Computational study of concrete-filled steel tube columns produced with aggregates from construction and demolition waste

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Abstract. The use of concrete-filled steel tube columns – CFSTC had begun about 70 years ago and, until today, these elements have been widely used worldwide. The behavior of the steel-concrete system can be seen as an advantage, since it opens space for the possibility of using alternative materials in the manufacture of concrete for composite columns, once the stress triaxial state minimizes the strength reductions that can occur with the use of such alternative materials. For this reason, this work aimed to computationally analyze the behavior of composite columns of circular section filled with concrete (manufactured with aggregates of the type CDW – Construction and Demolition Waste) and subjected to centered compression. In this study, the influence of the use of CDW in short CFSTC subjected to axial compression was analyzed. In the present study, a computational model of short CFSTC was constructed. Two groups of models were analyzed. Considering the results, it was possible to affirm that the increase of strength and ductility verified in the CFSTC are very important characteristics to make possible, from the structural point of view, the use of CDW, in the production of the concretes used in concrete-filled steel tube short columns.

Keywords: concrete-filled steel tube columns, computational modeling, recycled aggregate.

1 Introduction

Composite columns, according to Lima [1], can be defined as a composition between steel and concrete profiles (reinforced or simple) where, in this association, the elements must work together to resist the acting forces. Among the standards related to the subject, which bring important definitions to this study, are: the Eurocode 4: Design of composite steel and concrete structures [2-3] and the NBR 8800/2008: Design of steel and composite structures for buildings [4]. These standards address several recommendations for the design of the filled composite columns, worthy of note that the Brazilian standard was created based on Eurocode 4: Design of composite steel and concrete structures [2-3].

According to NBR 8800/2008 [4] there are three categories of composite columns, namely: composite column of steel coated with concrete, composite column of steel partially coated with concrete and composite column of steel filled with concrete. The latter can have a square, rectangular, octagonal or circular section and has several advantages when compared to reinforced concrete structures, such as: no need for formwork and shoring; lower self-weight; reduction in columns dimensions; reduced consumption of structural steel; increased resistant capacity (since the materials work together); reduction of global and local buckling effects; greater dimensional accuracy and greater ductility of the set due, in large part, to the confinement of the concrete. These advantages are also pointed out by De Nardin [5-6], Figueiredo [7] and Oliveira [8].

According to Oliveira [8] and Gomes [9], the increase of the ductility of the steel-concrete system due to the confinement effect is more significant in concrete-filled steel tube columns (CFSTC) and therefore deserve a special focus, because due to this increased ductility it is possible to incorporate alternative materials to the concrete that fill them, such as artificial aggregates, ash, fibers, polymers and recycled aggregates that, directly or indirectly, end up affecting the strength of the concrete, but which, due to the confinement of the concrete core , do not cause great reductions in its resistance. In this study, the mechanical properties of concrete produced with recycled aggregates were used, more specifically, coarse aggregates of crushed concrete from construction and demolition waste (CDW).

According to Angulo [10], construction and demolition waste (CDW) comes from demolition, construction or reform activities and is composed of materials such as wood, concrete, ceramics, mortar, plaster and others. Due to the increase in the generation of these residues, the scientific and technical community has been researching different ways to use them in civil construction.

One of the purposes of this work was to contribute to the use of the CDW, more precisely, of the concrete residues, using them to replace the conventional coarse aggregate existing in the concrete-filled steel tube columns (CFSTC). In this way, the aim is to contribute not only to the preservation of the environment, but also to the reduction of concrete costs, since CDW aggregates have a lower cost than conventional aggregates, according to Cabral [11]. Therefore, this work was done to complement the experimental studies with numerical simulations, in order to obtain a more comprehensive view of the behavior of the aforementioned composite columns.

The use of the CDW in MCF was carried out by Gomes [9] at the Federal University of Ceará – UFC, however this author only conducted experimental studies about the behavior of the MCF with concretes made up of CDW aggregate, making clear the need of a computational analysis to cover the limitations related to the experimental tests. With the simulations, it was possible to better understand the behavior of the alternative material and, consequently, give greater reliability to the study. Thus, the objective of this work was to analyze, through a computational modeling, the structural behavior of the filled composite columns of circular section with concrete made up of CDW aggregate. The analyzes were performed using the computer package Ansys® Workbench 15.0 and the effect of confinement (triaxial stress state), the axial stresses, the strains, the ductility and others parameters were analyzed.

2 Materials and methods

2.1 Preparation of the computational model

In order to simulate CFSTC models that represent the Gomes' experimental models [9], the following steps were performed. These procedures were based in the studies of Queiroz [12], Rigobello and Munaiar Neto [13] and Dos Santos [14].

The properties adopted for the steel and the concrete are shown in the Tab. 1. It draws attention to the fact of most of these properties had been the same adopted for the steel profile and for the concrete core used in the Gomes tests [9], since the initial model generated in the Ansys® v.15.0 will be based on a real physical model tested by this author.

Table 1. Materials properties used in the modeling

Material	Modulus of Elasticity (MPa)	$\nu^{(1)}$	$f_{cm}^{(2)}$ (MPa)	$f_{tm}^{(3)}$ (MPa)	$f_y^{(2)}$ (MPa)	$f_t^{(3)}$ (MPa)
Steel	210,000	0.3	-	-	255	415
Concrete	29,250	0.2	30	1.5	-	-

$^{(1)}$ Poisson's ratio.
$^{(2)}$ compressive average strength for the concrete and yield stress for the ASTM A178 steel, respectively.
$^{(3)}$ tensile average strength for the concrete and tensile ultimate stress for the ASTM A178 steel, respectively.

To represent the behavior of the concrete under uniaxial compression, the isotropic multilinear model, available in the library of the Ansys® v.15.0, was used.

The strength criterion used for the concrete was that of William-Warnke. This criterion was also used by Queiroz [12] in the creation of other computational models of CFSTC. The William-Warnke model is based on the theory of plasticity and allows incorporating the effects of cracking and crushing. It uses five constants to define the collapse surface for the concrete (crushing or cracking). Ansys® v.15.0 allows combining this strength criterion to the constitutive model defined previously, making possible consider the following collapse modes for the concrete: plastification without crushing; plastification without cracking and plastification with cracking or crushing.

The constants mentioned are very important for the calibration phase, since the simulation of the behavior of the concrete is more complex than that of the steel. These constants are: Open Shear Transfer Coef, Closed Shear Transfer Coef, uniaxial cracking stress, uniaxial crushing stress and Hydrostatic Pressure. It is noteworthy that, in addition to these constants, it is necessary, to define the William-Warnke collapse surface in the Ansys® v.15.0, indicate the compressive and tensile strength of the concrete.

The parameters of the collapse surface of the model were introduced in the Ansys® v.15.0 through a computational code compiled by Lima [1] in APDL (ANSYS Parametric Design Language), which is the software's programming language. This language was developed based on the Fortran language, which allows the automation of commands and the use of parametric variables in the models. The initial values of these constants were adopted based on the study of Queiroz [12] and are: Open Shear Transfer Coef equal to 0.2; Closed Shear Transfer Coef equal to 0.6; Uniaxial Cracking stress equal to 6.0; Uniaxial Crushing stress equal to -1.0; and Hydrostatic Pressure equal to 0.0.

The determination of the values of the William-Warnke model constants for the CFSTC with CDW coarse aggregate was carried out from the values adopted by Queiroz [12], which were used as initial values and then modifications were made in these values with the aim of approximate the numerical response to the test results, as much as possible.

In the representation of the steel behavior, a multilinear elasto-plastic constitutive model with isotropic hardening was used, together with the von-Mises plastification criterion.

The model geometry was based on one of the physical models of Gomes [9] and was generated using the Design Modeler (CAD module available in the Ansys® v.15.0). The model dimensions are shown in the Tab. 2. The steel pipe and the concrete core were modeled three-dimensionally.

Table 2. Dimensions of the computational model

Steel tube (mm)	D_{int}	107.60
	D_{ext}	114.30
	e	3.35
	h	345
Concrete (mm)	D	107.60
	h	345

The finite elements adopted for the model's mesh are available in the library of the Ansys® v.15.0. These elements were used by Queiroz [12] in the construction of models of filled composite columns subjected to compression. The finite element mesh, as well as the other steps that follow, were produced in the mechanical analysis module of the Ansys® v.15.0, Ansys Mechanical.

In order to represent the same support and loading conditions as in the Gomes [9] tests, the following conditions were adopted: one end of the column was fixed in three directions and at the other end no binding was attributed. In this free end, increments of displacement in the direction of the longitudinal axis were applied, in order to represent the same characteristics of the axial compression test. These displacement increments were obtained based on the studies of Gomes [9] and Queiroz [12].

2.2 Calibration of the numerical model

To calibrate the model (described in the previous subsections), firstly adjustments were made in the parameters of the collapse surface of the William-Warnke model and, subsequently, the force-strain curve was drawn and compared with the curves of the experimental models. The values of the parameters for the numerical model that had the force-strain curve closest to the curves of the experimental models were: Open Shear Transfer Coef equal to 0.425; Closed Shear Transfer Coef equal to 0.915; Uniaxial Cracking stress equal to 2.391; Uniaxial Crushing stress equal to -2.403; and Hydrostatic Pressure equal to 0.0.

Finally, the force-strain curve of the calibrated numerical model (Fig. 1) was compared with the force-strain curves generated for the filled composite columns of circular section, tested by Gomes [9]. The concretes of these CFSTC contain 0%, 50% or 100% of addition of recycled coarse aggregate from crushed concrete specimens, with thickness equal to 3.35 mm and average strength equal to 30 MPa. However, it is important to point out that to give more reliability to the calibrated data, the validation of these data was carried out through the simulation of another computational model (simulated with the parameters set above), comparing the force-strain curves of the experimental models with the one of the numerical model used in the validation.

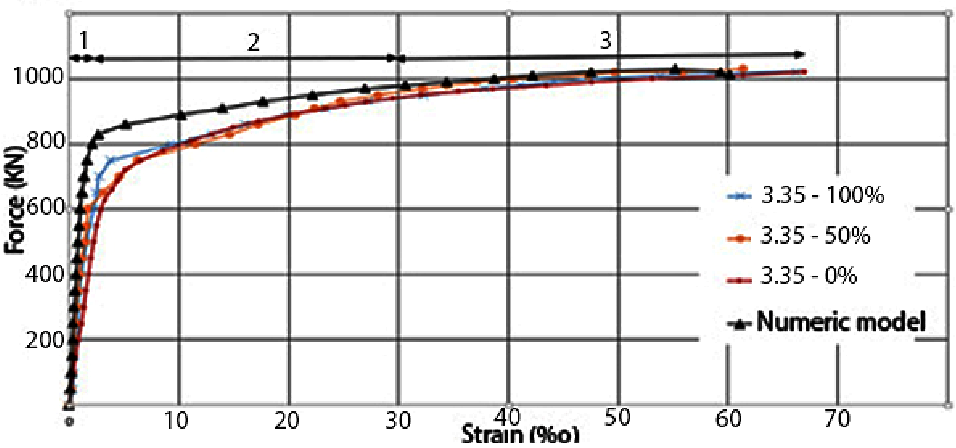

Figure 1. Comparison between experimental and numerical force-strain curves

2.3 Validation of the parameters used in the calibration

In the validation of the parameters of the collapse surface of the William-Warnke model, a model was used with: dimensions shown in the Tab. 3, equal to those of another model tested by Gomes [9]; compressive average strength equal to 30 MPa and the same percentages of addition of recycled coarse aggregate of the previous subsection (0%, 50% and 100%).

Table 3. Dimensions of the model used in the validation

Steel tube (mm)	D_{int}	102.26
	D_{ext}	114.30
	e	6.02
	h	345
Concrete (mm)	D	102.26
	h	345

The initial data for this model were the same as for the previous subsections. The calibrated values for the constants that define the William-Warnke surface were used. It is expected that the force-strain curve of this model, constructed keeping the calibrated parameters fixed, does not present significant difference in relation to the force-strain curves of the experimental models, with percentage of addition of CDW coarse aggregate of 0%, 50% and 100%. Considering the graph of the Fig. 2, it is observed that the force-strain curve of the numerical model is very close to the curves of the experimental models.

It is also observed that the numerical model is more rigid than the experimental models at the end of the segment 1 and beginning of the segment 2. The final segment of the numerical curve is very close to the final segments of the experimental curves. In this way, the parameters used in the concrete modeling can be considered valid and the existing differences between the analyzed values can be attributed to the adopted simplifications, mainly regarding the contact conditions in the steel-concrete interface.

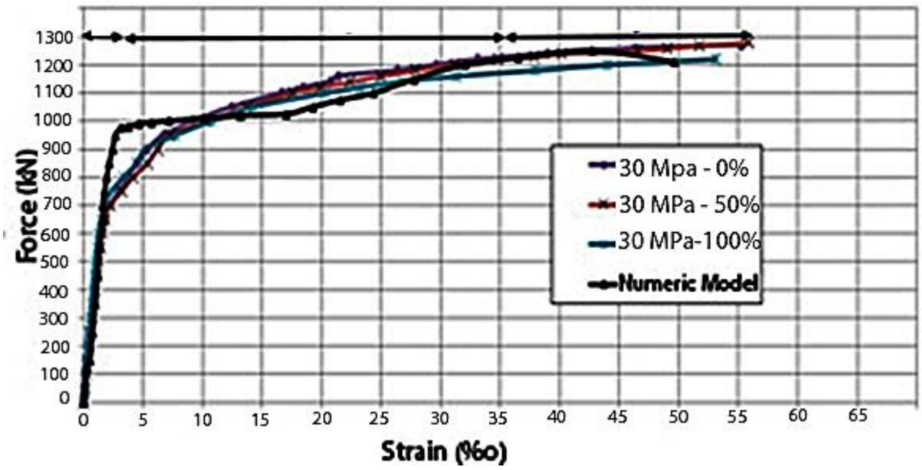

Figure 2. Comparison between experimental and numerical force-strain curves

3 Results and discussions

The extrapolation of this model is presented, varying the following parameters: steel tube thickness (e) and compressive average strength (f_{cm}). In order to analyze the behavior of the extrapolated CFSTC models using the William-Warnke constants validated in the section 2.3 which considers the use of CDW aggregates, the force-strain curves of these models were compared with the curves of the simulated CFSTC models with the constants adopted by Queiroz [12] that were determined considering the use of natural coarse aggregates. Subsequently, in order to analyze the increase in strength and ductility of the CFSTC, the results of the extrapolated CFSTC models were compared with those of the concrete models simulated in isolation (without the presence of the steel tube).

3.1 Model extrapolation (parametric analysis)

Ten models were generated from the initial (validated) model, five models with variation in the "R_i" parameter, in order to analyze the influence of the variation of the steel tube´s thickness on the confinement of the concrete core and the rest of the models with variation in the "f_{cm}" parameter to evaluate the influence of the concrete´s compressive average strength in its confinement.

Finally, twelve more CFSTC models were generated with the same variations of "f_{cm}" and "R_i" of the extrapolated models, however, for these models, the constants of the study of Queiroz [12] (William-Warnke constants) were used in the constitutive model of the concrete core. The force-strain curves of these models were compared with those of the extrapolated models. It is expected that this comparison permits a better understanding of the difference of CFSTC´s behavior with concrete cores manufactured with natural aggregates (Queiroz constants) and with CDW aggregates (constants validated in the section 2.3).

The nomenclature, used in the graphs and tables below, was as follows: Base Model: validated initial model; PA_i: parameterized models, with i from 1 to 10; R_n: radius of the steel tube in mm, where "n" can be "internal" or "external"; H_{PMP}: height of filled composite column of circular section in mm; Q: indicates that the model was simulated with the constants of the study of Queiroz [12] (William-Warnke model for the concrete); e: thickness of the steel tube in mm; f_{cm}: compressive average strength of the concrete in MPa; σ: axial stress of the CFSTC´s concrete core in the last loadstep in MPa; σ': axial stress of the simulated concrete in isolation (without the steel tube) in the last loadstep in MPa and σ_r: radial stress of the CFSTC´s concrete core in the last loadstep in MPa.

In the graph of the Fig. 3, it is possible to observe the behavior of the extrapolated CFSTC models considering the variation of the steel tube´s thickness.

Considering only the representative models of concretes manufactured with CDW aggregates, it can be seen that the model with the highest ductility was the PA_5 model (model with the smallest thickness of the steel tube).

The model with the greatest thickness of the steel tube was the one that presented greater strength and rigidity. Analyzing the curves of these models, it is evident that when the thickness of the steel tube is increased, the steel-concrete assembly becomes more resistant, but it also ends up showing less ductility, which is often not suitable from the point of view of use of this structural element. The observations made only for the representative models of concretes manufactured with CDW aggregates are also valid when only representative models of concretes manufactured with natural aggregates (Queiroz constants) are considered. It is also observed that the representative models of concretes made with natural aggregates present greater strength and less ductility than their corresponding models with CDW aggregates.

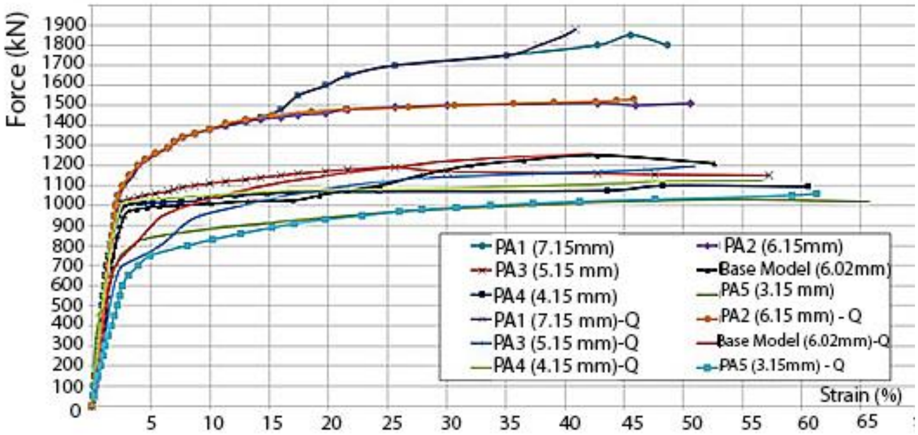

Figure 3. Force-strain curves for the extrapolated models

The concrete´s strength highly changes the strength of the steel-concrete set, because, according to Gomes [9], Oliveira [8] and Queiroz [12], the variations in the concrete´s strength, together with the thickness variations of the steel tubes, provide the highest variations in the strength of the composite filled steel tube column.

In the graph of the Fig. 4, it can be seen that the PA_6 model showed higher ductility due to the lower strength of the concrete, due to the lower modulus of elasticity and due to the lower cracking, since part of the strains was prevented by the steel tube walls, thus resulting a triaxial stress state of the concrete core (confinement effect). Regarding the strength of the composite column, it is clear that the greater the strength of the concrete core, the greater the strength of the column. However, Gomes [9] and Oliveira [8] state that CFSTC with higher strength of the concrete cores tend to present failure by crushing of the concrete. It is observed that the models of concrete with natural aggregates presented higher strength and less ductility than their corresponding models with CDW aggregates.

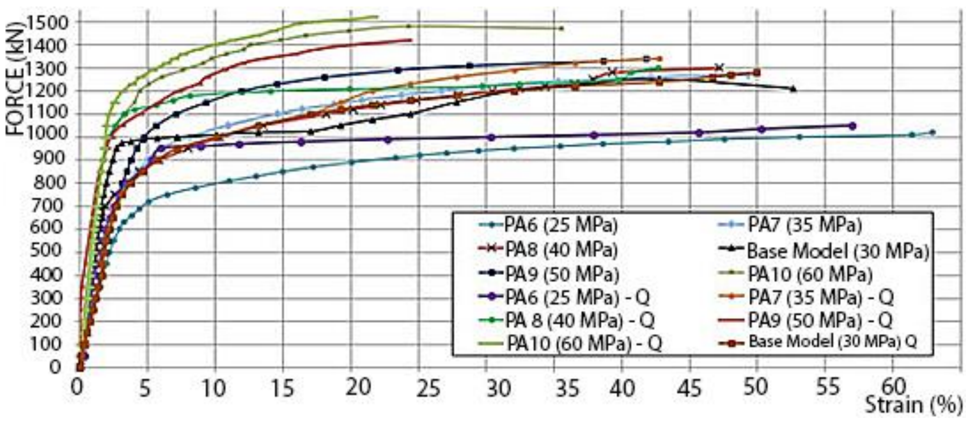

Figure 4. Force-strain curves for the extrapolated models

4 Conclusions

Based on the results presented in the graph of the Fig. 3, it can be concluded that the thickness of the steel tube has a significant influence on the structural behavior of the CFSTC. It should be noted that higher thickness values tend to generate CFSTC with higher strength and with concrete cores subjected to higher stresses. On the other hand, thinner steel tubes tend to generate CFSTC with greater ductility. Furthermore, it should be noticed that tubes with thick steel walls, increases the costs of the CFSTC, and increases the stiffness of these elements too, leading, in general, to a sudden failure by crushing of the concrete core, as Oliveira [8] also states.

In the observed cases of ductility increase of the concrete core used in the CFSTC, according to Oliveira [8], this is attributed to the triaxial stress state of the concrete core. Reiterating what Gomes [9] claims, regarding the use of alternative materials that can cause reductions in the compressive strength of the concrete, these reductions can be partially offset by the triaxial state of stress of the concrete core. However, it is worth noting that high strength concretes, in addition to generating high costs, require strict technological control and often generate high stiffness CFSTC, which collapse abruptly, without prior warning of failure.

It was also possible notice that for concretes manufactured with CDW aggregates, the parameters of the William-Warnke surface do not differ much from the parameters used for concretes manufactured with conventional aggregates. It can also be verified that in the experimental study by Gomes [9], the structural behavior of the CFSTC using concretes manufactured with conventional coarse aggregates does not differ much from the behavior of the CFSTC using concretes with CDW coarse aggregates. Therefore, the contribution of this research was achieved, considering that the conclusions obtained by numerical extrapolations allow a better understanding of the mechanical behavior of CFSTC

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