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Monotonic and cyclic flexural behaviour of square/rectangular rubberized concrete-filled steel tubes

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A B S T R A C T

This paper focuses on the assessment of the behaviour of Concrete Filled Steel Tube (CFST) columns with square/rectangular cross-section, made with Rubberized Concrete (RuC), under flexural loading. The study aims to evaluate the differences between this type of composite members and typical CFST members made with standard concrete (StdC), namely in terms of the influence of the rubber aggregate replacement ratio on member strength, ductility, and energy dissipation capacity. The experimental campaign comprised the testing of 16 square members, 12 RuCFST and 4 StdCFST, and 4 rectangular RuCFSTs. A number of parameters were investigated, namely the cross-section slenderness (i.e., the width-to-thickness ratio of the steel tube), the aggregate replacement ratio (i.e., the percentage of sand aggregate of the concrete mixture that is substituted by rubber particles), axial load level and lateral loading type. The test results are compared with the member capacities obtained with the application of Eurocode 4. The results show a minimal influence of the type of concrete infill on the monotonic and cyclic behaviour of the members and also allow concluding that the European code is conservative in predicting the capacity of the specimens. Furthermore, the results obtained demonstrate that the cross-section slenderness has an important role on the behaviour of these members. Nonetheless, the requirements pertaining this parameter that are currently defined in Eurocodes 4 and 8 can be relaxed.

1. Introduction

The use of concrete filled steel tubes (CFSTs) in the construction practice has witnessed a steady increase in recent years, due to a number of advantages they pose against more conventional structural solutions. On one hand, CSFTs can take full benefit of the use of concrete, as it is fully encased by the steel tube. Under certain circumstances, the latter may even provide confinement to the concrete core, enhancing both its material strength and ductility. Moreover, the contribution of the steel tube to the axial bearing and flexural capacity of the member can be quite substantial, leading to more cost effective and lighter solutions than reinforced concrete. Perhaps more important is the fact that the concrete core can delay the development of outwards local buckling of the steel tube walls to higher levels of deformation, whereas inwards local buckling is prevented. This, in turn, largely benefits the ductility of the member in comparison to a hollow steel tube equivalent, as briefly demonstrated by Silva et al. [1] for circular CFSTs. Due to these and other advantages, such composite members show better seismic performance when compared to equivalent members of reinforced concrete or hollow steel tube sections.

Regarding the behaviour of CFST members, this has become an active research topic, with a large portion of the work being targeted towards the behaviour of short members under compression. Sakino et al. [2], for example, conducted a 5-year research endeavour on concrete-filled steel tubular short columns under compression. The authors considered a total of 114 specimens, with different levels of depth-to-tube wall thickness ratios (d/t and h/t) and concrete strength, and concluded that the concrete core can restrain the steel tube wall and delay the occurrence of local buckling. Furthermore, the results showed that the confinement effect of the concrete core can be estimated as a linear function of the tube yield strength. Schneider [3], on the other hand, carried out both experimental and analytical research work on the behaviour of short concrete-filled steel tube columns concentrically loaded in compression up to failure. The author considered a total of fourteen specimens with different depth-to-tube wall thickness ratios and cross-section shapes, concluding that square or rectangular steel tubes exhibit much lower post-yield axial ductility than circular cross-sections. Although underdeveloped, there have been important research contributions regarding the flexural behaviour of CFSTs. Elchalakani and Zhao [4], for example, analysed the monotonic and cyclic flexural behaviour of long CFST members of circular cross-section, with a wide range of diameter-to-thickness ratios. The authors demonstrated that cyclic loading can be quite detrimental to the capacity of

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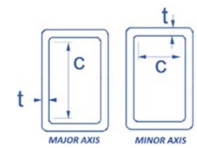
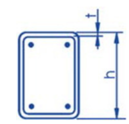
circular CFST members, particularly for those with slender steel tubes. Furthermore, Han [5] used experimental data of CFST members of different cross-sections under monotonic bending, acknowledging that Part 1-1 of Eurocode 4 [6] is conservative in predicting the capacity of the members. This observation was corroborated by the findings of Jiang et al. [7], which performed bending tests on square and rectangular thin-walled CFSTs, also concluding about the conservativism of the European code.

The application of recycled tire rubber in concrete (RuC, Rubberized Concrete), has become an important research topic during the last few decades, allowing for scrap rubber re-usage. As shown by Khatib and Bayomy [8], the total replacement of normal concrete aggregate by rubber aggregate results in a significant reduction in concrete strength. However, with reduced levels of aggregate substitution, namely lower than 20% of the total aggregate volume, the effect on concrete strength can be minimal. According to Xue and Shinozuka [9], RuC structural members pose higher energy dissipation capabilities than equivalent concrete members, underlining its potential use as a structural material for seismic applications. Recently, the application of this material to CFST members was also investigated, namely by Duarte et al. [10] for stub columns under compression and Duarte et al. [11] for stub columns under cyclic bending. From the results obtained in the research studies, the authors denoted the inferior standard concrete in comparison to rubberized concrete. It is important to note, however, that the use of stub composite columns mainly allows for the assessment of the behaviour under the development of local phenomena, whilst long members allow for the study of the global response. Regarding the latter, the flexural behaviour of RuCFST members of circular cross-section has also been recently investigated by Silva et al. [1]. In this study, the authors inferred that the type of concrete infill (i.e. standard versus rubberized) plays a minimal role on the flexural behaviour and ductility of the members, when subjected to monotonic and cyclic lateral loads, given that the comparison of the experimental responses yielded little to no difference between CFST and equivalent RuCFST specimens. Finally, a recent contribution by Silva et al. [12], in which the authors assessed the seismic performance of moment-resisting frames with the use of CFST columns, allowed concluding that not only does the use of CFSTs in detriment of European H-Section steel profiles lead to savings on the overall steel weight of the structure, but also improve the seismic performance of the frames in comparison to equivalent steel only structural solutions.

According to Part 1-1 of Eurocode 4, the methods for the calculation of the capacity of composite members, including CFSTs, are provided. As stated in the code, EC4-1-1 aims to prevent the development of local buckling through a limitation of the cross-section slenderness of the member. For square and rectangular members, this is attained by imposing maximum limits to the h/t ratio, where h is the maximum external dimension of the steel tube and t is the thickness of the tube wall. This upper value is in between the requirements of Part 1-1 of Eurocode 3 [13] for Class 3 tubular steel sections in compression and in bending, but closer to the more critical threshold, i.e. simple compression, as shown in Table 1. This approach is slightly different than that implemented for circular cross-sections, as reported by Silva et al. [1]. Regarding the European seismic design code, the two structural ductility classes set within Part 1 of Eurocode 8 [14] for a dissipative structural behaviour concept, namely medium (DCM, $1.5<q\leq2$) and high (DCH, $q>4$), with q being the so-called behaviour factor, clearly acknowledge some improvement of CFST behaviour in comparison to the tubular steel section, by presenting more loosened h/t limits for each ductility class, as shown in Table 2, where f_y is the yield strength of the steel tube material. However, for medium ductility class DCM with $2<q\leq4$ the European seismic code stipulates the same h/t limit prescribed in EC3 for Class 2 tubular steel sections in compression, which effectively does not account for any contribution of the encased concrete core. It should be noted that the h/t limits prescribed in Eurocodes 4 and 8 do not make any distinction between the type of internal forces applied to the cross-section (e.g., simple compression, simple bending or combined bending with compression). Furthermore, these limits are closer to the requirements of EC3 for simple compression than for simple bending scenarios. It is important to note that, contrary to Eurocode 3, both Eurocode 4 and Eurocode 8 make no distinction between square and rectangular cross-section types in terms of the prescribed h/t limits. Finally, it is also worth highlighting that the currently defined expressions in Eurocode 8 differ from those provided in Table 2, namely in terms of the coefficient that accounts for the yield stress of the steel. Whilst in Table 2 they are presented in the same format of Eurocodes 3 and 4, i.e. $\sqrt{235/f_y}$, in Eurocode 8 they are wrongly presented as $\sqrt{f_y/235}$, as denoted by Elghazouli and Castro [15].

In order to provide a meaningful contribution to the state of the art, namely pertaining the flexural behaviour of CFST members, this paper is centred mainly on: 1) the experimental investigation of the influence of the level of rubberized concrete (RuC) usage and cross-section slenderness level in CFST members of square and rectangular cross section, under both monotonic and cyclic bending; 2) gauging the accuracy of Eurocode 4 in predicting the experimental flexural capacities.

Table 1
Cross-section slenderness limits for square/rectangular CFSTs in EC3 and EC4.

Code	Class	Limit		Legend
		Bending	Compression	
EC3	1	$c/t\leq72\times\sqrt{235/f_y}$	$c/t\leq33\times\sqrt{235/f_y}$	
	2	$c/t\leq83\times\sqrt{235/f_y}$	$c/t\leq38\times\sqrt{235/f_y}$	
	3	$c/t\leq124\times\sqrt{235/f_y}$	$c/t\leq42\times\sqrt{235/f_y}$	
EC4	–	$h/t\leq52\times\sqrt{235/f_y}$		

2. Experimental campaign

2.1. Definition of test specimens

In the context of this research study, a somewhat comprehensive experimental campaign was carried out, consisting on the testing of 20 CFST columns. Of this set, 14 were of square cross-section, out of which 12 were filled with rubberized concrete (RuC) and 4 with standard concrete (StdC), and 4 rectangular RuCFST columns. All members were loaded with an applied lateral load on top, with a free testing length of 1.35 m, combined with different levels of compressive axial load. To define the members, a number of important parameters were accounted for, namely the cross-section slenderness ratio, h/t, the concrete aggregate replacement ratio, β, the normalized axial load level, n, and the lateral load type. In order to study the influence of the

Table 2
Ductility class requirements for square/rectangular tubular sections in EC8.

Type	DCM	DCM	DCH
	$1.5<q\leq2$	$2<q\leq4$	$q>4$
Steel CFST	EC3 Class 1, 2 or 3 $h/t\leq52\times\sqrt{235/f_y}$	EC3 Class 1 or 2 $h/t\leq38\times\sqrt{235/f_y}$	EC3 Class 1 $h/t\leq24\times\sqrt{235/f_y}$