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ABSTRACT

Glass fiber reinforced polymer (GFRP) pultruded profiles are being increasingly used in civil engineering applications. Although they offer several advantages over traditional materials, such as high strength, lightness and non-corrodibility, GFRP profiles present low elasticity and shear moduli, which together with their slender walls makes them very prone to buckling phenomena. Several previous studies addressed the global and local buckling behavior of GFRP pultruded members under concentric loading. However, little attention has been given to the effect of small eccentricities, which may arise from material geometrical imperfections or construction errors. This paper presents results of experimental and numerical investigations about the structural behavior of GFRP pultruded columns subjected to small eccentric loading about the major (strong) axis. To accomplish such goal, three series of 1.50 m long GFRP I-section $(120 \times 60 \times 6 \text{ mm})$ columns were tested in compression applied with the three following eccentricity/height of the cross-section ratios: e/ h=0.00, 0.15 and 0.30. It was found that such small eccentricities are of major importance for the behavior of GFRP pultruded columns. Although the initial axial stiffness of eccentrically loaded columns was similar to that of concentrically loaded ones, for increasing loads the stiffness considerably decreased due to bowing and second-order $P-\delta$ effects. Furthermore, results show that the load capacity of columns subjected to loads applied within the kern boundaries is reduced up to 40% at an approximately linear trend. Results obtained from the experimental campaign were compared with analytical predictions and numerical simulations using (i) the finite element method (FEM) and (ii) the generalized beam theory (GBT). In general, a very good agreement was obtained between experimental data and analytical and numerical results.

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1. Introduction

During the last decades the costs related to strengthening and maintenance of civil engineering structures made of traditional materials (such as steel or reinforced concrete) have been rising considerably. Moreover, there has been an even greater demand for lighter and faster construction [1]. Due to their low self-weight, high strength, high durability and reduced maintenance requirements, fiber reinforced polymer (FRP) pultruded profiles are becoming a competitive option as structural materials. However, the use of FRP pultruded profiles is being hindered by their high deformability (serviceability limit states), buckling sensitivity (ultimate limit states) and lack of consensual design codes. The structural behavior of FRP pultruded profiles is different from that exhibited by traditional materials (steel and reinforced concrete). They are considered to have linear elastic and orthotropic behavior until failure, which occurs generally in a brittle failure mode [2].

Conventional FRP pultruded profiles, usually made of glass fibers embedded in a polyester or vinylester polymeric matrix (GFRP), are particularly susceptible to local buckling when compressed due to their low in-plane moduli and high wall width-to-thickness ratio. Such phenomenon has been studied by many researchers using experimental, numerical and analytical tools. For instance, Tomblin and Barbero [3] studied such phenomenon on GFRP compressed members. The analytical results obtained from the modified Southwell method fitted very well the experimental values. Turvey and Zhang [4] also performed experimental and numerical studies aiming at studying the initial failure of post-buckled GFRP short columns, with length-toradius of gyration ratios (from now on referred to as slenderness) varying from 4.7 to 19.0. A phenomenological failure criterion was proposed (Tsai-Wu criterion) and incorporated in the FE models to simulate the web-flange junction initial failure, providing good correlation with the experimental results.

Regarding the global buckling phenomenon, there are several studies addressing the behavior of both beams and columns made of GFRP. Correia et al. [5] and Silva et al. [6] studied the structural behavior of GFRP cantilevers by both experimental and numerical means. Nguyen et al. [7] performed a numerical study about the

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Table 1

Mechanical properties and input data for numerical models.

Property	E_L (GPa)	E_T (GPa)	<i>G_{LT}</i> (GPa)	ν(-)	$\sigma_{L,t}$ (MPa)	$\sigma_{L,c}$ (MPa)	$\sigma_{T,t}$ (MPa)	$\sigma_{T,c}$ (MPa)	τ_u (MPa)
Average \pm std. dev.	$\begin{array}{l} 28.9 \ \pm \ 0.1 \\ \text{Full-scale test (series BC)} \\ 3 \end{array}$	8.5	3.89 ± 0.44	0.279 ± 0.031	308 ± 27	360 ± 65	121	121 ± 8	30.8 ± 1.2
Test method		(1)	ISO 527-5	ISO 527-4	ISO 527-4	ASTM D695	(2)	ASTM D695	ISO 527-5
No. of specimens		-	3	3	8	8	-	8	3

(1) Provided by manufacturer.

(2) assumed to be identical to $\sigma_{T,c}$.

influence of the load height as well as of the boundary conditions and geometric imperfections on the lateral–torsional buckling of FRP beams. Zureick and Scott [8] studied the short-term behavior under axial compression of GFRP slender members, with slenderness varying from 19.2 to 85.0. Several specimens with different slendernesses were tested and their critical loads were then compared with analytical predictions obtained from (i) Euler's buckling equation and (ii) the equation proposed by Engesser [9], which takes into account the shear deformation (often relevant in orthotropic materials with $E_L \gg G_{LT}$). Results showed good agreement between experimental data and analytical predictions (relative differences between 1% and 15%). The authors also provided a step-by-step design guideline and a sample calculation for GFRP slender members under compression.

The interaction between local and global buckling in GFRP columns was also studied by several authors. Hashem and Yuan [10] proposed a criterion to distinguish short from long GFRP columns, based on a critical slenderness ratio. A total of 24 full-scale specimens with different cross-sections and slendernesses ranging from 3.79 to 78.9 were tested. Experimental results were then compared to predictions provided by Euler's buckling equation and the classical plate theory showing that such critical slenderness ratio is about 50. Barbero and Tomblin [11] proposed a design equation that takes into account the interaction between local and global buckling in FRP columns. The experimental verification of such equation was also performed by Barbero et al. [12]. While each isolated local or global buckling mode has a stable post-critical path, the coupled mode arising from interaction at similar buckling loads is unstable and highly sensitive to imperfections. Such equation was also used by Correia et al. [13] and it gave satisfactory predictions of buckling loads of FRP pultruded short columns.

The literature regarding the structural behavior of GFRP eccentrically compressed members is very scarce. Barbero and Turk [14] carried out an experimental study regarding the effect of eccentric loading about the minor (weak) axis of WF and I-section profiles. Results showed that the main factors controlling failure in beamcolumns are the eccentricity, the member length and the specimen's mechanical and geometrical properties. The authors considered only one eccentricity (e=25.4 mm, corresponding to an eccentricity/height ratio (e/h) of 0.125–0.25 for the different cross-sections tested), and unfortunately they did not perform any numerical simulations to study the effect of different eccentricities. Mottram et al. [15] carried out an experimental study regarding the effect of eccentric loading about the major (strong) axis and moment gradient in GFRP members with WF cross-section. They analyzed different levels of high eccentricity, with e/h ranging from 0.5 to 2.0, aiming at studying the influence of combined compression and bending when joints in braced frames are simple to semi-rigid. In this investigation, numerical simulations were not performed.

According to the authors' best knowledge, no studies were reported up to present on the effect of small eccentricities¹ about the major (strong) axis in GFRP compressed members. Although in structural design the axial loading in columns may be assumed to be concentric, such eccentricities often exist due to both (i) geometrical imperfections of the materials and (ii) construction errors (e.g., member axis misalignment). This paper presents results of experimental and numerical investigations on the structural behavior exhibited by GFRP pultruded columns subjected to small eccentric loading. To accomplish such goal, three series of GFRP I-section columns were tested in compression applied with the three following eccentricity/height ratios (e/h=0.00, 0.15 and 0.30). Results obtained from the experimental campaign were compared to numerical simulations using (i) the finite element method (FEM) and (ii) the generalized beam theory (GBT).

2. Test programme

2.1. Materials

The GFRP pultruded material used in this experimental campaign was produced by the company Fiberline DK and consisted of an I-section profile with $120 \times 60 \times 6$ mm (height \times width \times wall thickness). The profile was supplied in lengths of 6 m and is made of alternating layers of type-E glass fiber rovings oriented in the longitudinal direction (rovings) and continuous strand mats, all embedded in a resin matrix of polyester. Burn-off tests indicated an inorganic content of roughly 70% (in weight).

Table 1 summarizes the main mechanical properties of the GFRP profile obtained from coupon-testing, indicating the test standard and the number of specimens used in each case. The values of the following material properties are listed: longitudinal (E_L) and transverse (E_T) elastic moduli, shear modulus (G_{LT}) , Poisson ratio (ν) , longitudinal tensile $(\sigma_{L,t})$ and compressive $(\sigma_{L,c})$ strengths, transverse tensile $(\sigma_{T,t})$ and compressive $(\sigma_{T,c})$ strengths and shear strength (τ_u) . All parameters with the exception of E_L , E_T and $\sigma_{T,t}$ were obtained by testing coupons cut from the profile. The value of E_L was obtained from strain gauge measurements in the test of a full-scale column (from series BC, cf. Section 2.2), the value of E_T was provided by the manufacturer and the value of $\sigma_{T,c}$.

2.2. Experimental series

To study the effect of eccentric loading in pultruded GFRP profiles, the following four different series were tested: (i) concentric loading in non-braced columns, series *NBC* (this series was tested mainly to calibrate and provide further validation to analytical and numerical models); (ii) concentric loading in braced columns, series *BC*; (iii) eccentric loading (level I) in braced columns, series *EBCI*; and (iv) eccentric loading (level II) in braced columns, series *EBCI*. Table 2 specifies for each series the general loading, boundary and bracing conditions.

For each series, three replicate specimens were tested, with lengths of 1.5 m. The structural behavior of each profile was

¹ In the context of the present paper, small eccentricities means that the load application point is located inside the cross-section kern, i.e. only compressive stresses develop. The kern of a cross-section is the area in which the (eccentric) compressive load is applied leading only to compressive stresses within the cross-section area.

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