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Estimation of load-carrying capacity for thin-walled composite beams

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ABSTRACT

The paper deals with thin-walled channel section beams made of composite laminates (epoxy resins reinforced with unidirectional long fibres). Two types of laminates have been analysed: carbon fibre reinforced polymer (CFRP) and E-glass fibre reinforced polymer. Thin-walled channel section beams subjected to pure bending in plane with the lowest second moment of area have been taken into consideration. Numerical and experimental investigations of columns loaded till failure have been performed. Also, models at the atomic level for analysing interactions between fibres and an epoxy resin have been prepared, and the obtained results have been correlated with a structural analysis of damaged beams. A comparison of the experimental results with the results of numerical simulations and the structural test results leads to a conclusion that tests allow one to predict the manner in which composite laminates are destroyed not only at the macro or micro, but also at atomic level. The above-mentioned experimental study permits the development of methods for estimating the ultimate load using numerical simulations.

1. Introduction

At the end of the last century, modern construction materials which such as laminate composites, including fibre composites, found a growing interest of designers and manufacturers. The most spectacular construction approved for use in recent years is a large passenger aircraft built mostly (over 50%) of composites. Different types of laminates are increasingly used, which enforces intensification of works in the area of structural analysis and behaviour of structures made of these materials in the entire load range. The research conducted in recent years indicates structures in which composites, because of their properties, are most often used – these are mainly aerospace structures [1], wind turbines [2], and many others.

The buckling, postbuckling behaviour and failure of thin-walled structures made of traditional materials (different types of steel), unlike composite laminate structures, have been widely described in the literature (e.g., [3–5]) – the results of investigations have been applied in different standards and used by designers. Knowledge of the behaviour of thin-walled structures in the postbuckling and failure range is essential not only in lightweight and durable designs but also to estimate their capacity and anticipate situations that lead to their total destruction.

The presented work concerns the behaviour of thin-walled composite beams subjected to the whole range of load until failure. Particular attention is paid to the destruction and the determination of load-carrying capacity of laminated beams.

Thin-walled structures have been a subject of many works presented in the literature for over 100 years. Numerous works could be cited here, in which authors focus mainly on stability [4,6], postbuckling behaviour [3,5,7–10], load-carrying capacity and a phase of destruction [11–13,15]. In most cases, these are the works presenting analytical, numerical and analytical–numerical solutions. The number of publications presenting the results of experimental studies is significantly lower [8,9,14], particularly of those devoted to failure and load-carrying capacity estimation of thin-walled composite structures subjected to compression, bending or combined load. The above mentioned works do not take into account the behaviour of composite components at the atomic level, however. In contrast, the present paper takes into account different types of physical and chemical interactions at the composite component interface. The experimental results for composite materials are mainly published in the references on laminate structures damaged by low or high velocity impact in the normal direction to the laminate surface (e.g., [16,17]). In authors' opinion, there are not enough papers devoted to the results of experimental studies on load-carrying capacity and the failure range of composite profiles subjected to operating loads in the world literature. Therefore, it has been decided to describe the failure of thin-walled laminate structures. The channel section profile made of an epoxy

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resin laminate reinforced with glass fibres (GRRP) or carbon ones (CFRP) is taken into consideration. On the basis of the experimental investigations and the numerical calculations, the failure load has been estimated. Independently, two models of the atomic interaction between composite components on their boundary phase have been developed. The results from the atomic scale have been correlated with the results obtained in the macro scale.

2. Experimental investigations

Within the experimental investigations, a four-point bending test, macroscopic evaluation of the beam destruction and microscopic tests of the destructed breakthroughs were carried out. The four-point bending test was performed until destruction and then the failure load was determined.

The channel cross-section beams under investigation were made of two types of composite laminates – an epoxy resin reinforced with E-glass fibres and an epoxy resin reinforced with carbon fibres. The CFRP beams were manufactured of unidirectional tape prepregs – the HexPly system (Hexcel) with the codename M12/35%/UD134/AS7/300. In the case of the glass–epoxy composite, the unidirectional tape prepregs made by Gurit company (glass–epoxy composite codenamed SE70/EGL/300/400/35%/PoPa) were used. In both cases, the nominal volume fraction of the reinforcing fibres in the composite was about 60%.

The tested profiles made of both the considered materials have the same length of $L = 275$ mm and similar cross-sectional dimensions of 80 × 40 mm (Fig. 1). All considered beams are made up of eight layers with the same lay-up arrangement $[0/-45/45/90/90/45/-45/0]_T$. Due to differences in the thickness of prepreg types, both types of sections (CFRP and GFRP) differ in the wall thickness – channel section beams made of an epoxy resin reinforced with glass fibres have a wall thickness equal to $t = 2.08$ mm (one layer thickness $t_l = 0.26$ mm), and CFRP beams have a wall thickness $t = 1.048$ mm (layer thickness $t_l = 0.131$ mm).

The autoclaves technique was used to prepare the profiles for tests. The samples were put into a vacuum package, which was connected to a vacuum pump providing the vacuum p_V. The polymerisation process was carried out by a rapid increase in temperature under controlled pressure, isothermal annealing in the time required to cure the resin, and, finally, a cooling process. Autoclaving parameters taken into consideration for both types of material are summarised in Table 1.

Mechanical properties of a single layer of the GFRP laminate were determined on the basis of tensile tests, compression tests and a shear test carried out in accordance with the relevant standards. Material properties of the epoxy resin reinforced with carbon fibres were derived from the work by Debski et al. [8]. Young's modulus in the fibre direction E_1 and in the direction perpendicular to fibres E_1, the Kirchhoff module G_{12}, the Poisson ratio ν_{12} and the strength of tension in both directions T_1, T_2, the compression C_1, C_2, and the shear S_{12} are summarised in Table 2.

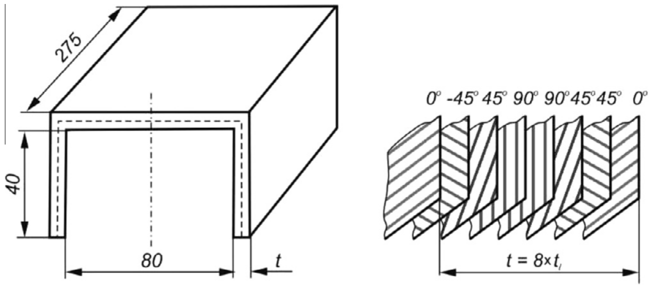

Fig. 1. Cross-section of the investigated profiles.

Table 1
Assumed autoclaving parameters for the manufactured composite laminate structures.

Process ID	Curing temp. [°C]	Heating/cooling rate [°C/min]	Curing time [min]	Pressure [MPa]	Vacuum [MPa]
CFRP	135	2	120	0.4	0.08
GFRP	100	1	60	0.4	0.085

2.1. Four-point bending test

The investigated 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 dimensions describing the span of support and the span of load is presented in Fig. 2.

The bending test was performed on the INSTRON testing machine modernised by Zwick/Roell, equipped with specially designed grips. The values of the loading force applied to the system and the displacement in points, where the load was applied, were obtained directly from the machine sensors. In addition, strain gauges were stuck on the profile web in its geometrical centre on both sides of the wall. In the case of the carbon-fibre reinforced C-shape beam, the deflection of the beam and the web of profile was additionally measured at mid-span. In the case of the fibre-glass reinforced channel section, an Aramis optical measurement system was employed.

The determined failure bending moments M_f are summarised in Table 3, and the destroyed beams are shown in Figs. 3 and 4, respectively.

On the basis of observations of the macroscopic destruction of the bent beams (Figs. 3 and 4), one might suppose that the courses of destruction in both cases are different. However, the cause and origin of the damages in both cases are the same, as will be demonstrated by a comparison of the results of numerical calculations and the experimental (including a microstructural analysis) results.

2.2. Microstructural analysis

The morphology of the samples was analysed with a HITACHI S-3000N scanning electron microscope. The mechanism of molecular interactions at the epoxy resin/carbon fiber interface was analysed with the CD/ChemSketch Freeware, version 10.00, Advanced Chemistry Development, Inc., Toronto, ON, Canada and Mercury 3.3, Cambridge Crystallographic Data Centre, UK.

The morphological analysis of the samples subject to the bending test showed that in all of the considered cases, the failure of the composite was triggered by the adhesion failure at the epoxy resin/carbon fiber interface (Fig. 5a and b). As Chung [18] and Dresselhaus [19] have shown, carbon fiber has the same crystallographic structure as graphite, therefore a weak van der Waals interaction is observed between graphite sheets. This may explain why groups in the epoxy resin molecules weakly interact with the carbon fiber prepreg. It can only be claimed that a physical interaction between aromatic groups of the epoxy resin and carbon fibers is possible. In other words, van der Waals forces between individual graphite sheets are locally restored (Fig. 5c). Nevertheless, their extent is rather marginal, which consequently leads to a rapid failure of the composite once the carbon fiber ruptures during the bending test. The stress–strain curve generated during the bending test (Fig. 9) is similar to the curves obtained for brittle materials. Due to absence of any interaction at the carbon fiber/matrix interface, carbon fiber with traces of epoxy resin was found at the surface of the fracture. This proves that no chemical bonds formed at the phase boundary.