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Seismic performance of concrete-encased column base for hexagonal concrete-filled steel tube: numerical study

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ABSTRACT

The seismic performance of concrete-encased column base for hexagonal concrete-filled steel tube (CFST) columns was investigated through finite element analysis (FEA) modeling. A FEA model for the seismic analysis of the column base was first established and verified with test results. The numerical model was subsequently used to study the mechanical behavior of the column base, including the typical failure modes, the load transfer mechanisms, and the interaction among components and the internal force distribution. Finally, a parametric study was carried out to investigate the effect of salient parameters on the behavior of the column base. It was found that the parameters of the outer RC component, as well as the axial load level, have significant effects on the seismic behavior of the column base, while the effects of the parameters of the CFST column and the base plate connection were moderate within the investigated parameter range. In addition, the accuracy of a simplified strength model for the column base proposed by the authors was verified with the FEA model.

1. Introduction

The bases for the columns in residential or industrial buildings serve as the connections between the upper structure and the foundation. It has been noted that the bases for steel columns can be typical damage locations under seismic load [1]. So it is of great importance to design the column bases with sufficient strength, stiffness, as well as energy dissipation capacity. It has been summarized that generally there are three types of column bases in engineering practices, namely the exposed base-plate connection, the embedded connection, and the concrete-encased connection, as shown in Fig. 1 [1, 2]. The exposed base-plate connection consists of a base plate and anchor bolts and is widely used in relatively low-rise buildings. The embedded connection achieves strength and stiffness through embedding the column into the foundation. The concrete-encased connection can be seen as an enhanced version of the base-plate connection, in which its exposed base, as well as part of the column end, is encased by an outer reinforced concrete (RC) component. There have been extensive studies on the seismic performance of base connections for steel columns, most of which focus on exposed base-plate connections (e.g., [3–5]) and embedded connections (e.g., [6, 7]). However, studies on the concrete-encased connections for steel columns are still quite limited, as summarized by [2].

In the last several decades, concrete-filled steel tubular (CFST) members have been extensively used as main structural components in large-scale structures and infrastructures, such as high-rise and super high-rise buildings, bridges and subway stations [8]. There have been several groups of studies on the design and performance of column bases for CFST structures [9–14]. It is noted that most of the existing studies focused on the embedded type of connection, such as the experimental studies by Roeder and co-authors [9–11]. Such connection is relatively simple for construction and could achieve excellent ductility at the connection, indicating good potential for applications like bridge piers in seismic regions.

While the embedded type of connection could achieve the required strength and stiffness for many CFST constructions, it would meet construction difficulties once the size of the columns become extremely large and thus requires very deep embedment. One recent example is the mega CFST columns used in the super high-rise building China Zun [2]. The sectional size of the columns can be as large as 80 m^2 and it is unrealistic to achieve strength and stiffness for the column bases either through embedded or exposed base-plate connections. For such kind of CFST constructions, it deems suitable to employ the concrete-encased type of column base due to its relatively high stiffness and strength and moderate constructional complexity.

However, as reviewed above, there is still a lack of systematic studies and design methods such connections, which hinders their applications in engineering constructions. The authors have conducted seismic tests on 6 concrete-encased column base specimens with hexagonal CFST columns recently [2]. In the specimens, the hexagonal shape CFST section is a simplification of the actual CFST section employed in the aforementioned super high-rise building China Zun. Two types of failure modes, namely failure at the bottom section of the column base and

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Nomenclature

A_a	Cross-sectional area of anchor bolts
A_c	Cross-sectional area of concrete in CFST
A_s	Cross-sectional area of steel in CFST
B	Section width of hexagonal CFST
B'	Effective width of hexagonal CFST
d_c	Compressive damage coefficient of concrete
d_t	Tensile damage coefficient of concrete
E_c	Elastic modulus of concrete
E_s	Elastic modulus of steel
E_{total}	Accumulated energy dissipation
f_{cu}	Cube compressive strength of concrete
f_c'	Cylinder compressive strength of concrete
f_y	Yield strength of steel
H	Height of outer RC component
L	Effective length of CFST column
M	Moment
M_{FEA}	Predicted maximum moment by FEA model
M_{max}	Measured maximum moment ($=P_{max}L + N_0\Delta_{max}$)
M_{uc}	Ultimate flexural strength of hexagonal CFST
N_0	Axial load
N_u	Ultimate compressive strength of CFST column
n	Axial load level ($=N_0/N_u$)
P	Lateral load
P_{FEA}	Predicted maximum lateral load by FEA model
P_{max}	Measured maximum lateral load
t_s	Thickness of the steel tube
w_c	Compressive stiffness recovery coefficient of concrete
w_p	Width of the base plate beyond the steel tube
w_r	Thickness of outer RC component
w_t	Tensile stiffness recovery coefficient of concrete
α	Steel ratio of CFST ($\alpha = A_s/A_c$)
ε	Strain
ε_y	Yield strain of steel
Δ	Displacement
Δ_{max}	Displacement corresponding to maximum load
Δ_y	Displacement corresponding to yield load
ρ_a	Anchor bolt ratio
ρ_l	Longitudinal bar ratio
ρ_v	Volumetric stirrup ratio
σ	Stress
μ	Friction coefficient

failure at the CFST section above the encased RC component, were observed during the tests. Test results also showed that the concrete-encased CFST column bases possess excellent ductility and energy dissipation capacity. It should be noted that while a series of valuable observations and analysis has been made based on the test results, the parameters employed in the tests, including the size of the specimens, the material properties, and load parameters, were quite limited due to the constraints of the test apparatus. To further study the seismic behavior of concrete-encased column base for hexagonal CFST columns, numerical modeling is employed to carry out a systematic parametric study on the column base in this paper. A finite element analysis (FEA) model is first established to simulate its response under seismic loading. The cyclic material model of steel, modeling of concrete crack in the bottom section and modeling of base plate connection are specially discussed in the FEA model. The feasibility of the FEA model is verified against test results from the authors and other researchers. The FEA model is subsequently used to analyze the seismic performance of the column base, including the failure mode and the load transfer mechanisms. A parametric analysis is finally conducted to investigate the effects of salient parameters on the seismic performance of the concrete-encased column base, which is also employed to verify the accuracy of a simplified strength model for the column base.

2. Finite element analysis (FEA) model

A three-dimensional FEA model was established to simulate the seismic behavior of concrete-encased column base for hexagonal CFST columns with the general purpose FEA package ABAQUS [15]. The established model is an attempt to accurately simulate the interaction among different components of the column base under seismic loading, and thus all of its major components, namely the hexagonal CFST column, the concrete-encased connection and the foundation, were constructed in the FEA model. A schematic view of the FEA model is shown in Fig. 2. Part of the instances has been removed to demonstrate the inside details of the model. It can be seen that the concrete-encased connection part has two major components, namely the inner base plate connection and the outer RC component. For a clearer presentation of the structure of the case, three representative sections have been presented in the figure, as section I-I (CFST section), II-II (concrete-encased CFST section) and III-III (based plate and outer RC section).

2.1. Elements, interactions, and boundary conditions

Four-node space shell elements are used for the modeling of the steel tube and base plate. Eight-node space solid element is used for the modeling of the concrete components, namely the core concrete in the CFST and the outer concrete the concrete foundation. Space truss element is used for both the reinforcements and anchor bolts.

There are several interfaces in the FEA model between different components, e.g., the interfaces between the steel tube and the core concrete, the base plate and the outer concrete, as well as the reinforcements and the concrete foundation. For the interface between the steel tube and the core concrete, "hard contact" model is used for the normal behavior and the "Coulomb friction" model is used to simulate the tangential behavior, with the main parameter as the friction coefficient μ. For the interface between steel tube and core concrete, μ is set as 0.6 [16], and for the interface between base plate and concrete, μ is set as 0.4 according to CECS-230-2008 [17]. According to [18], μ for the interface between steel tube and outer concrete should be set as 0.6 and the reinforcements are embedded into the concrete. Note that one of the specimens used shear studs to strengthen the connection between the outer RC component and CFST. The shear studs are simulated by nonlinear spring elements provided in ABAQUS, and a load-slip relation suggested by Ollgaard et al. [19] is used for the spring elements.

The bottom surface of the foundation is fixed to the ground. The column base is subjected to a constant axial load at the top of the column and cyclic lateral load is applied at the same location. The displacement controlled loading strategy is applied to the lateral loading. When simulating the test results, the applied maximum displacement values at each load cycle during the tests were extracted and used as input in the numerical model.

2.2. Cyclic constitutive models for concrete and steel

Concrete is modeled with the concrete damaged plasticity (CDP) model provided by ABAQUS, which have been proven to be effective in modeling the cyclic behaviour of CFST structures in the past [20, 21]. The elastic modulus of concrete (E_c) is set as $4700\sqrt{f_c'}$ (N/mm^2) according to ACI [22], where f_c' is the cylinder compressive strength of concrete. The Poisson's ratio (μ_c) is set as 0.2. The compressive σ-ε relation suggested by Attard and Setunge [23] is used for unconfined concrete in the model, i.e., the outer concrete and foundation concrete, while the compressive σ-ε relation for confined concrete suggested by