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Finite element study to address the axial capacity of the circular concrete-filled steel tubular stub columns

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ABSTRACT

This paper presents finite element analysis using the software ABAQUS to the circular CFST stub columns. The produced FE model is verified by comparing results of the FE simulation, failure load, and load-axial strain curves, to the experimental results. Then a parametric study has been done to examine the effect of the steel tube yield strength and size. A method is then proposed to calculate the confined concrete compressive strength. The proposed model was verified against 382 previously tested data. It has been found that both the FE and the numerical model are in excellent agreement with the experimental data. The numerical model proposed in this paper compared to the models proposed by leading design codes and previously proposed models by other researchers. It has been found that the current model predicts the ultimate capacity of these columns with excellent accuracy while the compared-with numerical models were generally providing conservative predictions.

1. Introduction

The concrete-filled tube systems have been widely used for construction during the last few decades. As a result of their reliable and efficient performance, they have been used for the construction of high-rise buildings and bridges. Although they have been constructed to resist all the major types of loads such as compression, flexural, and torsional forces, their main usage was in the form of compression members.

Among the various types of these composite systems, the circular CFST systems were the most common type of these structures. The high interest towards these structures can be attributed to their excellent response under both static and dynamic loading. Therefore, a more attention has emerged in the recent years to more study and understand the behavior of circular CFST stub, short, and long columns.

Their improved ductility, increased impact, and increased energy absorption contributed in improving their behavior under dynamic loads such as earthquakes and blasts. On the other hand, the core of concrete played a significant role in increasing the stiffness of these structural members which eventually made them capable of undergoing high static loads with minimum deflections.

The steel tube contributed a great deal by applying confinement pressure to its in-filled concrete. This resulted in providing triaxial stresses towards the core of concrete and that in turns improved the compressive strength of the concrete core, f_c'. In addition to these enhanced structural characteristics, the steel tube usually used as a formwork which reasonably reduced the construction costs.

For all these advantages and more, the circular CFST stub columns were the target of numerous experimental studies [1–41] to more understanding such structures. Despite this great interest towards this type of structures, the methodologies proposed in analyzing and designing them were not promising, as it will be discussed further in this paper.

For instance, ACI code [42] still, up to now, ignoring the confinement effect provided by the steel tube in increasing the load capacity of these columns. While, the Eurocode 4 [43], unlike the ACI code, has addressed the confinement of the steel tube of this type of structures in its design methods. However, the calculation procedures adopted in it were complicated and provided relatively conservative predictions towards the capacity of these columns. On the other hand, even though the Chinese code DL/T [44] method in this context was the most accurate among the other Chinese design codes, yet it showed more conservative predictions than the Eurocode 4.

Several numerical studies by other researchers [45–62] were carried out to propose empirical formulas to determine the capacity of these columns, based on FE "finite element" and/or mere statistical analysis. Three main parameters, $\frac{D}{t}$, f_y, and f_c', took the most focus in these researches with more emphasis on the first parameter $\left(\frac{D}{t}\right)$, which appeared very often in these researches.

Giakoumelis et al. [9] investigated, experimentally, the response of such columns under axial loading by changing the value of the three parameters with more focus on f_c'. They examined the interaction,

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between the concrete core and the steel tube, impact by using grease material to eliminate the friction which is suspected to have influence in increasing the ultimate load of these columns.

S. P. Schneider [19] investigated the behavior of these columns under axial loading, by testing the change influence of f_y, $and \frac{D}{t}$. S. P. Schneider detected the strain hardening role in increasing the load carrying capacity as well as the ductility of these columns.

Han et al. [35] experimentally studied the response of these columns when associating high strength Self-Consolidated Concrete with two grades of steel, normal and high strength. D/t was ranged from 30 to 134 in their study. They proposed based on their research findings simplified equations to determine the ultimate load of these composite columns.

On the other hand, few research studies used the FE and other numerical modeling approaches to study these columns. For instance, Liang et al. [53], using the fiber element analysis, studied a set of previously tested specimens by [27,32,34]. For convenience, they confirmed their numerical model by comparing its results with the experimental results. They carried out a parametric study to propose a method to calculate the confined concrete compressive strength by calculating the confining pressure provided by the steel tube.

Starossek et al. [56] and based on FE simulation using the commercial code ABAQUS, analyzed the confined concrete response when undergoing triaxial stresses using the concrete damage plasticity model. Their methodology consisted of catching the essence of the confinement pressure and its impact on increasing the concrete core compressive strength by using bolts screwed near the ends of these columns, as it was expected that these locations will receive a maximum confinement. These bolts acted as mechanical shear connectors and hence has been used to address the interaction between the two components of these columns.

Tao et al. [59] created FE model using ABAQUS and developed a method to use the uniaxial stress-strain material combined with plasticity model available in ABAQUS to predict the response of 142 circular CFST stub columns. They found that the values of the damage plasticity parameters, the dilation angle of concrete (ψ), ratio of the second stress invariant on the tensile meridian to that on the compressive meridian (K_c), and the ratio of the compressive strength under biaxial loading to uniaxial compressive strength $\left(\frac{f_{b0}}{f_c'}\right)$, were very sensitive to these columns behavior under axial loading. Accordingly, they used existing equations to calculate the values of these parameters instead of merely adopting fixed values for these parameters, which was the case for many previous studies.

In spite of this high interest to addressing the confinement nature of the circular CFST stub columns, the outcomes were not harmonious. The models proposed previously were generally conservative and somehow failed to highlight the real interaction nature of these columns. This paper produces an analytical study which includes simulating the circular CFST stub columns response under axial loading using enhanced FE model created with the help of the software ABAQUS.

Part of the reasons that made the previous research failing to catch the essence of the interaction nature between the two components of these columns was using the parameter $\left(\frac{D}{t}\right)$ as an indicator of the confinements pressure degree. This drawback is terminated in this paper by presenting a more suitable method where another parameter, $\%A_s$[1] “Steel content”, has been proven to be a better indicator of the confinement pressure degree.

Aside from the steel content, the parameter f_y has also an important influence in increasing the tri-axial stresses and ultimately increasing the load carrying capacity of these columns. Up to now, the focus of previous researches on this parameter wasn’t on the required level. In best cases, f_y has been given a small part in their proposed formulas. Shams et al. [45], for instance, considered in their research a zero influence of f_y in increasing the degree of the confinement pressure.

On the other hand, many previous researchers overestimated the influence of f_c' by assuming a significant effect on the confinement and hence improving the load carrying capacity of these columns. This assumption has been eliminated from this study as it has been noted by analysis that this parameter, f_c', has negligible effect in increasing the confining pressure. Similar observations were also found in previous researches, e.g. [53].

The goal of the current study is to propose a method encounters the effect of confinement of the steel tube to calculate the capacity of circular CFST stub columns. A finite element model using the software ABAQUS is produced. The accuracy of the created FE model is verified against test results. An insight towards the nature of the interaction between the core of concrete and its confining steel tube is also provided in this study. Lastly, the current study aims to propose a simple design procedure to address the capacity of the circular CFST stub columns. As the old methods were generally inaccurate and/or contains rather complicated procedures.

2. FE model details

2.1. Boundary conditions, load application, and mesh details

Most of the experimental work which has been done to test the axial load carrying capacity of circular CFST stub columns was performed by fixing the bottom end against every possible movement while applying the load at the upper end. To duplicate such a procedure, the bottom end of the simulated specimens was fixed against all degrees of freedom. Simultaneously, the upper end was also restrained against all degrees of freedom, except the one in direction of the axial deformation. The load has been made by applying displacement at the upper end while the load bearing capacity of the column was measured using a reference point at the lower end. Fig. 1 shown below, depicts the FE model details:

In terms of meshing, the model was discretized in such a way that reserves obtaining the most accurate results possible in exchange for the lowest computing time. A typical specimen meshing has been conducted by generating 24 elements along the outer peripheral. The center of the concrete core was meshed in a sliced way to prevent non-uniformed element shapes from existing to avoid possible inaccuracies. The gross cross-section of the column consisted of 144 elements, while the axial direction contained 2.5 the number of elements in the lateral direction, as it was suggested by Tao et al. [59].

2.2. Concrete core constitutive model

Modeling the response of the concrete material is the most challenging task, as it comprises simulating the tri-axial response and predicting the confined compressive strength of the concrete material. This can be mainly attributed to the presence of the confinement, and the strain hardening behavior of the steel material. Up till now, there have been two main approaches to simulate the tri-axial-stress state of concrete. The first one is to provide the confined stress-strain curve with the confined concrete compressive strength. While the second is to provide the uniaxial stress-strain along with the concrete unconfined, uniaxial, compressive strength and predicting the confinement by using the damage plasticity model [63], which is controlled by changing value of the parameters, the dilation angle of concrete (ψ), ratio of the second stress invariant on the tensile meridian to that on the compressive meridian (K_c), and the ratio of the compressive strength under biaxial loading to uniaxial compressive strength $\left(\frac{f_{b0}}{f_c'}\right)$.

The response of the core of concrete under axial loading in the

[1] $\%A_s$ is the steel content, which can be defined as the ratio of the cross-section area of the steel tube to the column’s gross cross-section area.