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Collapse of channel section composite profile subjected to bending. Part I: Numerical investigations

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ABSTRACT

The paper deals with four-point bending tests of thin-walled channel section beams, made of eight-layer GFRP laminate. In the performed tests two scenarios were investigated: beams were bent in the plane with lowest second moment of area and beams were subjected to bending in the plane passing through the geometrical centre of the flanges of channel section profile and parallel to the plane with the highest second moment of area. Six arrangements of layers were analysed: $[0/-45/45/90]_S$, $[90/-45/45/0]_S$, $[90/0/90/0]_S$, $[0/90/0/90]_S$, $[45/-45/45/-45]_S$, $[45/-45/90/0]_S$. The experimental research was conducted with the use of the ultimate testing machine, additionally designed test stand and the digital image correlation system Aramis®. Numerical analyses have been performed in the Ansys® software, based on the finite element method. In geometrically nonlinear analysis two algorithms, indicating failure mechanisms, were applied: progressive failure analysis with material property degradation method and anisotropic Hill potential theory with assumption of perfect plasticity.

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1. Introduction

The prediction of the maximum load of composite structure is very desirable feature. The composite materials are still expansive group of materials nevertheless with regard to their lightness and high strength replace the traditional materials as steel or aluminium. As far as composite materials are concerned, at present those materials are mostly manufactured for thin-walled structures. Taking a look at the literature, there are many papers concerning the theoretical and experimental studies of different thin-walled structures built of composite materials, among others. Teter, Dębski and Samborski [1] analysed buckling and post-buckling state of short thin-walled lipped-channel columns under compressive load. Kolakowski and Teter [2] dealt with the interactive buckling of thin-walled columns with the top hat cross-section and the lip channel cross-section made of functionally graded materials. Dębski and Jonak [3] investigated the nonlinear stability and limit states of axially-compressed thin-walled composite columns with channel section. Daniel [4] presented the Northwestern theory to predict lamina yielding and failure on the basis of multi-axial states of stress and strain rate effect. Seyedmohammad and Rani [5] analysed the effects of scratch geometry on the delamination of laminated composite under tension loading experimentally and numerically. Kubiak and Kaczmarek [6] analysed the thin-walled channel section beams built of composite laminates under pure bending. Urbaniak, Teter and Kubiak [7] determined the critical load, post-buckling state and failure load of composite channel-section columns under axial compression force. Kolakowski and Mania [8] considered the semi-analytical method of the second order approximation to analyze the local post-buckling of thin-walled closed cross-section composite structures. Kolakowski [9] studied the interaction of global buckling modes of open and closed cross-section laminate composite columns subjected to static and dynamic compression load. Silva et al. [10] investigated the buckling of open composite columns on taking into account non-linear generalized beam theory. The results of numerical and experimental investigations of composite material failure were conducted among others in Refs. [11–13,15–19,65–67]. Wong and Wang [14] dealt with the analysis of the behaviour of the pultruded glass fibre reinforced plastics (GRP) channel columns due to compression both at ambient and elevated temperatures. Lately one can find more and more works concerning progressive failure analyses of composite materials which deeply manage to describe the phase of the failure, among others in [20–24,44]. The deflection and pre-buckling behaviour of composite structures were analysed by Feo et al. in papers [25–29]. Authors of paper [30–32] investigated functionally graded Kirchhoff plates and functionally graded Saint-Venant beams on the

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basis of novel analytical solution. Feo et al. in papers [33–35] dealt with functionally graded Timoshenko nanobeams using Eringen model. Kotelko, Lim and Rhodes [36] analysed experimentally behaviour of steel box section beams subjected to pure bending. Ungureanu, Kotelko, Mania and Dubina [37] investigated local plastic mechanism of short members of thin-walled steel section subjected to compression and bending on the basis the yield line mechanism method. This paper concerns the numerical and experimental results of thin-walled composite C—shaped channel section columns subjected to four-point bending in two separately planes. Mania et al. [38–43] analysed the stability of the thin-walled beams made of fibre metal laminate (FML). Authors of paper [45] investigated the behaviour and strength of cold-formed lipped channel beams under elevated temperatures. To assess the ultimate strength for higher temperatures it was used Direct Strength Method (DSM). Carrera and Pagani [68] extended the Carrera Unified Formulation (CUF) to analyze large displacements and post-buckling response of composite laminated beams. Several numerical assessments was proposed, including post-buckling of symmetric cross-ply beams and large displacement analysis of asymmetric laminates under flexural and compression loadings. The Progressive Failure Analysis (PFA) in analysed study was performed with the use of material property degradation method (MPDG), which can be successfully implemented to geometrically nonlinear analysis [23] as well as to dynamic issues [69]. Gliszczyński and Kubiak [23] investigated the influence of the damage variable on the load-carrying capacity of thin-walled composite channel section columns subjected to uniaxial compression and Heimbs et al. [69] used MPDG method to analyze the phenomenon of the low velocity impact on CFRP plates with compressive preload.

The paper concerns the numerical and experimental results of thin-walled composite C-shaped channel section columns subjected to four-point bending. For estimation maximum load, two types of numerical approach were applied: Progressive Failure Analysis and Hill criterion for perfect plasticity. Numerical calculations were developed in Ansys® 17.0 software based on the finite element method [49]. Moreover, during tests the Aramis® system [60] recorded the deformations of the beams till complete specimen breaking.

In the authors opinion, there are not enough publications comparing the results of experimental investigations to the numerical simulations using different approaches to damage modelling. Therefore, the authors of the present paper have decided to present a FE model coupled with progressive failure method and Hill potential theory, used to reduce stiffness after first damage and further propagation. The second approach allowed to omit the application of the widely used failure criteria to estimation the load-carrying capacity. A comparison of the results obtained in the numerical simulations to the results obtained in the experimental investigations has allowed to validate the proposed numerical models.

2. Progressive failure analysis (PFA)

In a damage mechanics all the failure modes can be represented by the degradation of the material stiffness on the meso-scale (lamina level) [50]. Due to heterogeneity of the composite materials, the application of the fracture mechanics is more complex compared to its application to isotropic materials because it is a need to apply not one but several damage parameters d, responsible for the destruction of its individual elements in the failure analysis of composites: d_F – fibre damage variable, d_M – matrix damage variable, d_S – shear damage variable. The damage effect tensor in Voigt notation is given as (1):

$$\begin{Bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_6 \end{Bmatrix} = \begin{bmatrix} \frac{1}{(1-d_F)} & 0 & 0 \\ 0 & \frac{1}{(1-d_M)} & 0 \\ 0 & 0 & \frac{1}{(1-d_S)} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} \tag{1}$$

It can be noticed that when d_F=0 and d_M=d_S=1, equation (1) represents the degradation scheme of the ply discount method. The Hashin criterion (1980) [51], implemented to analyze the progressive failure analysis as a damage initiation criterion, is applied to the identification of the damage initiation, and in his description it takes into account the following four damage modes: fibre tension (rupture), fibre compression (kinking), matrix tension (cracking), and matrix compression (crushing). The two-dimensional versions of the failure criteria, in a space of the effective stresses, are summarized in Table 1.

In accordance with the quantities given in the Table 1, the symbol $\bar{\sigma}_{ij}$ refers to elements of the effective stress tensor, T_1 and C_1 are respectively the tensile strength and the compressive strength in the direction of the fibres, T_2, and C_2 refer respectively to the tensile strength and compressive strength in the direction perpendicular to the fibres and S_{12} is the shear strength in the plane orthotropy (cf. Table 2). In accordance with the World-Wide Failure Exercise conclusions [52–54] most criteria were unable to capture some of the trends in the failure envelopes of the experimental results. Nevertheless, due to the physical character of the Hashin's criterion, which separate the effects of the fibre failure and the matrix destruction, and the increasing applicability of this criterion in normative issues, the authors decided to apply the Hashin criterion to the progressive failure analysis. To determine the degraded element of the stiffness matrix of the composite layer, the model proposed by Matzenmiller [55] has been adapted. Using the relation (1) and the quantitative evaluation of the degradation of the Poisson's ratio (Laws et al. [56]), the damaged elasticity matrix [D] can be presented in the following form (2):

$$D = \frac{1}{A}\begin{bmatrix} (1-d_F)E_1 & (1-d_F)(1-d_M)\nu_{21}E_1 & 0 \\ (1-d_F)(1-d_M)\nu_{12}E_1 & (1-d_M)E_2 & 0 \\ 0 & 0 & A(1-d_S)G_{12} \end{bmatrix} \tag{2}$$

where:

$$A = 1 - \nu_{12}\nu_{21}(1-d_F)(1-d_M)$$

The matrix and the fibre damage parameters can have a different values in tension (d_{FT}, d_{MT}) and in compression (d_{FC}, d_{MC}) and the shear damage variable d_S is not independent and can be expressed as a function of the remaining damage variables [d_S(d_{FT}, d_{MT},d_{FC},d_{MC})]. The PFA was performed with the use of material property degradation method (MPDG) [23,69], which is an "instant stiffness reduction" method and the material stiffness is instantly reduced based on the damage variables. Damage can progress through the model into other elements in the mesh with the increasing load, but the damage within a particular element is modelled as a step function: either damaged or undamaged.

3. The anisotropic Hill potential theory (HILL)

For the purpose of consideration of short state of alleged plasticity in composite material, one takes the Hill criterion [61–63]

Table 1
Hashin criteria for plane stress.

Constituent	Tension	Compression
Matrix	$f_M = \left(\frac{\sigma_2}{T_2}\right)^2 + \left(\frac{\sigma_6}{S_{12}}\right)^2$	$f_M = \left(\frac{\sigma_2}{2S_{12}}\right)^2 + \left(\frac{\sigma_6}{S_{12}}\right)^2 + \left[\left(\frac{C_2}{2S_{12}}\right)^2 - 1\right]\frac{\sigma_2}{C_2}$
Fibre	$f_F = \left(\frac{\sigma_1}{T_1}\right)^2 + \left(\frac{\sigma_6}{S_{12}}\right)^2$	$f_F = -\frac{\sigma_1}{C_1}$

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