EXP}$ for the first composite layer. As seen from the charts, the load value does not put an end to the column's load-carrying capacity, which is proved by the subsequent increase in the structure's load until the limit load value $P_{f\text{-}EXP}$, when the structure fails.

The numerical simulations for the evaluation of structural damage were conducted using the Tsai-Wu failure criterion. The value of failure initiation load for the first layer was set to be the value of load $P_{f(1)\text{-}NUM}$, equal to attaining failure parameter *1* in the first layer of the composite material. The simulations were being run until the failure criterion was met for all layers, attaining a load value equal to the failure load $P_{f\text{-}NUM}$. The load values obtained are compared in Table 1.

$P_{f(1)\text{-NUM}}$	$P_{f(1)\text{-EXP}}$	$P_{f\text{-NUM}}$	$P_{f\text{-EXP}}$
5500 [N]	5174 [N]	6750 [N]	6581 [N]

Table 1. Comparison of failure load values.

The results demonstrate that there is a high quantitative agreement between the values of failure initiation load for the first layer and those of limit load, as the maximum differences do not exceed 6%. This confirms the suitability of the designed numerical models that simulate real conditions of the experiment.

6. Conclusion

The study presented the research on post-critical and limit states of thin-walled channel section columns made of composite materials subjected to compression. The obtained results allow to describe the problem of non-linear stability and structural damage with the use of interdisciplinary research methods. Experimental tests performed on real structures are of particular significance here, because they allow that measurements be made by independent methods. In effect, the structure being examined can be described for entire load range, including a moment of failure. The conducted tests proved the suitability of applying the Acoustic Emission Method to analyze the experimental results. The results obtained thereby helped interpret the phenomena that occurred in loading and allowed to identify failure moment of the first layer of the composite material.

The experimental results allowed the development of adequate FEM numerical models that simulate real conditions of the experiment. This is proved by the obtained high agreement between the first layer's failure initiation load and limit load obtained in the experiments.

ACKNOWLEDGEMENTS: An article written under the ministerial research project no. N N507 241440 financed by the Polish National Science Centre.

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