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Local buckling, post-buckling and collapse of thin-walled channel section composite columns subjected to quasi-static compression

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ABSTRACT

A post-buckling behaviour analysis and an ultimate load estimation of thin-walled composite channel columns under a constant rate of end shortening are presented. The columns with C-sections were made of a carbon-epoxy composite – a laminate consisting of eight symmetrically oriented plies. Four different layer arrangements were taken into consideration. The main objective of the study was to investigate the behaviour of the considered columns under quasi-static compression to achieve their collapse. The experimental tests were performed under standard conditions on a universal ZWICK Z100 testing machine. To collect the experimental data, strain gauges for strain measurements, a laser gauge for deflections and acoustic emission testing equipment were employed. A numerical analysis was conducted with the Abaqus commercial FEM software package. The experimental results were then used to develop FEM models that allowed one to describe the post-buckling behaviour and to estimate the ultimate load-carrying capacity of the composite channels under investigation.

1. Introduction

Nowadays strength and rigidity of load-carrying structures is of great importance in such structural members as thin-walled composite beams and columns. For example, beams and columns are widely used in production of modern means of transport [1], as they ensure both higher load-carrying capacity of the whole assembly and lower energy consumption because of a reduced mass. It is, therefore, not surprising that there is a growing demand for composite structural members on the world market.

Thin-walled structures are used to reinforce casings or fuselages, thus their rigidity and strength are a crucial component of the entire structure strength. Composite channel columns are the most widely applied profiles that often work under complex loads. Due to the fact that they are thin-walled structures, profiles with C-sections are prone to a stability loss. As the practice of thin-walled structures maintenance demonstrates, they can often carry loads in the post-buckling state provided that the respective equilibrium paths are stable [2,3]. This means that designers and researchers should have extensive knowledge on the strength and rigidity of these structures in a full load range until their collapse. A description of the post-buckling behaviour of thin-walled structures is, however, a complex problem. Particularly, when it applies to hi-tech composite materials such as carbon-epoxy laminates. Owing to their high specific strength, composite materials supplant traditional isotropic structural materials, e.g., metals and metal alloys. Although numerous works are devoted to the post-buckling behaviour of isotropic materials [3–8], there is a lack of publications providing the experimental results for thin-walled laminate structures produced with high-tech manufacturing techniques that could be used to validate the numerical finite element method (FEM) models. The majority of published studies on the post-buckling behaviour of structures made of fibrous composites (laminates), for instance [9–21], offer only theoretical discussion. In the world literature, there are some papers presenting the experimental investigations of fibrous-composite members [20,22,23], but they are mainly pultruded fibre-reinforced plastics (FRP) rather than the laminated columns or beams.

Rasmussen and Hancock [24] compared the analytical and experimental values of ultimate loads of thin-walled channel section columns prone to local buckling, considering two different cases of boundary conditions. This enabled precise determination of the columns' strength with no necessity to introduce the

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beam-column design approach, as well as to account for various effects of local buckling. Lee et al. [25] studied buckling of the thin-walled symmetric angle-ply composite columns with open cross-sections and stiffeners, subjected to compression. The authors solved the eigenvalue problem and predicted the buckling load using the FEM. They concentrated on a role of the stiffener and the layup on the profile's load-bearing capacity and mode shapes. Kolakowski and Teter [26] analyzed static case of coupled buckling of thin-walled functionally graded material (FGM) columns with two different closed cross-sections. The columns were compressed axially through articulated joints at ends. The authors solved the problem of non-linear buckling with variational method for the Koiter's theory. The global–local buckling interaction was analysed in static equilibrium regime using the Green's strain tensor and the second Piola–Kirchhoff's stress tensor within a framework of the classical laminate plate theory (CLPT). The study allowed for the effect of the imperfection sign, as well as nonsymmetrical stable post-buckling path on the FGM profiles' strength. Ragheb [27] developed an analytical model for the local buckling of pultruded fibre-reinforced composite profiles compressed eccentrically. The Levy's solution was employed for the profiles, assumed to be composed of plates and the parametric stability analysis was performed. The method turned out to be loading-case sensitive. Salem et al. [28] studied a post-local buckling of I-section columns with different web or flange width to thickness ratios. The columns were compressed both through the section's center of gravity and eccentrically, axially and biaxially. The simultaneous FEM study of the models with imperfections was performed. The authors concluded, that the post-local buckling load carrying capacity was dependent on the loading case. Moreover, the increased load eccentricity led to a decrease in the columns strength.

Knowing the nature of thin-walled composite structures, it is necessary to conduct thorough theoretical and experimental investigations in an interdisciplinary research team. This is particularly important when composite materials with regard to their post-buckling behaviour are investigated and when the collapse load occurs suddenly and is hard to be predicted. The set of failure criteria for laminates offered in [29–31] can only be used to perform a preliminary analysis of failure of these materials. In order to obtain a full picture of the phenomena occurring at collapse, it is necessary to perform experimental tests on real structures, as only such tests will provide sufficient information on the behaviour of composite structures in a full load range.

The results of a non-linear buckling analysis of short thin-walled channel composite columns subjected to a constant rate of shortening are presented in the current article. A recent paper in Thin-Walled Structures [32] depicted behaviour of thin-walled columns of top-hat cross-section within the full load range – till collapse of the structure. On contrary, the current article covers the non-linear stability and failure of the compressed channel-section profiles. There is a substantial difference between the two types of profiles's behaviour in the post-critical range, as well as in the very mechanism of failure, which basically yields from their different stiffness. The previously studied top-hat profiles were equipped with an additional flange compared to the channel-section ones considered here and as such the former structures exhibited stable behaviour practically till the very moment of failure. The latter profiles showed different failure mechanism, i.e. first ply failure phenomenon took place at relatively low loads. Nevertheless, the structure kept its stiffness and the deterioration was gradual till a complete loss of the channel-section column's load-carrying capacity. Such a behaviour was observed both during the experiments and in numerical simulations exploiting the Tsai–Wu tensor failure criterion. High level of compatibility of the experimental and computational results was achieved both for the first ply failure load and for the limit load. The previous paper emphasizes the fundamental differences in post-critical behaviour of the composite structures, varying only with the additional flange, which changed the channel-section profile to the top-hat one.

The main objective of the present study was to investigate the behaviour of these structural members subject to a whole range of loading. The experimental, as well as numerical tests were conducted. The latter used the Abaqus commercial FEM software package [35]. The instantaneous failure phenomena of the tested composite material were monitored with the acoustic emission (AE) equipment. The experimental results were then used to develop FEM models that enabled a description of the post-buckling behaviour and an estimation of the ultimate load-carrying capacity for the composite channels subject to testing.

2. Material and specimens

In the tests, short thin-walled channel columns made of a carbon-epoxy composite were used. The autoclaving technological process for preparing specimens ensured both high production repeatability and very good strength properties of the structures thus manufactured. All columns were inspected as regards the production accuracy. Only the columns free from any defects were used in further tests. Moreover, the tested columns were cut to a required length to obtain both smooth edges and ideally flat sections of the column ends. The tested columns were made of a laminate consisting of 8 plies that were symmetrically oriented. The specimens with four different configurations of plies were marked as: C1 – $[0/-45/45/90]_s$ ply configuration, C2 – $[90/-45/45/0]_s$ ply configuration, C3 – $[(0/90)_2]_s$ ply configuration, and C4 – $[45/-45/90/0]_s$ ply configuration, respectively. After hardening of the composite, the plies had the same thickness of 0.131 mm. The overall thickness of the channel walls was 1.048 mm. The

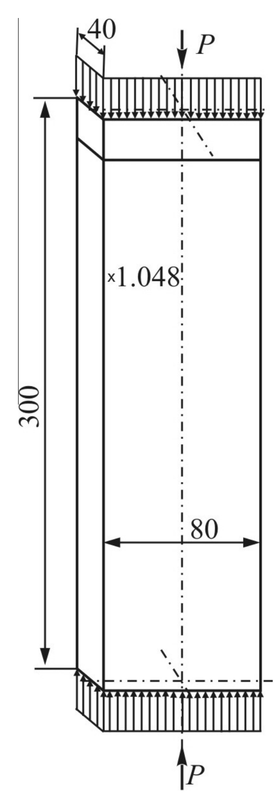

Fig. 1. Channel columns and their nominal geometrical dimensions.