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Finite element modelling of short steel tubes filled with rubberized concrete

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ABSTRACT

This paper presents a numerical investigation on the ductility and strength of short steel tubes filled with Rubberized Concrete (RuC), which is a composite material that mixes concrete with rubber particles. This research concerns the enhancement of both ductility and energy absorption of CFST by considering a core of RuC instead of normal concrete (NC). First, a brief literature review on the topic is presented. Then, based on an experimental programme conducted by the authors, numerical models of CFST and RuCFST columns are developed. The results of non-linear analyses (ultimate strengths, load-shortening curves and failure modes) are validated using experimental data, and good agreement is shown. Finally, a numerical study on the properties of confined NC and RuC is conducted. It is concluded that the concrete damaged plasticity model can be used to simulate RuC. The dilation angle plays a key role in RuC and its lower value (compared to that of NC) influences the concrete confinement. Taking into account the RuC dilation angle, steel yield stress and tube local slenderness, a new formula is proposed to predict the concrete core confinement of the studied CFST and RuCFST columns with circular sections.

1. Introduction

One of the urgent demands for today's sustainability is recycling scrap tyres. Many companies are working towards putting together sustainable programs to create more opportunities for tyres to be recycled instead of discarding them in landfills. One possible solution is to use rubber tyre particles as aggregates in concrete. In the resulting Rubberized Concrete (RuC), the natural aggregates are partially replaced by rubber aggregates, which can be fabricated from tyres via either a cryogenic process or a mechanical process. Additionally, this replacement of natural aggregates by rubber particles implies less extraction of natural resources, thus reducing the environmental impact.

During the last three decades, several authors have investigated RuC. During the 90's, Topçu [1] and Li et al. [2] pioneered the study of the mechanical properties of RuC. These authors concluded that most mechanical and physical properties of RuC are worse than those of normal concrete (NC), the exception being its improved ductility, thus recommending its use in applications where energy absorption capacity is required and high strength is unnecessary. Li et al. [2], and later Zheng et al. [3], concluded that the use of RuC decreases the natural frequency of a structural element and leads to an increase of its damping ratio value compared to those of NC.

Several factors, such as the rubber particle size, the process of production (mechanical or cryogenic), the percentage of replacement, and the replacement of fine, coarse or total natural aggregates with rubber particles, may play a key role on the properties of RuC. Recently, Valadares et al. [4] studied the mechanical properties of 12 RuC mixes by extensively varying the parameters previously referred to. In short, even though the aforementioned studies present a widespread set of parameters regarding RuC compositions, overall conclusions indicate that RuC has lower mechanical properties than NC, namely lower Young's modulus and lower (compressive and tensile) strength. This is a natural consequence of the lower strength and stiffness of rubber particles, in comparison with natural aggregates (NA). On the other hand, RuC is lighter than NC because rubber particles have lower density than natural aggregates. Because the decrease of stiffness is higher than the decrease of mass, RuC structures have vibration frequencies slightly lower than NC ones. However, the higher damping ratio of RuC systems can be an advantage in some structures subjected to dynamic loads. Additionally, RuC also has ultimate strain (extension) higher than NC, which is a valuable property regarding ductility and energy absorption requirements.

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Concrete Filled Steel Tubes (CFST) are one of the most successful composite structural solutions available in the construction industry. In fact, in CFST columns, the steel tube acts as formwork and provides confinement to the concrete core, improving its strength and ductility, whereas the concrete core reduces the steel tube sensitivity to local buckling. In case of thin (and very thin) steel tubes, the susceptibility to local buckling increases and, consequently, the ductility of the tube decreases and its ability to dissipate energy from dynamic actions also decreases [5–7]. Therefore, if thin-walled steel tubes are used in CFST solutions, particular attention should be paid to their ductility, a mandatory requirement for structures located in seismic areas. In this scope, to increase the CFST column's ductility, by increasing the ductility of its concrete core, would have clear advantages, and this can be achieved by replacing NC with RuC. In reality, this replacement has two major benefits:

- The drop of RuC strength, in comparison to NC, must be lower if concrete is confined. Thus, the strength decrease of confined RuC (in parallel to NC) shall not be as severe as in the unconfined case.
- The gain in energy absorption must be higher when using RuC instead of NC. Thus, the ductility of Rubberized Concrete Filled Steel Tubes (RuCFST) columns shall increase in comparison with their CFST counterparts.

Taking advantage of both the structural performance of the CFST columns and of the improved ductility and energy dissipation capacities of RuC compared to those of NC [1–4], RuCFST were recently studied [8,9]. Duarte et al. [8] conducted an experimental investigation on short cold formed steel tubes, considering three cross section geometries (circular, square and rectangular), filled with three concrete mixes (one NC and two RuC mixes with 5% and 15% replacement of total NA volume with coarse rubber aggregates), subjected to monotonic concentric compression. The authors' main conclusion was that, even though the strength and stiffness of RuCFST columns were lower than those of CFST columns, the former presented higher ductility than the latter, especially for columns with circular sections. As previously mentioned, this is a major benefit for structures in seismic areas, where energy dissipation requirements are mandatory. Silva et al. [9] experimentally studied the flexural behaviour of long RuCFST circular columns subjected to both monotonic and cyclic bending testing. These authors observed that the RuCFST column (i) with diameter of 219 mm and tube thickness of 5 mm and (ii) infilled with RuC15, presented a maximum drop of lateral force ranging between 6% (monotonic) and 8% (cyclic) of its CFST counterpart. The drift for maximum lateral load of the RuCFST column presented an increase between 6% (monotonic) and 22% (cyclic) of that exhibited by the CFST column.

The main objective of the research presented herein was to develop and calibrate numerical models of both CFST and RuCFST short columns experimentally studied by Duarte et al. [8] and to analyse and draw conclusions regarding their performance. During the last decade, several numerical investigations [10–13] have been carried out to study the behaviour of CFST columns with different types of concrete inside (e.g. high-strength concrete). This paper presents, for the first time, the modelling and simulation of the structural behaviour of RuCFST columns. Hence, the first challenge of this study results from how to model the mechanical behaviour of rubberized concrete. Since, as described before, most studies on RuC properties have mainly an experimental nature [1–4], Duarte et al. [14] decided to firstly develop a numerical study on RuC at a macroscale material's level. These authors employed an Image Processing-Extended Finite Element Method coupled procedure, allowing the separate modelling of rubber particles and concrete matrix with the latter presenting crack initiation and propagation. Taking into account the previous assertions, the study described in the present paper intends to provide a numerically study of RuC properties, but now at a structural level and within the context of CFST columns. In particular, one of the objectives is to assess if the concrete damaged plasticity model, usually employed for standard concrete simulations, can be extended to the simulation of RuC. Firstly, the development of the numerical models of the circular, square and rectangular CFST and RuCFST tested columns [8] is described in detail, with special attention given to the modelling aspects of the concrete mixes (NC and RuCs). Then, the numerical models are validated by comparing the numerical and experimental collapse strengths, compressive load-axial shortening curves and collapse configurations. Finally, as the numerical models show good agreement with the experimental tests, an analysis of the behaviour of confined standard and Rubberized Concrete is made and conclusions are drawn.

2. Description of numerical models

In this section, the numerical models of the short columns tested by Duarte et al. [8] are described. Regarding the geometry of the columns, all sections (circular, square and rectangular) experimentally studied by Duarte et al. [8] were modelled. For each cross-section geometry, the five (four in the case of rectangular sections) configurations (variations of steel tube diameter/width and thickness) and, for each of these, the three steel grades of the tested columns [8] were investigated (S235, S275 and S355). Regarding the concrete cores, the three concrete mixes previously investigated [8] were considered: (i) a normal concrete mix (NC) and two Rubberized Concrete (RuC) mixes, obtained by replacing (ii) 5% (RuC5) and (iii) 15% (RuC15) of the total natural aggregates volume of the NC composition with coarse (4–11.2 mm size) tyre rubber particles, in the coarse fraction of aggregates.

Static monotonic non-linear geometrical analyses of the models were performed using the finite element (FE) commercial package ABAQUS [15] and an incremental-iterative scheme based on the modified Riks method.

2.1. Geometry and FE mesh

The geometry, size, steel grade and concrete mixes of the columns are shown in Table 1 [8]. Taking the specimen labelled R120x2_235_0 (Table 1) as an example: (i) "R" stands for the rectangular cross-section shape ("C" – circular and "S" – square), (ii) "120x2" are the nominal major exterior width and nominal tube thickness in millimetres, respectively, (iii) "235" is the S235 steel nominal yield stress in N/mm^2 and (iv) "0" stands for a NC core ("5" – RuC5 and "15" – RuC15). Additionally, in Table 1: (i) B is the nominal exterior and nominal major exterior width of the square and rectangular columns, respectively, (ii) b is the nominal exterior minor width of the rectangular columns, (iii) D is the nominal exterior diameter of the circular columns, (iv) t is the measured tube (wall) thickness, (v) r_e is the measured exterior corner radius of square and rectangular columns and (vi) H is the height of the short columns (i.e. specimen length between 300 mm and 500 mm).

Fig. 1 provides an overview of the circular, square, and rectangular columns FE models' geometry and mesh. Due to the double symmetry of the columns, only one fourth of each specimen was modelled with adequate boundary conditions provided [10,11]. Hence, nodes from both concrete and steel parts in the XZ symmetry plane were restrained in the Y axis direction and nodes in the symmetry plane YZ were restrained in the X axis direction. This option allowed the use of a refined mesh, thus improving the numerical solution without additional computational time (see Appendix A).