Experimental and numerical investigations on iron columns reinforced by FRP under axial compression

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Abstract

This paper presents experimental and numerical investigations on iron columns under axial compression, strengthened with high modulus carbon fibre reinforced polymer (FRP) sheets. It is shown that the resistance and stiffness of iron columns can be increased significantly with the use of longitudinal FRP sheets as a result of the reduction of the column slenderness, but also that transverse FRP sheets should be used to prevent any local buckling of the longitudinal FRP sheets.

Introduction

The present study is a part of the European project PROHITECH whose main objective is to develop sustainable methodologies for the use of reversible mixed technologies in the seismic protection of existing constructions with particular emphasis to historical and monumental buildings [1]. In this framework, one of the contributions of the University of Liège (ULg), in collaboration with University of Naples "Federico II", is devoted to derive design rules for the iron columns reinforced by Fibre Reinforced Polymer (FRP) sheets.

In the literature, design rules are available to predict the resistance of steel elements reinforced by FRP sheets subjected to tensile loads or to bending moment [2], but no rules have yet been addressed to predict the buckling resistance of these elements under bending and/or axial compression, especially when they are submitted at the same time to earthquake. Three main buckling problems may occur with such loading: compressive buckling associated to members under axial compression, lateral torsional buckling associated to members under bending and compressive flexural buckling associated to members under bending and axial compression.

For the simplicity’s sake, it is possible to solve all these problems through the solution found for the compressive buckling associated to members under axial compression:

a) *Members under bending (Lateral Torsional Buckling – LTB):* No information relative to the resistance of iron members affected by lateral torsional buckling seems available. As an alternative to the study of the actual LTB effects, it is possible to refer, for I-shape elements, to a traditional approach which consists in considering LTB as a transversal buckling of the compression flange.
b) *Members under bending and axial compression*: An iron member in bending and axial compression is affected, at the same time, by compressive buckling and by LTB. Accordingly, it is possible to refer to an elastic interaction criterion to combine these two phenomena.

In addition, lateral force method (i.e. equivalent static loading of earthquake) can be used when a structure satisfies criteria on the regularity and vibration period conditions (Eurocode 8). That is why the priority of this research is first to focus on the investigation of the buckling resistance of iron columns reinforced by FRP under static axial compression.

FRP material

The applicability and the effectiveness of strengthening with FRP depend largely on the material and the nature of the member to be strengthened. When applied as reinforcement, the strengthening material should have a similar or higher stiffness compared to the member to be strengthened. The strengthening of steel or iron members with FRP may be both mechanically and economically satisfactory in retrofitting due to ease of installation and the potential of eliminating welded and bolted repairs. In particular, for historical buildings, the overall aim is to preserve the appearance of all structural elements to be reinforced, what is possible with the FRP technique.

For all the reinforced specimens within the test campaign, “Mbrace fibre alta resistenza” sheets provided by BASF Italy have been used; the nominal mechanical properties of the latter are given in table 1. Three longitudinal (3x0.165mm) and one transversal (0.165mm) FRP sheets have been used for tested columns. As no information is available concerning the compressive strength for this material, it has been assumed that the latter is equal to the tensile strength, i.e. 2500 Mpa, when the transversal FRP sheets have been also used to prevent any out-of-plan buckling of the longitudinal sheets.

Table 1 - Mechanical characteristics of "Mbrace fibre alta resistenza" sheets

	MBrace Fibre Alta resistenza
Tipo di fibra	Carbonio
Spessore equivalente di tessuto secco, mm	0,165
Modulo elastico medio a trazione, ASTM D3039, MPa	230.000
Deformazione ultima media a trazione, ASTM D3039, %	1,3
Resistenza caratteristica a trazione f_{tk}, ASTM D3039, MPa	2.500
Coefficiente di dilatazione termica, K^{-1}	10^{-7}
Conduttività termica, $J \cdot m^{-1} \cdot s^{-1} \cdot K^{-1}$	17
Resistività elettrica, $\Omega \cdot m$	$1,6 \cdot 10^{-5}$ Conduttivo

Iron material

The mechanical properties of iron material are highly dependent on the origin and production period of the iron. Usually, iron material possesses a relatively ductile behaviour in compression, but a brittle one in tension. The ratio of the two ultimate strengths ($\sigma_{i,u,t}/\sigma_{i,u,c}$), in tension and in compression, may range from 0.1 to 0.2 (see [4]).

Following the conclusions stated in [4] and [5] for the studied irons, their full behaviour can be expressed by a non linear part in compression with four parameters E_i, $\sigma_{i,0.2,c}$ n and $\sigma_{i,u,c}$ (Ramberg-Osgood law – formula (1)), and a linear part in tension with two parameters E_i and $\sigma_{i,u,t}$. Figure 1 shows that the so-defined model permits to represent with a good accuracy the behaviour of iron materials if compared to experimental results (curves BT2 to BT5).

$$\varepsilon = \frac{\sigma}{E_i} + 0.002\left(\frac{\sigma}{\sigma_{i,0.2,c}}\right)^n \tag{1}$$

Table 2 – Experimental iron material properties of columns A and B

Column	**E_i** N/mm²	**$\sigma_{i,0.2,c}$** N/mm²	**n**	**$\sigma_{i,u,c}$** N/mm²	**$\sigma_{i,u,t}$** N/mm²
A	106319	334.0	6.75	549.82	134.26
B	108678	467.4	8.85	666.48	150.17

Table 2 describes different material parameters used for columns A and B which have been experimentally determined.

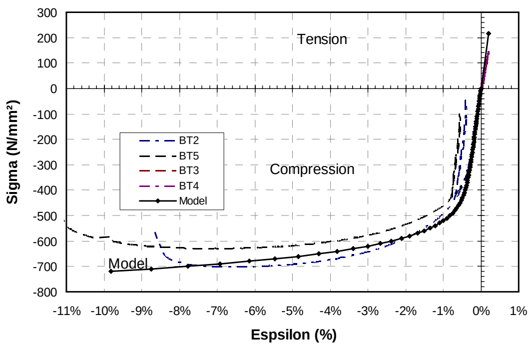
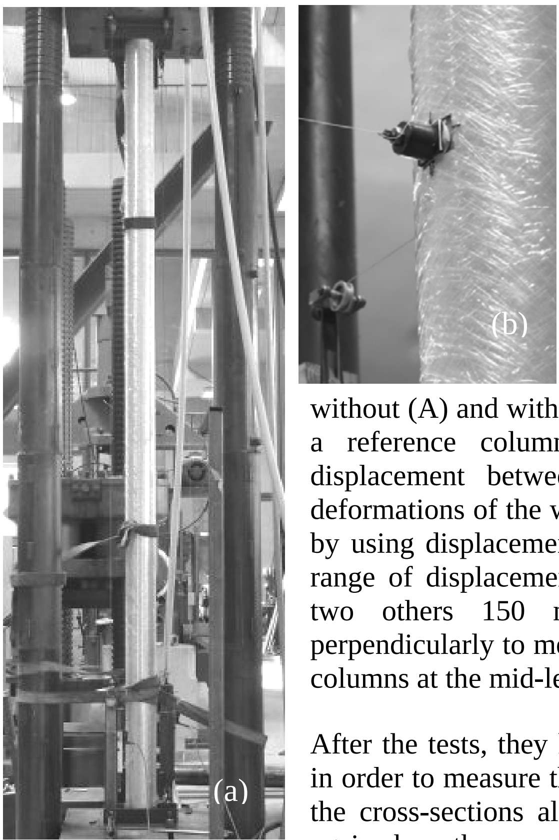


Figure 1 - Comparison of the defined analytical model for the iron behaviour law to experimental test results [5]

Tests on iron columns with and without FRP sheets



Descriptions of tests

Figure 2 - Testing system for columns A and B under axial compression: (a) General view of testing system, (b) transducers for measuring the deflections at the mid-length of columns

The AMSLER 500 Tonnes power's machine has been used to perform tests on columns without (A) and with (B) FRP sheets. Column A acts as a reference column for column B. The relative displacement between the platforms (or the axial deformations of the whole columns) has been measured by using displacement transducers which may cover a range of displacement equal to 100 mm. In addition, two others 150 mm's transducers were placed perpendicularly to measure the lateral deflections of the columns at the mid-length (figure 2b).

After the tests, they have been cut in several segments in order to measure the actual geometrical properties of the cross-sections along their length. These segments again show the non regularity of the wall thickness due to the manufacturing mode B (figure 3a). Especially, the interior mould can still be seen in column B (figure 3b).

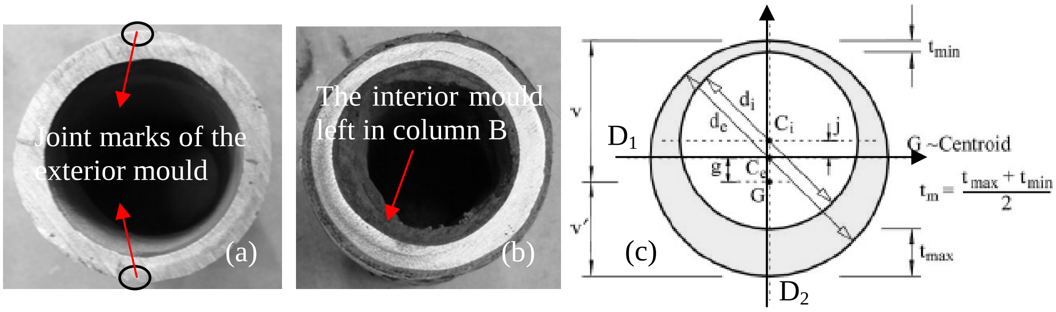


Figure 3 - Imperfections in cross-sections: (a) Column A's cross-section, (b) Column B's cross-section, (c) Model of cross-section imperfections.

Experimental results

The mechanical responses of columns A and B ("column A" and "Column B") are presented under the "axial deformation-load" curves (figure 5), obtained from the relative displacements of the platforms and the applied forces as described above. The difference between the response of columns A and B demonstrates that the FRP sheets can manifestly enhance the stiffness and the resistance of an iron column. Without FRP sheets, a buckling resistance equal to 460 kN is obtained for column A; with the reinforcement, a resistance equal to 640 kN is obtained for column B; what corresponds to an increase of more or less 40%.

Numerical investigations

A numerical model, based on beam elements, is proposed in [7] to predict the buckling resistance of iron columns under axial compression. The following pages present experimental geometrical properties of the tested columns introduced into the model.

Cross-section properties

Based on the obtained geometry of column A, the average values of the exterior and interior diameters (d_e = 122.10 mm and d_i = 96.75 mm, i.e. the average wall thickness (t_m) equal to 12.675 mm) have been used to describe all cross-sections of the column. The minimum measured wall thickness t_{min} (10 mm) has been adopted for the most critical cross-section; and then the maximum wall thickness (t_{max}) has to be equal to 15.35 mm (table 3).

As columns A and B seem to come from the same production, the geometrical properties of the column B cross-sections should be close to the one of column A. Accordingly, all the geometric parameters of column A can be used for the geometrical characterisation of column B. In addition, Three longitudinal FRP sheets (t_f = 0.495 mm) also have been taken into account for the cross-section resistances (table 3).

Table 3 - Experimental cross-section properties adopted for columns A and B

Column	L_{column} mm	d_e mm	d_i mm	t_m mm	t_{max} mm	t_{min} mm	t_f mm
A	3400	122.10	96.75	12.675	15.35	10.00	-
B	3400	122.10	96.75	12.675	15.35	10.00	0.495

Cross-section and member imperfections

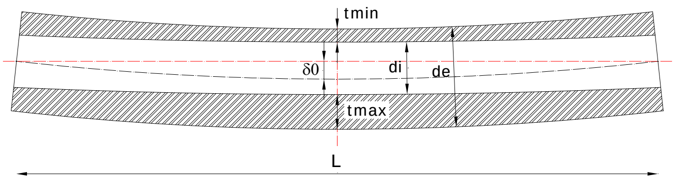


Figure 4 - Adopted imperfections for the numerical model, scenario 1

Iron members present significant cross-section and member imperfections which can take place in any directions [6]. Then, it is quite impossible to represent exactly the latter within a numerical model. Accordingly, the following scenario (scenario 1) has been adopted for the definition of these imperfections (table 4):

- The eccentricity of the hole j (figure 3) is supposed to vary according to a sinusoid along the length of the column in direction D_2 only and to reach the maximum values at the mid-length. This variation is expressed through the following formula:

$$j = j_{max} \sin\left(\frac{\pi x}{L}\right) \qquad (2)$$

  j equal to zero at one end (x = 0) and j_{max} at the mid-length (x = L/2)
- The member imperfections are supposed to take place also in direction D_2 so as to amplify the effect of the cross-section imperfections. They can be also expressed by formula (3).

$$\delta = \delta_0 \sin\left(\frac{\pi x}{L}\right) \qquad (3)$$

  δ_0 is the maximum value of the member imperfections at the mid-length, i.e. the deflection of the column.

Table 4 - Cross-section and member imperfections adopted for columns A and B

Column	j_{max} mm	$g_{i,max}$ mm	δ_0 mm
A	2.675	4.51	6.40
B	2.675	4.51	5.02

That should be the worst scenario when the compressive loads are assumed to apply by the nominal axe of the column, associated to the exterior diameter de (figure 4).

Results and discussions

With the so-defined geometrical and material properties, numerical “axial deformation-load” curves have been obtained for columns A (“Num. A”) and B (“Num. B”) (figure 5). For both columns, the obtained curves show a good agreement with the experimental results for the predicted stiffness ($E_{eq}A_{eq}/L$, 136 kN/mm for column A and 152.12 kN/mm for column B) but not for the resistances. The lake of precision concerning the prediction of the resistances may be explained by the definition of the imperfections which have been used. Indeed, to define the latter, the worst scenario was adopted, what was not necessary the case for the tested specimens. This assumption leads to an under-estimation of the resistance in the numerical simulations.

Accordingly, the imperfections introduced in the numerical simulations have to be moderated. So, in the second scenario, the member imperfections (δ) have been assumed to develop again in direction D_2 but in the opposite direction according to j. The so-obtained results (“Num. A*” and “Num. B*”) are reported in figure 5. This modification leads to an increase of the resistances when compared to the previous numerical results. For “Num. A*”, the adopted scenario even leads to an overestimation of the buckling resistance of column A.

It appears so quite difficult to demonstrate the validity of the numerical modelling as long as the actual imperfections are not known. However it can be observed that the obtained results are on the safe side if the first scenario is adopted (worst situation in terms of imperfections). This way of doing may therefore be recommended for further numerical works.

Conclusions

The impossibility of modelling the actual imperfections within the tested specimens does not permit to accurately predict numerically the buckling resistances in comparison with the experimental tests. One of the proposed approach permits to obtain a safe prediction of the buckling resistance of iron members with or without FRP and a very good prediction of the column stiffness. As a perspective to the present work, more experimental tests should be performed to:

- Characterise the behaviour of FRP sheets in compression, especially when they are bonded to iron members.
- Validate the proposed model with a large range of column slenderness and for different collapse modes (in compression or in tension).

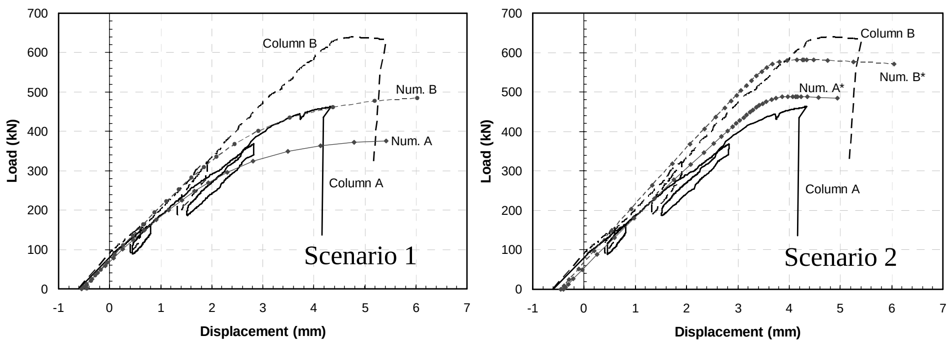


Figure 5 - Experimental and numerical "axial deformation-load" curves of tested columns A and B

Acknowledgements

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References

[1] F.M. Mazzolani (2008), "The PROHITECH research project", Proc. of Int. Conference on Structural Analysis of Historic Constructions SAHC 2008, Bath UK

[2] "Studi Preliminari finalizzati alla redazione di Istruzioni per Interventi di Consolidamento Statico di Strutture Metalliche mediante l'utilizzo di Compositi Fibrorinforzati", Commissione incaricata di formulare pareri in materia di normativa tecnica relativa alle costruzioni, CNR-DT 202/2005.

[3] Amr Shaat, Amir Fam (2007), "Fiber-Element model for slender HSS columns retrofitted with bonded high-modulus composites", J. Struc. Eng. ASCE.

[4] Rondal J. and Rasmussen K.J.R (2003), "On the strength of cast iron columns", Research report N°R829.

[5] Ly L., Demonceau J.F., Jaspart J.P. (2008), WP7 "Tests on iron materials", Prohitech project, ref. 02.07.01.02.

[6] Ly L., Demonceau J.F., Jaspart J.P. (2008), WP7 "Tests on iron columns reinforced by FRP", Prohitech project, ref. 02.07.02.02.

[7] Ly L., Demonceau J.F., Jaspart J.P. (2008), WP8, Sub-systems, "Iron columns reinforced by FRP under axial compression", Prohitech project, ref. 02.08.02.02.

[8] Xiao-Ling Zhao, Lei Zhang, "State-of-the-art review on FRP strengthened steel structures", Engineering Structures 29 (2007) 1808-1823.