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Numerical study of circular steel tube confined concrete (STCC) stub columns

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ABSTRACT

In this paper, a new finite element (FE) model using ATENA-3D software was developed to investigate the compressive behavior of circular steel tube confined concrete (STCC) stub columns with taking into account various concrete strengths. The "CC3DNonLinCementitious2User" material type for concrete in ATENA-3D with some modifications of material laws was adopted to simulate the behavior of concrete core with consideration of the confinement effect induced by steel tube. Both ultimate load and axial load versus strain obtained from FE model were compared with those from previous test results. This comparison indicates that the new FE model in ATENA-3D is capable of predicting the compressive behavior of circular STCC stub columns. An extensive parametric analysis using this established FE model was then conducted to examine the influence of concrete compressive strength, steel yield strength and steel tube thickness on the strength and the ductility of circular STCC stub columns. Furthermore, based on previous test database, some analytical model for concrete confined by steel tube was evaluated and a simplified formula for predicting the ultimate load of circular STCC stub columns was also proposed. There was a good agreement between the predictions of the ultimate load using this proposed formula and FE model.

1. Introduction

It is well established that lateral confinement induced by steel tube can result in significant improvements in both compressive strength and ductility for concrete. Moreover, due to the best attributes of both steel and concrete, concrete filled steel tube columns (CFSTCs) possess numerous structural benefits over equivalent reinforced concrete or steel structures, such as a better fireproofing property, higher stiffness, formwork economy, possibility of delaying the local buckling of steel tube, reduction of cross-section and high seismic resistance [13]. Therefore, CFSTCs have attracted a great deal of research attentions and widespread applications throughout the world.

It has been proven that, for CFSTCs under axial loading, the confinement effect becomes more effective with the load applied to only the concrete core compared to the case where the entire section is loaded [14,19,24,46,47]. According to many previous researchers (e.g., Schneider [36], Shams et al. [38], De Nardin and El Debs [4]), CFSTCs with circular section present the best gain of load capacity due to the significant confinement effect and offer much more post-yield axial ductility compared to CFSTCs with other shapes of cross sections such as square or rectangular sections. For this reason, most of studies have mainly concerned with circular CFSTCs. As recommended by Yu et al. [51] and Han et al. [14], to ensure the most important design factors including the strength and the ductility, CFSTCs should be loaded only on the concrete core. This loading pattern refers to the form of steel tube confined concrete (STCC) columns where the steel tube is mainly used to provide lateral confining pressure to the concrete core rather than to carry the axial load together with the concrete [18,19,32,51]. Fig. 1 shows a concept of circular STCC columns suggested by Sun [42].

Earlier studies on short circular STCC columns published by Gardner and Jacobson [9], Tomii et al. [44], Sakino et al. [34], Orito et al. [29], Schneider [36], Johansson [18,19], O'Shea and Bridge [28], Han et al. [14], Huang et al. [17] found that, in the case of loading on the concrete section, there is a restraining effect of the steel tube on the concrete core as soon as the lateral deformations of the concrete core develop. In addition, the bond strength between the concrete core and the steel tube has a significant influence on the confinement effect and the structural behavior as well, whereas there is no effect of bond strength in the case of loading on the entire section. Results of these studies demonstrated that short circular STCC columns are

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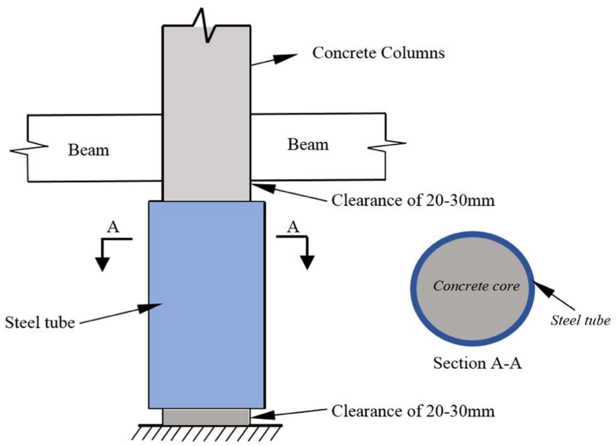

Fig. 1. A concept of STCC columns (following Sun [42]).

characterized by very high levels of energy dissipation, ductility and loading capacity due to greater confinement efficiency compared to circular CFTSCs under loading on the entire section or only on the steel section. It was also identified that higher compressive strength of concrete core can lead to lower confinement efficiency. Following these preliminary studies, De Oliveira et al. [6] performed studies on the passive confinement in circular STCC columns with a wide range of concrete compressive strengths, length to diameter (L/D) ratios and diameter to thickness (D/t) ratios. It was observed that the columns using normal strength concrete (NSC) including C30 and C60 displayed a good ductility without loss of capacity after reaching the peak load, but that was not found for the columns employing high strength concrete (HSC) consisting of C80 and C100. These authors also reached the conclusion that thicker steel tube is needed to promote the confinement effect for circular STCC columns using HSC.

In recent years, with the rapid development of concrete technology, ultra-high strength concrete (UHSC) has become a potential alternative to NSC and HSC because of superior performance such as extremely high compressive strength, an usable tensile strength and very high durability properties [7,47,49,54,55], thus allowing engineers to reduce the size of structural members and to increase the load bearing capacity [24,25]. However, UHSC exhibits enormous compressive brittleness accompanying with the increase of concrete strength, leading to some limitations for its applications in construction. To overcome this drawback, research effort has been directed towards circular STCC columns using UHSC. Liew and Xiong [23,24], Xiong [47] presented an extensive experiments on CFSTCs using high strength materials including UHSC with compressive strength up to 200 MPa and high strength steel tube with yield stress up to 700 MPa. Research findings indicated that for all circular CFSTCs, the brittleness of UHSC causes a sudden load drop after reaching the peak load and there is no significant confinement effect that could be developed before the peak load for the case of loading on the entire section. However, these authors recommended that strength and ductility of circular CFSTCs using UHSC can be further improved by imposing the load only on the concrete core where the tri-axial confinement effect is maximum. Likewise, Tue et al. [45,46] and Schneider [35] investigated on short circular STCC columns using ultra high performance concrete (UHPC) with compressive strengths ranged between 150 and 180 MPa and various steel tube thicknesses varying from 2.5 mm to 8.0 mm. It was highlighted that the sudden load drop can be overcome by sufficient confinement of steel tube through loading only on the concrete core and increasing steel tube thickness, thus enhancing the strength and the ductility.

From the literature review as mentioned above, it can be seen that although there is a large number of studies on CFSTCs with the load applied to the entire section, combined theoretical and experimental studies on STCC columns are still limited. Furthermore, the majority of studies on circular STCC columns have been concerned with the use of NSC and HSC, whereas to the best knowledge of the authors, apart from the experimental studies reported by Liew and Xiong [22–25], Xiong [47], Tue et al. [45,46] and Schneider [35], no such studies has been carried out with circular STCC columns using UHSC or UHPC.

Despite the fact that experiments play an important role for an investigation on STCC columns, they are quite expensive and time consuming, particularly for the tests with a wide range of concrete strengths or steel yield strengths and thicknesses. Hence, numerical studies are much needed to provide supplementary information to previous experiments and to enable further parametric studies, thereby contributing to the prediction of the behavior of structure without testing. In the past, there have been numerous investigations on CFSTCs using finite element (FE) technique (e.g., Johansson and Akesson [18], Gupta and Singh [11], Hu et al. [16], Tao et al. [43], Yu et al. [51], Song and Liew [40]), but most of these FE models have mainly focused on CFSTCs under loading on the entire section and employing NSC or HSC. Tao et al. [43] developed a refined FE model where a new three-stage model including the strain hardening and softening rule for confined concrete was proposed and adopted in ABAQUS software in combination with calibration of some key material parameters in Concrete Damaged Plasticity Model. This new FE model is capable of simulating short CFSTCs under axial compression with a variety of concrete strengths. An et al. [1] has recently introduced a FE model using ATENA-3D for circular STCC columns under concentric loading with three types of concrete comprising NSC, HSC and UHPC. The mechanism of circular and square STCC stub columns infilled with NSC under axial compression was inspected by Yu et al. [51] through a FE analysis using ABAQUS software. Similarly, Haghinejad and Nematzadeh [12] performed a nonlinear FE analysis in ABAQUS software of axially loaded circular STCC stub columns by using new confinement relationships for NSC core. From the survey of available literature, it has been found that there is relatively little attention for numerical study of circular STCC columns, especially FE model which covering different concrete strengths.

To address the aforementioned research gap, the main purpose of this study is to investigate the compressive behavior of circular STCC stub columns with a wide range of concrete strengths based on a new FE model in ATENA-3D and collected database. Firstly, some analytical strength models for confined concrete is evaluated through a comparison with previous experimental results. Secondly, a new formula obtained from a regression analysis of database for predicting the ultimate load of circular STCC stub columns with taking into account the confinement index is proposed. Then, a new FE model using ATENA-3D software is developed to simulate circular STCC stub columns with various concrete strengths. The validity and accuracy of the FE model are verified by comparing with some previous test results. Lastly, a parametric study on the effects of concrete strengths, yield strengths and thickness-to-diameter ratios of the steel tube are conducted using this FE model.

2. Simplified model for prediction of axial ultimate load

2.1. Summary of experimental data

As regards the classification of concrete compressive strength, the following limitations were suggested by Liew and Xiong [22,23]:

- Normal strength concrete (NSC): $f_c \le 60$ MPa
- High strength concrete (HSC): $60 < f_c \le 120$ MPa
- Ultra-high strength concrete (UHSC): $f_c > 120$ MPa

where f_c is the compressive strength of concrete cylinder.

Based on the compressive behavior of circular CFSTCs within uniaxial compression tests using various slenderness ratios, a short column