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# Constitutive model for confined ultra-high strength concrete in steel tube

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## HIGHLIGHTS

- A constitutive model for confined ultra-high strength concrete is proposed.
- The dilation angle model is a function of lateral pressure and plastic deformation.
- The hardening/softening rule is dependent on pressure and plastic deformation.
- The interaction between the steel tube and the confined concrete can be predicted.

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## ABSTRACT

With the development of material science and production technology, ultra-high strength concrete (UHSC) with uniaxial compressive strength up to 200 MPa has been made available commercially and used for concrete filled steel tubular (CFST) columns in high-rise buildings. Finite element analysis is a necessary tool to analyze CFST columns, but its accuracy depends on the generic constitutive model for the confined UHSC in the steel tube. This paper proposes a new constitutive model for confined UHSC based on (1) a yield criterion which is a function of hydrostatic pressure and lode angle, (2) a non-associated flow rule with a dilation angle that is a function of the confining pressure and the equivalent plastic strain, and (3) a hardening/softening rule which is dependent on the confining pressure and the equivalent plastic strain. The parameters of the proposed constitutive model are calibrated by a series of uniaxial compression, biaxial compression and triaxial compression tests of UHSC specimens. The constitutive model is then implemented in ABAQUS and verified by the test results of short CFST columns. Comparison of the test and predicted results in terms of compression load versus axial strain and lateral strain curves demonstrates that the proposed model can predict accurately the maximum resistance of the stub CFST columns as well as the interactive behavior between the steel tube and the confined concrete core.



## 1. Introduction

Concrete filled steel tubular (CFST) columns have been increasingly used in high-rise buildings, offshore structures and large span structures, as they can take full advantages of both steel and concrete, such as high strength, high stiffness and good ductility. Due to the synergistic interaction between concrete core and steel tube, the best usage of construction materials can be achieved. The compressive strength and ductility of concrete are enhanced owing to the confinement effect provided by steel tube, while the inward local buckling of the steel tube is prevented by the concrete core. With the recent advances in material science and production technology, the concrete of higher compressive strength over 120 MPa and up to 200 MPa has been made available commercially. Characterized by the extremely high uniaxial compressive strength, this new type of material is denoted as ultra-high strength concrete (UHSC) in the literatures [1,2]. UHSC has been employed mainly in columns for high-rise building construction to improve the structural efficiency in term of smaller strength to column size ratio [1,3]. Finite element (FE) method has been widely used to generate additional data of CFST columns and their accuracy was

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verified by comparing the predicted results with the test data [4–10]. To simulate the interaction between the steel tube and concrete core interface and hence to obtain an accurate prediction of the behavior of CFST columns, an accurate constitutive model for the confined ultra high strength concrete is necessary. However, an accurate constitutive model that can predict the failure of UHSC under tri-axial stresses is currently unavailable. Most of the research work on confined concrete model was derived from the test data of stub CFST columns with normal strength concrete and high strength concrete [4–10]. This type of model ignored the fact that UHSC exhibited a more brittle post peak behavior than that of normal and high strength concretes when it was under compression [11]. Moreover, the previous numerical work focused mainly on predicting the compression resistance of CFST columns instead of investigating the confinement behavior and the failure mechanism of the confined concrete core in the steel tube. Most of the proposed constitutive models fail to capture the plastic dilation of the concrete core in CFST columns.

Associated flow rule was adopted in literatures [4–6,8] and non-associated flow rule with a constant value of dilation angle was assumed in the literatures [7,9,10,12]. As pointed out by Yu and Teng et al. [13,14], those assumptions on flow rule are not in line with the experimental findings that the flow rule of concrete is dependent on confining pressure and plastic deformation [15]. Therefore, the cross-sectional dilation of concrete cannot be accurately described by the flow rule with a constant value, even for non-associated flow rule. With those adopted flow rules, it is not possible to expect a reasonable simulation of the interaction between the concrete core and steel tube. On the other hand, in order to simulate the confinement effect on the plastic behavior of concrete core, uniaxial stress-strain relationship was modified by matching the FE prediction with the result of the tested CFST stub columns via trial and error process. This approach leads to an empirical solution to a particular problem. In this way, the researchers proposed various empirical stress-strain models for the confined concrete in CFST columns [5–10]. However, the accuracy of such empirical stress-stain model is restricted to the given specimen subset, since the trial and error method makes no attempt to generalize the solution (stress-strain model) to other specimens with varying parameters such as cross sectional shape, diameter to thickness ratio, width to thickness ratio, steel grade, etc., out of the prescribed experimental range. Moreover, due to the deviation of the predicted cross-sectional dilation of concrete core caused by using inappropriate flow rules, compensations were implicitly made in the determination process of the uniaxial stress-strain relationship, which indicated that the proposed stress-strain model was not able to represent the real behavior of the confined concrete in the CFST columns.

A review of the existing numerical models of CFST stub column revealed the limits of the current constitutive model and highlighted the need to develop a comprehensive and generic constitutive model for confined UHSC. The measurements of cross-sectional dilation of the concrete core and the confining pressure exerted on the interaction surface between concrete core and steel tube are unfeasible due to the configuration of CFST specimens. To this end, the knowledge of concrete under multiaxial stress states established from uniaxial compression, biaxial compression and triaxial compression tests can be used in the development of the constitutive model for steel tube confined concrete. After the pioneering study by Richart et al. [16], systematic investigations have been carried out on the behavior of confined normal strength concrete [17–20]. Several researchers have studied the behavior of high strength concrete under multiaxial stresses [21–25]. A comprehensive review of unconfined and actively confined concrete test results indicates the stress-strain behavior and lateral strain-to-axial strain relationship are different from normal strength concrete to high strength concrete [15,26]. Thus, concerns have been expressed in the performance of UHSC under uniaxial compressive and tensile loadings [27,28] and biaxial compressive loading [29,30].

The present work aims to develop a previously unavailable constitutive model for steel tube confined UHSC, which is of good generality and accuracy. The paper starts with the discussion on key characteristics of such constitutive model. Then, the concrete plasticity model is described in term of yield criterion, flow rule, and hardening/softening rule, in the following section. A type of UHSC with uniaxial compressive strength over 200 MPa was tested under triaxial compressive loading with various confinement pressures from 25 to 400 MPa by the authors [11]. Based on these experimental results the model parameters are calibrated. After that, the developed constitutive model is implemented in general FE software ABAQUS by the user-defined subroutine VUSDFLD and finally the predicted results are verified against the test data of steel tubes infilled with such UHSC.

## 2. Key characteristics of a constitutive model for steel tube confined concrete

Concrete elements under laterally confining pressure can undergo pronounced inelastic axial deformation prior to reaching the failure load. A constitutive model based on plasticity theory is appropriate to describe the material response of such concrete. Due to the difficulties in measuring the lateral dilation of concrete and the confining pressure on the interface between the steel tube and concrete core, the previous constitutive models [5–10] were developed by matching the predicted axial force-displacement response of CSFT columns with those from tests via a trial and error process. This semi-empirical approach, however, provides a good agreement between the FE prediction and the test results, but it is not a sufficient condition to establish a generalized constitutive model.

Fig. 1 shows a CFST column subjected to compression. Under axial compression, the concrete core shows cross-sectional dilation. At the initial stage of elastic deformation, the inner surface of steel tube may separate from the concrete because the Poisson's ratio of steel is higher than that of concrete. Thus, there is no confinement effect in the early stage of loading. With the increasing of axial load, the formation and propagation of micro cracks in the core concrete increase the rate of radial dilation. Consequently, the core concrete gets in contact with the steel tube and pushes the latter outwards causing radial deformation. This induces hoop stress, $\sigma_h$, in the steel tube as shown in Fig. 2a. This hoop stress is counter-balanced by the confining pressure, $\sigma_{cp}$, exerted on the concrete core as shown in Fig. 2b. Owing to the confinement effect, the strength and ductility of the confined concrete are enhanced.

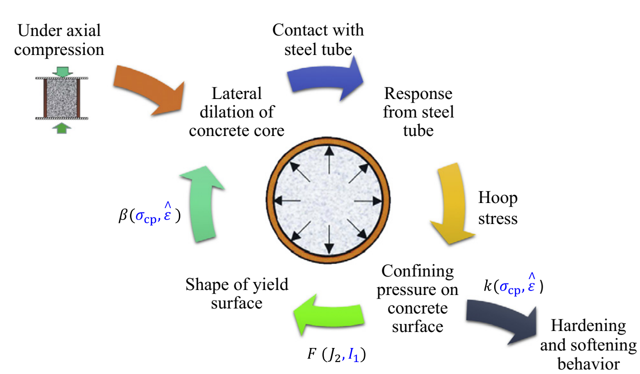


**Fig. 1.** Interaction between steel tube and concrete core.