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Failure analysis of thin-walled composite channel section columns

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ABSTRACT

The paper presents the numerical and experimental results of investigations into nonlinear stability and limit states of axially-compressed thin-walled composite columns with channel section. The primary aim of the research was to examine the process of composite failure using the finite element method. The phenomenon of composite failure was described by the Tsai–Wu failure criterion using the commercial software suite ABAQUS®. The numerical results were then compared with the results of experiments wherein physical models of channel section structures were subjected to a full range of load conditions until their failure. This approach provided instant validation of designed FEM numerical models for describing limit states of the tested structures.

1. Introduction

The results of research on thin-walled structures reveal that these structures can carry loads even following loss of stability, in the so-called post-buckling elastic state [1]. This means that the loss of stability of a thin-walled structure does not lead to its sudden failure, as the structure retains a great deal of elasticity. This is particularly true of parts made of composite materials which have a greater elasticity margin than elements made of standard engineering materials (e.g. metals) [2–5]. Given their good mechanical and operational properties, composite materials are more and more often used in contemporary structure design, e.g. in recent aircraft designs (Boeing 787 Dreamliner, Airbus A 350) or automotive designs (Formula 1 bolides). Consequently, the scope of research on composite materials has been extended. Nonetheless, the range of studies on composite materials reported in the literature is still far from being exhaustive. Specifically, this pertains to composite failure which is a very complex process and its investigation requires the use of interdisciplinary research methods. The failure criteria for laminates reported in the literature [6–8] are only a preliminary attempt at describing the mechanism of composite failure, and there exists no unambiguous method for verification of applied composite failure criteria based on the results of experiments performed on real structures.

The nature of thin-walled composite structures requires in-depth numerical and experimental investigations conducted by an interdisciplinary research team. This is particularly true of deep pos-buckling states and structure failure, a process which is sudden and very difficult to predict. These phenomena can be fully described if experimental tests are conducted on real structures to provide information on structure operation under a full range of load conditions. Unfortunately, however, although there are numerous publications on isotropic materials and their post-buckling behaviour [9–14], there are insufficient studies on composite materials with orthotropic properties. Even though one can find a number of publications on post-buckling behaviour of fibrous composites (laminates), e.g. [15–27], these studies predominantly offer theoretical considerations of the problem.

This paper presents the numerical and experimental results of investigations into nonlinear stability and limit states of axially-compressed thin-walled composite columns with channel section. The primary aim of the research was to examine the process of composite failure using the finite element method. The phenomenon of composite failure was described by the Tsai–Wu failure criterion using the commercial software suite ABAQUS®. The numerical results were then compared with the results of experiments wherein physical models of channel section structures were subjected to a full range of load conditions until their failure. This approach provided instant validation of designed FEM numerical models for describing boundary states of the tested structures.

2. Channel section columns

The study involved performing a series of experiments on channel section columns made of carbon/epoxy composite by the autoclave technique which ensures high strength properties, low

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porosity, high surface quality and repeatability of specimen dimensions. All these factors are significant, as most thin-walled structures are sensitive even to the slightest geometrical imperfections. To ensure high quality of the profiles, the condition of the composite structures was monitored by nondestructive testing (NDT) methods, which meant that only specimens with no internal defects in the form of delamination and porosity were admitted to testing. Moreover, in order to eliminate the effect of boundary conditions on the general state of strain, the edges of profile ends were cut to ensure the highest possible flatness of the section.

The channel section columns used in the tests had a symmetric plies arrangement relative to the laminate mid-plane. The column walls had 8 composite plies, each with 0.131 mm thickness in hardened state, oriented at $[45/-45/90/0]_s$, where the 0^0 orientation overlapped with the axis of the column. The overall wall thickness of the channel section profile was 1.048 mm. The investigated short columns had an overall length of 300 mm and the following cross sectional dimensions: an 80 mm wide column plate and a 40 mm long arm (Fig. 1).

The produced composite material was subjected to strength tests in order to determine its basic mechanical properties in the principal orthotropic directions, i.e.: tensile modulus E_T, Poisson's ratio in the ply plane ν_{12}, and shear modulus G. The variables would help define the orthotropic material in a two-dimensional state of stress by nonlinear FEM numerical computations. In addition, the failure tests involved determining the following boundary variables of the composite material: tensile strength F_{TU}, and compression strength F_{CU} in the directions 1 and 2 as well as shear strength in the ply plane F_{SU}. All tests were performed in compliance with the appropriate ISO standards for composite materials [28]. The boundary values of the composite are given in Table 1 [21].

3. Research procedure

The investigation of deep post-buckling and limit states of thin-walled channel section columns was performed using several independent research methods to enable describing the structure's behaviour under a full range of load conditions. The application of interdisciplinary analysis methods enabled thus a more thorough description and evaluation of the nature of failure in the tested composite structures. Compared to standard metal structures, composite structures require a much more complex and versatile approach to results analysis because their load capacity loss is usually complex and sudden, often in the form of brittle cracking.

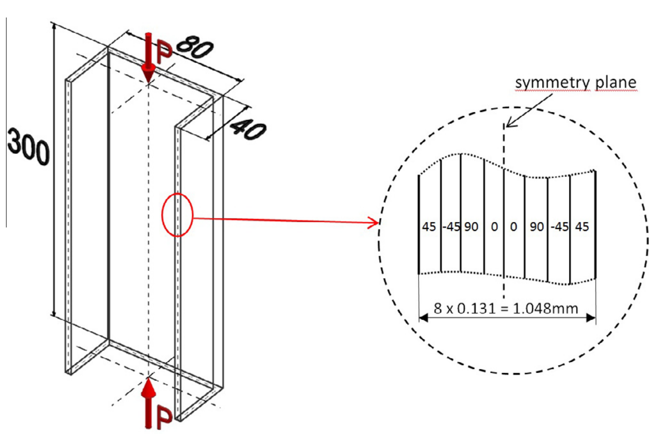

Fig. 1. Schematic design of the tested channel section columns and their nominal geometrical dimensions .

The problem of composite failure was primarily investigated numerically by the finite element method. Specifically, we performed a non-linear numerical analysis of the models of structures with initiated post-buckling deformation corresponding to the lowest local buckling mode. The amplitude of the introduced geometrical imperfections was 0.1 of the wall thickness of the tested column. We used the commercial ABAQUS® software as a numerical tool, and the problem of geometric non-linearity was solved by the Newton–Raphson method [29]. The composite material's failure was estimated by the Tsai–Wu criterion [6,8] based on the material's boundary values determined in the experiments. The moment of failure initiation in the composite material was taken as the value of load $P_{f(ini)\text{-}FEM}$ when the first-ply failure criterion was met, while the value of failure load $P_{f\text{-}FEM}$ was defined as a load when the Tsai–Wu criterion was met in all plies.

The discretization of thin-walled composite columns was performed using SHELL multi-ply elements which enable the modelling of composite structures by independent definitions of plies orientation and their properties in element structure. The applied type of element was defined by a model of orthotropic material in a two-dimensional state of stress, where the main orthotropic directions overlapped with the directions of fibre orientation in the plies. The applied *S8R* is an eight-node reduced integration shell element with six degrees of freedom at node, described by quadratic shape function [29]. The discrete model was described by a FEM mesh, where every element had a 2 mm edge. The applied discretization method produced a model consisting of 12,000 elements in total.

The boundary conditions of the numerical model were defined for the sections of the column ends via applying zero-displacements to the nodes located at the lower and upper sections of the column, perpendicular to the plane of each wall (displacements: $u_x = 0$ and $u_y = 0$). In addition to this, we blocked vertical displacement of the nodes of the column's lower end ($u_z = 0$). In the experiments, the upper head can move on a ball-and-socket joint in the plane of lower rigidity prior to the moment of load-capacity loss. Consequently, the boundary conditions of the column's upper section end were set to map this behaviour of the structure in numerical modelling. Fig. 2a shows a schematic view of the boundary conditions applied in numerical modelling.

The developed numerical models were directly verified in this respect by the experimental results. The tests involved measuring the composite structure's failure by a high-speed camera, while strains were measured by strain gauges and deflections by laser sensors. We measured the load acting on the structure, column wall deflection and strains on the opposite sides of the web of channel section columns in the spot of the highest web deflections. The test variables were measured with a frequency of 1 Hz using a measurement system manufactured by Hottinger. The results enabled determination of post-buckling equilibrium paths which describe the structure's behaviour in deep post-buckling and limit states. The test stands of composite column compression were conducted with a ZWICK-manufactured testing machine, at a constant cross-beam speed set to 1 mm/min.

The composite material's structure was monitored by the acoustic emission method (AEM). Together with the post-buckling equilibrium paths, the AEM-measured signal enabled identification of load-related phenomena occurring in the composite material during the loading process. Due to suitable synchronization, the loads recorded by the testing machine and AEM signals were measured with an accuracy of up to 5%. The AE tests were performed using the AMSY-5 set manufactured by Vallen Systeme Gmbh, equipped with a special piezoelectric sensor for composite materials [30].