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STRUCTURAL RESPONSE OF PULTRUDED GFRP PROFILES SUBJECTED TO BENDING

BY

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Abstract. Glass fibre reinforced polyesters (GFRP) composite profiles represent a viable alternative to structural members made of conventional structural materials such as steel, aluminium, or wood. When used for structural applications, the GFRP beams have the advantages of high strength/low weight ratio, while corrosion resistance, thermal and electrical insulation properties represent other desired qualities of these elements. Usually, GFRP are mainly reinforced with unidirectional glass fibres but these profiles integrate more fibre architectural products such as veils, mats or fabrics aiming to resist the mechanical and thermal stresses along non-principal directions. Polymeric matrices such as epoxy or vinyl ester resins can be successfully utilized for continues phases of the composite materials for pultruded shapes. In this paper, the authors present an experimental and numerical analysis to obtain the structural response as well as the flexural stiffness and the shear stiffness relating to GFRP “I” pultruded beams subjected to bending using the three points loading test procedure. The experimental results are compared with the analytical calculations and the numerical modelling using structural response curves and stress-strain maps.

Keywords: glass fibre composites; pultruded profiles; structural response; bending strength; failure envelope.

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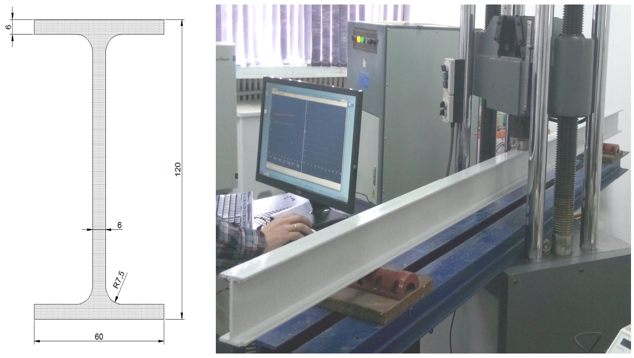
1. Introduction

Fibre reinforced polymer composite materials are nowadays utilised in structural applications for new building structures with special requirements or to strengthen the old constructions deteriorated during exploitation. Composite beams obtained through pultrusion are considered thin-walled members, being recognised as high quality engineering products which are capable to satisfy all structural requirements of a load bearing element. The behaviour of the GFRP pultruded beams depend on the mechanical properties of the composite components (the fibres and the matrix), the orientation of the loading with respect to that of reinforcing fibres and on the fabrication procedure of the GFRP products. Currently the fibre volume fractions of the pultruded profiles is in the range of 35,...,60%. The anisotropic nature of fibre reinforced polymer composite materials requires theoretical calculations using micromechanics relations, standard experimental tests for proper evaluation of mechanical and numerical modelling using finite element analysis (Barbero, 2011; Bank, 1989).

The most important aspects in the designing of the pultruded GFRP beams are stiffness, strength and stability. To underline those factors, the authors present a comprehensive study based on bending tests on GFRP pultruded I beams used for the determination of the shear moduli of elasticity and the maximum deflection utilizing three points loading test method; these tests have also enabled the identification of the buckling failure modes.

2. Experimental Setup

Pultruded shapes used in the experimental test are “I” shape beams 120 × 60/6/6 mm presented in Fig. 1 *a*, having the characteristics given in Table 1 (Fibreline, 2003).



a *b*

Fig. 1 – GFRP pultruded beam: *a* – cross section dimensions; *b* – test program.

Table 1
Properties of Structural Shape I GFRP Beam

h [mm]	b [mm]	t_1 [mm]	t_2 [mm]	r [mm]	A [mm^2]	I_{xx} [mm^4]	W_{xx} [mm^3]	I_{yy} [mm^4]	W_{yy} [mm^3]	E_0 [MPa]	E_0I_{xx} [Nmm^2]
120	60	6	6	7.5	1.42×10^3	3.10×10^6	51.7×10^3	0.22×10^6	7.3×10^3	23×10^3	71.3×10^9

The pultruded GFRP I beam is 3m long and the span is equal to 2.1m; the test has been carried in the three-point bend configuration, using a force cell 100 kN placed between hydraulic jack and steel spreading plates, and two circular bearings, Fig. 1 *b*.

The beam instrumentation was provided by a LVDT positioned at the midspan of the beam with a stroke of 100 mm and a precision of 0.01 mm to measure the transverse deflection and by bonding 5 Kyowa strain gauges-KFRP-5-120-C1-1 applied to the tensioned flange of the I GFRP beam to monitor the tensile strains.

The speed of the tests has been at a strain rate of 0.01 mm/mm/min provided by a constant crosshead movement according to ASTM D790-15e2.

3. Comparative Studies

In the analysis of a point load on simply supported GFRP pultruded beam the maximum bending moment $M_{\max}$ and the maximum deflection $\delta_{\max}$ can be calculated with the following equation:

$$M_{\max} = \frac{PL}{4}$$
$$\delta_{\max} = \frac{1}{48}\frac{PL^3}{EI} + \frac{1}{4}\frac{PL}{GA} \qquad (1)$$

where: P is the concentrated load, [N]; L – the support span, [mm]; EI – the bending stiffness of the GFRP pultruded beam, [N.mm^2]; GA – the shear stiffness of the GFRP pultruded beam, [N].

The force vs midspan deflection curves for tested beam and analytical calculus are plotted in Fig. 2. The experimental critical load compare with analytical prediction are in excellent agreement but the maximum experimental deflection is 9,38% less than analytical prediction of the deflection.

Based on previous research studies (Ţăranu *et al*., 2014; Popoaei *et al*., 2013; Mihai *et al*., 2013; Oprişan *et al*., 2013) some essential mechanical characteristics such as: tensile and compressive strength of pultruded GFRP plates, modulus of elasticity, shear modulus, shear strength and Poisson's ratios have been determined.

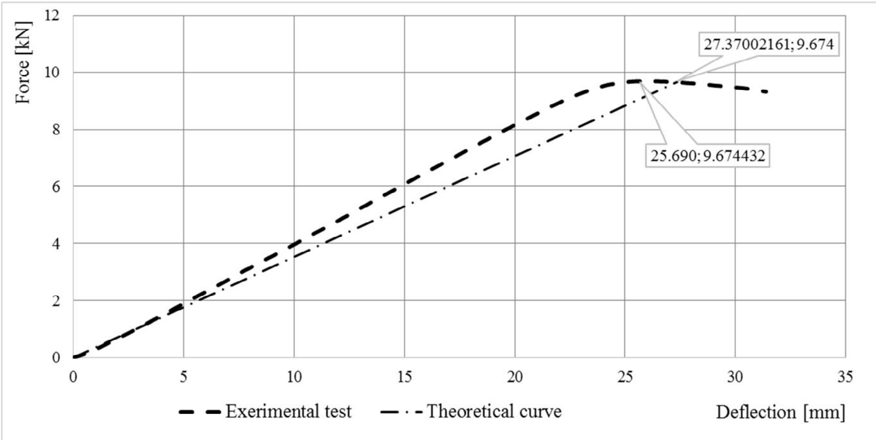


Fig. 2 – Force-deflection curve of the pultruded I beam made of GFRP 120 × 60 × 6.

Considering the maximum force 25.69 kN when the FRP beam fails the maximum flexural strength can be evaluated. This gives a value of 260.87 MPa flexural strength which is 10% higher than the design value recommended by the manufacturer. The maximum compressive and tensile strains have been recorded to verify the level of stresses in the GFRP pultruded beams by gluing strain gauges on the flanges. According to Fig. 3, 5 strain gauges were glued on the bottom of the flange of the I GFRP profile at distances of 175 mm, strain gauge number 3 being arranged in the middle.

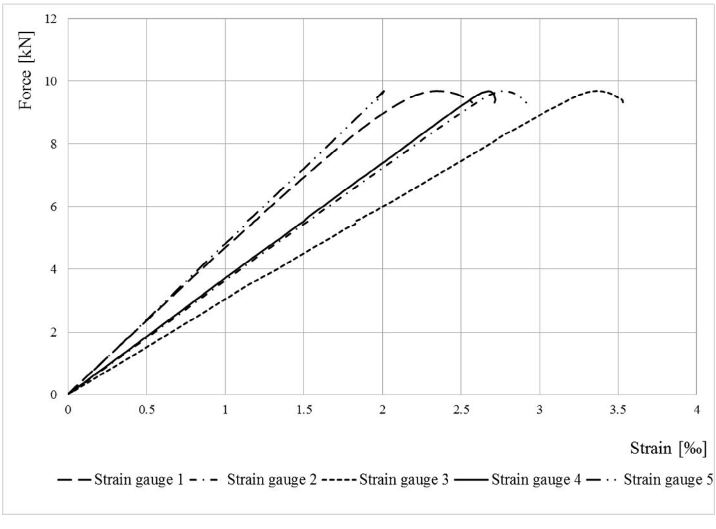
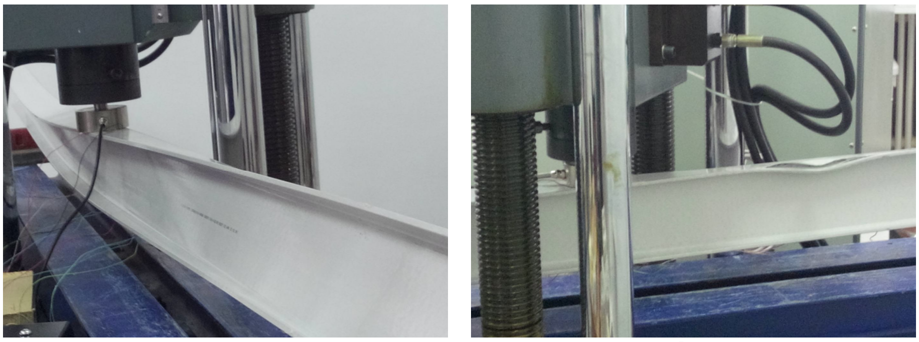


Fig. 3 – Tensile strain levels at the bottom flange of the GFRP "I" profile.

Two failure modes have been noticed: *lateral torsional buckling* of the compressed flange that displaces laterally and the section twists Fig. 4 *a*, and a *local buckling* failure in the region of the maximum moment, Fig. 4 *b*. Similar failure modes have been reported by other researchers in case of the FRP pultruded bent beams (Correira *et al*., 2011; Bank *et al*., 1999; Nicolais *et al*., 2012).



a *b*

Fig. 4 – Different type of failure modes:
a – lateral torsional buckling; *b* – local buckling of the compressed flange.

4. Numerical Simulation of the Quasi-Static Three Point Bend Test

Previous studies (Palmer *et al*., 1997; Bank *et al*., 1999) have demonstrated that the modelling techniques can be applied in the cases of the preliminary design and to check the experimental results in the three point bending test for the anticipation the failure envelope of the GFRP profiles.

A better protection of the pultruded GFRP elements to improve the corrosion resistance as well as the product handling are used by the manufacturer, these surface veils and glass mat are also needed to resist the non-principal axes stresses and to diminish the shrinkage.

In the numerical simulation the overlay veil has been considered as a thin fibreglass matting 0.1 mm in thickness for each layer with fibre orientation 0/–45/+45/90/+/–22.5, Fig. 5 (LUSAS, 2015).

A half of the GFRP beam has been modelled using thick shell QTS4 (LUSAS, 2015) structural elements for flanges and for the web, Fig 6. The orthotropic material attribute and simply supported boundary conditions at the ends have been assigned for the GFRP pultruded beam.

In the pre-processing stage the 6 mm in thickness for the web and for bottom and top flanges have been assigned, the element size being 15 mm for the entire surface mesh: 4 elements in x direction and 70 elements in z direction for flanges and 4 elements in *y* direction and 70 elements in *z* direction for the web. Young's modulus in *x*, *y*, and *z* direction, shear modulus *xy*, *y*z, *xz*, Poisson's ratio *xy*, *y*z, *x*z and mass density have been introduced from experimental test results and from the design manual of the producer.

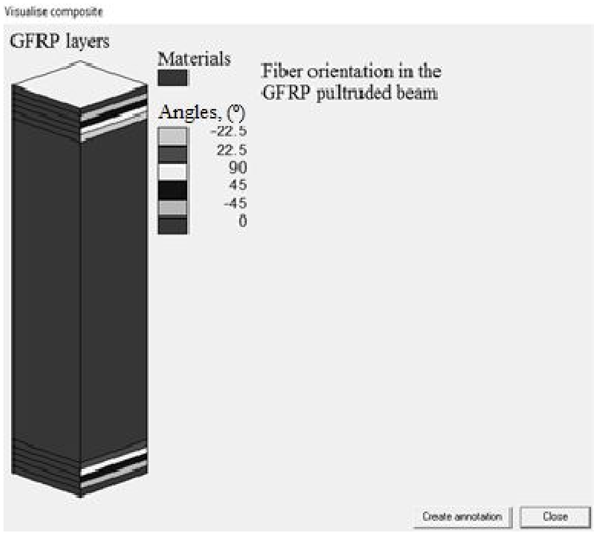


Fig. 5 – Defining of the composite material for the numerical modelling.

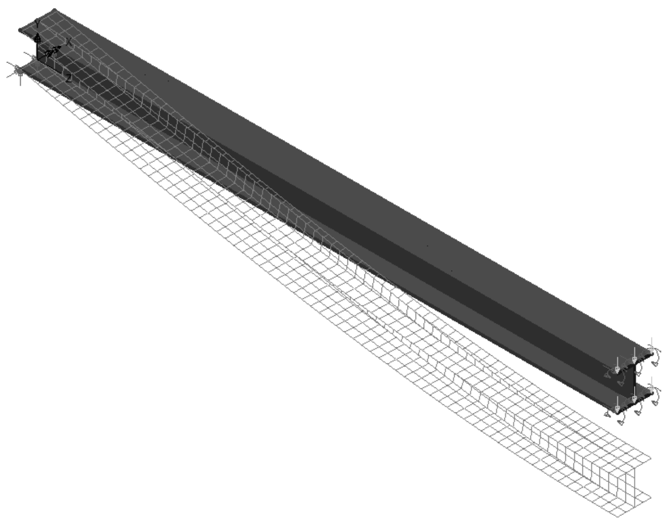


Fig. 6 – Deformed mesh of the GFRP beam.

Imposing the deflection equal to 30 mm the flexural strength of the GFRP beam was 161.45 MPa and 0.0056 for the maximum strains in the tensioned flange, Figs. 7 and 8.

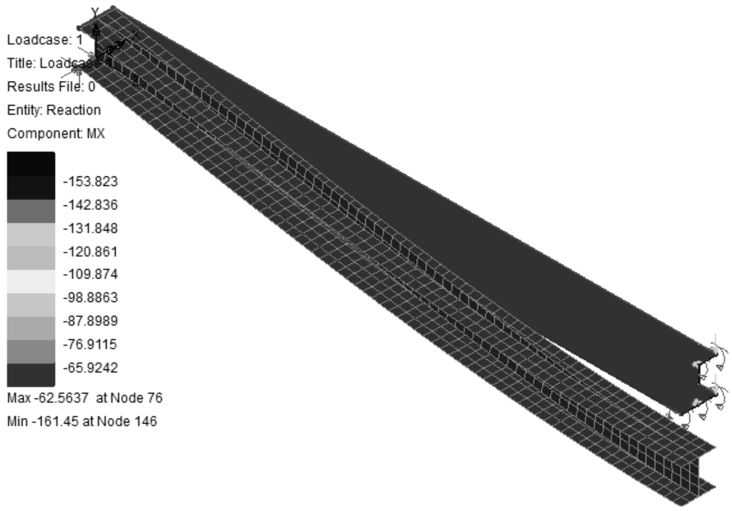


Fig. 7 – The flexural strength at the bottom of the GFRP flange.

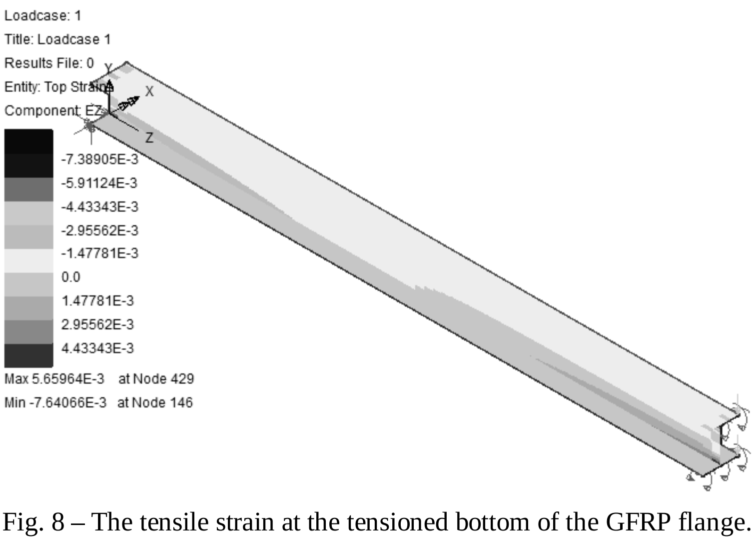


Fig. 8 – The tensile strain at the tensioned bottom of the GFRP flange.

5. Conclusions

All three GFRP tested beams exhibits a linear behaviour up to failure. The local buckling occurred when the mid-span deflection reached 9.67 mm which is equal to $\delta = L/217$. Two types of failure modes have been identified: lateral torsional buckling and local buckling.

The results from experimental tests are in good agreement with numerical modelling. More information regarding shear and bending strength and the level of strains on each composite layer or on the flange/web of GFRP beam can be obtained using the finite element analysis (FEA).

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ANALIZA GRINZILOR PULTRUDATE DIN CPAFS SUPUSE LA ÎNCOVOIERE

(Rezumat)

Profilele din compozite polimerice armate cu fibre de sticla (CPAFS) reprezintă o alternativă viabilă la elementele structurale realizate din materiale structurale convenționale, cum ar fi oțelul, aluminiul, beton, cărămidă sau lemn. Atunci când sunt utilizate pentru aplicații structurale, grinzile din CPAFS au o serie de avantaje rezistență ridicată raportată la o greutate mică, iar rezistența la coroziune, proprietățile de izolare termică şi electrică reprezintă alte calități ale acestor elemente. De obicei, CPAF sunt armate in principal cu fibre de sticla unidirecționale, dar în aceste profile sunt integrate şi fibre de produse arhitecturale, cum ar fi tesaturi cu fibre orientate aleatoriu cu scopul de a rezista solicitărilor mecanice şi termice de-a lungul direcțiilor care nu sunt principale. Matricile polimerice, cum ar fi răşini epoxidice sau vinilesterice pot fi utilizate cu succes pentru faza continua pentru realizarea pultrudate pultrudate din materiale compozite. În această lucrare, autorii prezintă o analiză experimentală şi numerică pentru identificarea răspunsului structural al grinzilor pultrudate din CPAFS precum şi rigiditatea la încovoiere şi rigiditatea la forfecare utilizând procedura de testare de încărcare patru puncte. Rezultatele experimentale sunt comparate cu calculele analitice şi modelarea numerică cu ajutorul curbelor de răspuns şi a hărților de tensiuni şi de deformații specifice.