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Local buckling and post-buckling of composite channel-section beams – Numerical and experimental investigations

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ABSTRACT

Local buckling and post-buckling of thin-walled composite channel-section beams under pure bending are described. Profiles were subject to bending in the plane of the lowest second moment of area. Thin-walled beams were made of an eight-layer GFRP composite with six different arrangements of plies. An asymptotic analytical–numerical method was used in the investigations, whereas the ANSYS software based on the finite element method and the experimental test results were employed in the numerical simulations. The analytical–numerical method is based on asymptotic Koiter's theory for conservative systems, modified by Byskov and Hutchinson. Two different finite element models were prepared: the first one with boundary conditions closer to the analytical–numerical method model and the second one with boundary conditions close to those present on the test stand. A four-point bending test was used in the experimental test. The results obtained in the above-mentioned numerical methods are compared to these obtained experimentally. The advantages and disadvantages of the applied methods and models are presented and discussed.

1. Introduction

Thin-walled structures belong to a group of lightweight and durable materials. Generally, it can be said that a range of operating loads of such structures is not determined by the yield limit of the material used but it corresponds to buckling load. In the world literature, there are numerous papers and books devoted to buckling and post-buckling of thin-walled structures made of isotropic and orthotropic materials subject to static and dynamic loads. The following scientists and their papers can be mentioned here: Euler and Bernoulli [5], Volmir [46] and Timoshenko [43] as precursors; Davis and Hancock [11], Graves-Smith [16] or Mulligan and Pekoz [39], whose papers deal with local buckling; Koiter [20–22], Byskov [9], Budiansky [7,8], Hutchinson [18], who developed the theory of post-buckling behaviour in the case of static and dynamic loads. A detailed literature survey on the buckling and post-buckling behaviour of isotropic and orthotropic thin-walled structures can be found, for example, in Kubiak [33] or Kolakowski and Kowal-Michalska [25].

As mentioned above, buckling and post-buckling of thin-walled structures made of isotropic materials are widely described in the world literature. On the contrary, thin-walled structures made of composite materials still need further investigations – there are not many references devoted to them. Papers dealing with buckling and post-buckling of thin-walled laminate structures started to appear in the 1990s. Thanks to new materials and technologies it is possible to optimize properties of structures not only by designing their geometry, but also via tailoring material composition, microstructure and texture. Beams made of FRP with a pultrusion method are generally used in structures for civil engineering. The deflection and pre-buckling behaviour of such structures fall in the area of interest of Ascione, Feo and Mancusi [1,2,15,35,36]. They developed their own method based on a 1D beam model for FEM calculations and compared the obtained results on the basis of the Vlasov theory or the Timoshenko beam theory. In the proposed models, axial, flexural, shear, torsional and warping displacements [36], as well as an influence of the web–flange junction stiffness [1] are considered. Contrary to the pultrusion method, FRP beams manufacturing is an autoclaving process consisting in curing and bonding of prepreg plies. Laminates manufactured with

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autoclaving technique have been used, for example, in aerospace structures [38], aircraft wing girders [19,41], blades of helicopters [14] or girders of wind turbine blades [4]. In the above-mentioned papers, it is indicated that layer arrangements exert an influence on the laminate behaviour. There are some papers showing the results of experimental investigations on thin-walled structures made of composite materials, for instance: [6,10,12,13,34,45,47]. Most of them present a comparison of the results of experimental investigations to the results obtained in FEM simulations. To understand better the phenomena appearing during buckling and post-buckling of thin-walled structures, analytical and analytical–numerical methods should be developed. In Refs. [3,30], analytical–numerical methods employed for buckling and post-buckling analysis of thin-walled composites are presented. However, in the authors' opinion, there are not enough publications comparing the results of experimental investigations to the numerical simulations using different methods of modelling (FEM and own software based on analytical methods). Therefore, the authors of the present paper have decided to present a FE model and an analytical–numerical model prepared on the basis of Koiter's asymptotic theory [20–22]. A comparison of the results obtained in the numerical simulations to the results obtained in the experimental investigations has allowed them to validate the proposed numerical models. The validation of the FE model and the analytical–numerical model has been carried out for beams of different layer arrangements.

2. Problem statement

Thin-walled composite channel-section beams subject to pure bending were considered. Buckling and post-buckling of such beams were analyzed. For many years, analytical–numerical and FE models were employed to calculate the bifurcation buckling load and to determine the post-buckling equilibrium path of the profile under consideration. Those investigations were mainly aimed at:

- validation of the analytical–numerical and FE models with the results of experimental tests;
- finding advantages and disadvantages of the simulation method employed;
- checking an influence of the layer arrangement on buckling load and post-buckling behaviour.

The thin-walled profiles (Fig. 1) under consideration were made of a glass-epoxy unidirectional prepreg tape (prepregs made by Gurit, the codename SE70/EGL/300/400/35%/PoPa) using autoclaving technique [6,9]. The nominal volume fraction of reinforcing fibres in the composite was about 60%. The thickness of each ply was approx. 0.25 mm. The considered beam was 275 mm long and the dimensions of the channel cross-section are presented in Fig. 2.

Fig. 1. Channel-section composite profiles under consideration.

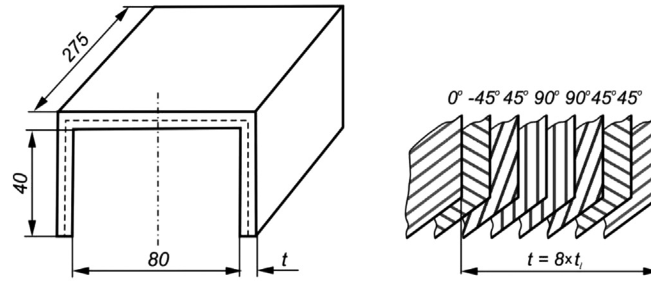

Fig. 2. Dimensions of the investigated profile with a sample layup.

The material properties of the beams were determined in tensile and compression tests. Samples were taken from representative areas of the composite plates. Sets of the samples were prepared in 0, 90 and ±45 layouts for tensile, compression and shear strength tests based upon applicable standards. The following material properties: Young's modulus in two orthogonal directions E_1 and E_2 (index "1" denotes the fibre direction and index "2" – transverse to the fibre direction), Poisson's ratio ν_{12}, and the shear modulus G_{12} were determined. These material properties are presented in Table 1 [6].

To check an impact of layer arrangements on buckling load and post-buckling behaviour of the thin-walled beam under consideration, six different layups were investigated. It was assumed that all layups had their general axis of orthotropy parallel to the wall edges (0° – fibres along the longitudinal direction or 90° – fibres in the transverse direction) or inclined to the wall edges by 45°. The beam walls had the following symmetrical, quasi-isotropic layer arrangements:

- C0: $[45/-45/90/0]_S$,
- C1: $[0/-45/45/90]_S$,
- C2: $[90/-45/45/0]_S$,
- C3: $[90/0/90/0]_S$,
- C4: $[0/90/0/90]_S$,
- C5: $[45/-45/45/-45]_S$.

3. Experimental tests

The tests were conducted on an Instron universal testing machine modernized by Zwick-Roel and equipped with specially designed grips. The composite beams were subjected to pure bending. This type of load was applied in a four-point bending test. A scheme of the performed bending test with the dimensions describing the span of support and the span of load is presented in Fig. 3.

Special grips (depicted in Fig. 3) were designed (Fig. 4a) and manufactured (Fig. 4b) to avoid stress concentration in the place where the beam was supported and loaded. The grips were used to provide the load corresponding to pure bending.

The tests were performed at a constant velocity of the cross-bar equal to 1.5 mm/min. The values of the loading force applied to the system and the displacement in the points where the load was applied were obtained directly from the machine sensors. To

Table 1
Material properties of the laminate in the columns under consideration [6].

E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12} [–]
38.5	8.1	2.0	0.27