Journal of Constructional Steel Research 122 (2016) 557–570

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental assessment of the flexural behaviour of circular rubberized concrete-filled steel tubes

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ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form 11 April 2016
Accepted 13 April 2016

Keywords:
Concrete-filled steel tubes
Rubberized concrete
Monotonic behaviour
Cyclic behaviour
Eurocode 4
Eurocode 8

ABSTRACT

The main objective of the research presented in this paper is to investigate the flexural behaviour of concrete filled steel tube (CFST) columns of circular cross-section, made with rubberized concrete (RuC). A second objective is to identify behavioural 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 paper describes the preparation and development of an experimental campaign, involving the testing of 16 circular specimens, 12 RuCFST and 4 StdCFST. The definition of the test campaign considered a number of parameters, namely cross-section slenderness, aggregate replacement ratio, axial load level and loading type. A special device was developed as part of an innovative testing setup, aimed at reducing both the cost and preparation time of the specimens. This paper also describes the comparison of the test results with design provisions from Eurocode 4. The test results show a marginal influence of the type of concrete infill on the monotonic and cyclic behaviour of the members and also allow concluding that Eurocode 4 is conservative in predicting the capacity of the tested specimens. Moreover, it is found that the cross-section slenderness does not have a significant influence on the monotonic and cyclic behaviour of the specimens, pointing out for the possible relaxation of the cross-section slenderness limits currently specified in Eurocodes 4 and 8.

1. Introduction

In recent years, the use of concrete filled steel tubes (CFSTs) has increased in many modern structures. One of the key benefits of CFSTs is the confinement effect of the concrete provided by the steel tube. Unlike typical reinforced concrete members, CSFT members can make full use of the concrete material as it is fully encased by the steel tube. The tube not only assists in the axial bearing capacity of the member, but also provides confinement to the concrete core. This leads to lighter and more cost efficient solutions than reinforced concrete. Moreover, the triaxial compression stress state of the CFST core can prevent the brittle behaviour of the material. From a structural point of view, the concrete core has the ability to delay local buckling of the steel tube therefore increasing the ductility of the member. Indeed, due to their high ductility and good energy dissipation capacity, CFST members have better performance under seismic loading in comparison with both reinforced concrete and steel tubular elements.

Schneider [1] conducted an experimental and analytical study on the behaviour of short concrete-filled steel tube columns concentrically loaded in compression up to failure. Fourteen specimens were considered with different cross-section shapes and depth-to-tube wall thickness ratios (d/t and h/t, respectively). The author pointed out that circular steel tubes exhibit much higher post-yield axial ductility than square or rectangular tube cross-sections. Sakino et al. [2] carried out a 5-year research on concrete-filled steel tubular column systems. In the study, a total of 114 specimens of different tube shape, depth-to-tube wall thickness ratio, and concrete strength were fabricated and tested. From the experimental results it was concluded that the difference between the ultimate strength and the nominal squash load of circular CFST columns, which is due to the confinement provided by the concrete, can be estimated as a linear function of the tube yield strength. According to the authors, the concrete can restrain the steel tube wall and delay the occurrence of local buckling. Giakoumelis and Lam [3] tested 15 short CFST columns of circular cross-section under compression, and compared the test results with different design codes. The authors found that Eurocode 4 [4] provides a good prediction of the axial strength of concrete filled steel tube columns.

Regarding the flexural behaviour of CFSTs, Elchalakani et al. [5] performed large deformation monotonic tests on circular concrete-filled steel tubes under pure bending, with diameter-to-thickness ratios, d/t, ranging from 12 to 110. The authors concluded that concrete filling fully prevents local buckling and ovalization of cold-formed steel tubes

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http://dx.doi.org/10.1016/j.jcsr.2016.04.016
0143-974X/

with d/t values between 13 and 40, whereas multiple plastic ripples were observed in the inelastic range for CFSTs with d/t between 74 and 110. Moreover, a close look at the moment-curvature responses presented in [5] allows concluding that the influence of d/t on the monotonic flexural behaviour is not very significant. Additionally, Elchalakani and Zhao [6] performed monotonic and cyclic bending tests, the latter using a constant amplitude loading history, on long CFST members of circular cross-section, with diameter-to-thickness ratios, d/t, ranging from 20 to 162. The results indicated that cyclic loading can have a considerable effect on the strength of circular CFST members, particularly for those made of slender steel tubes. Han [7] utilized, in addition to his test results of CFST members under monotonic bending, the experimental data of a number of research authors on the subject. Through a set of 51 CFST members of circular, square and rectangular cross-section, the author concluded that Eurocode 4 is conservative in predicting the capacity of the test specimens, with an average difference of about 10% between the code and the experimental results. More recently, Jiang et al. [8] performed bending tests on square and rectangular thin-walled CFSTs, with width-to-thickness ratios, h/t, ranging from 50 to 100. The author demonstrated that Eurocode 4 is conservative in predicting the flexural capacity of the test specimens, with an average difference of 9% between the code and the experimental results.

During the last few decades, the application of recycled tire rubber in concrete (RuC, rubberized concrete), has become an important research topic. This technology not only enhances the elastic properties of the concrete, but also allows for scrap rubber re-usage, something very much in line with current global trends of carbon footprint reduction. Although its application to asphalt concrete (RAC, Rubberized Asphalt Concrete) has been introduced in the 60s, with a prominent importance in the USA, RuC is still a recent, but very promising, topic. Typically, the total replacement of normal concrete aggregate, small or coarse, results in a significant reduction in concrete strength, whereas with a reduced rubberized aggregate usage, the sway on concrete strength can be minimal, as shown by Khatib and Bayomy [9]. According to the authors, aggregate replacement ratios should not be higher than 20% of the total aggregate volume. Regarding the behaviour of RuC members, Xue and Shinozuka [10] concluded, through free vibration tests, that the average damping coefficient of RuC columns is higher than that of equivalent normal concrete members. Therefore, the authors concluded about the higher energy dissipation capacity of columns with this type technology, highlighting its potential use as a structural material aimed at the improvement of structural behaviour in seismic areas. The application of this material to CFST members has recently been studied by Duarte et al. [11] for stub columns under compression and by Duarte et al. [12] for stub columns under cyclic bending. The authors highlighted the enhanced ductility of CFSTs with rubberized concrete in comparison to standard concrete. Very recently [13], these authors also developed finite element models to simulate the monotonic behaviour of stub CFST columns with RuC under compression and validated the numerical results through the comparison with experimental values.

From a design perspective, and in addition to the provided methods for the calculation of the resistance of composite columns, Eurocode 4 aims to prevent the development of local buckling through limitation of the cross-section slenderness of the tube, by imposing maximum limits of the d/t ratio, where d is the external diameter of the steel tube and t is the thickness of the tube wall. In this way, the cross-section capacity is expected to be governed by the material properties. For circular members this upper limit is the same as that prescribed in Eurocode 3 [14] for Class 3 tubular steel sections, which effectively indicates that no account is made for the influence of the concrete infill, as shown by the data presented in Tables 1 and 2. Eurocode 8 [15] medium (DCM) and high (DCH) ductility classes for dissipative elements acknowledge the improved CFST behaviour in comparison to the tubular steel section, by presenting more relaxed d/t limits for each ductility class, as illustrated in Table 3, where f_y is the yield strength of the steel tube material. It should be noted that the d/t limits prescribed in Eurocodes 3, 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).

Table 1
EC4 d/t limits for circular CFSTs (adapted from Eurocode 4).

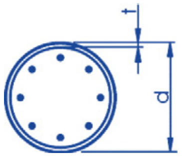
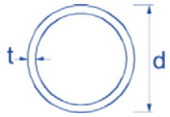
Type	d/t	
Circular	$d/t \leq 90 \times 235/f_y$	

Table 2
EC3 section classification for circular tubes (adapted from Eurocode 3).

Class	d/t	
1	$d/t \leq 50 \times 235/f_y$	
2	$d/t \leq 70 \times 235/f_y$	
3	$d/t \leq 90 \times 235/f_y$	

It is worth noting that the expressions provided in the current version of Eurocode 8 differ from those provided in Table 3, namely in terms of the coefficient that accounts for the yield stress of the steel. Whilst in Table 3 they are presented in the same format of Eurocodes 3 and 4, i.e. $235/f_y$, in Eurocode 8 they are wrongly presented as $f_y/235$ (Elghazouli and Castro [16]).

This paper mainly focuses on: 1) the experimental assessment of the influence of rubberized concrete (RuC) in CFST members under monotonic and cyclic bending; 2) the comparison of the experimental results with expected design capacities according to Eurocode 4.

2. Description of the Test Campaign

2.1. Specimen Definition

The experimental campaign consisted on the testing of a total of 16 circular CFST columns, 12 with rubberized concrete (RuC) and 4 with standard concrete (StdC), with a free length of 1.35 m, in bending. The considered parameters were the cross-section slenderness ratio d/t, the concrete aggregate replacement ratio β (detailed in Section 2.2.3), the normalized axial load n and the lateral load type. The axial load level n is defined as the ratio between the axial load applied to the specimen and the axial resistance of the cross-section, which was estimated based on the concrete compressive strength and on the available properties of the steel, which were obtained before the cold-forming process. Two levels of axial load were targeted in the test campaign, namely $n = 15\%$ and $n = 0\%$.

In order to study the influence of the cross-section slenderness on member ductility, both high and low values of d/t were considered, taking into account the requirements of Eurocode 8 for high and medium ductility class CFSTs. According to the cross-section slenderness

Table 3
EC8 ductility class requirements for circular tubular sections.

Type	DCM	DCM	DCH
	$1.5 < q \leq 2$	$2 < q \leq 4$	$q > 4$
Steel	EC3 Class 1, 2 or 3	EC3 Class 1 or 2	EC3 Class 1
CFST	$d/t \leq 90 \times 235/f_y$	$d/t \leq 85 \times 235/f_y$	$d/t \leq 80 \times 235/f_y$