Study on the Seismic Reliability of Eccentrically Loaded RC Columns under Different Design Reinforcement

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Abstract
In order to improve the seismic reliability of RC columns, an optimized design reinforcement of eccentrically loaded RC columns is studied in this paper. The simulated load-displacement curve and the failure modes are in good agreement with the experimental results, which indicates that in conditions of reasonable material constitution and FEA parameters, simulation of the stress state and failure mode of RC column is feasible. The components with flexural and flexural-shear failure can be classified into performance states: intact, slightly broken, light medium broken, medium broken, severe broken, ultimate state; the components with shear failure can be classified into two states: yielding and ultimate state. Then deformation limit values of RC column in different failure state are given which have been examined to make sure they are conservative values and can provide references to performance based seismic design.

Keywords: Seismic reliability, Eccentrically loaded, RC columns, Design reinforcement

1. INTRODUCTION

RC columns are important lateral force resistance components in structures, of which the deformation capacity and failure mode of damage have a great effect on the seismic performance of structures. At present, the seismic performance indices of RC column in the performance based design method of Chinese codes are just controlled by force instead of quantified by numbers, which lead to inaccurate evaluation of the degree of damage in the seismic design process. Reinforcement of RC frame column by traditional section enlargement method needs an overlapping layer. When the overlapping layer cannot be achieved due to the limited conditions, the upper load cannot be effectively transfer to the lower new concrete section, and can’t reach the expected effect of reinforcement. Our group proposed an innovation method to reinforce the compression bearing capacity of RC frame column by section enlargement based on the concept of confined beam-column joint, under the condition of non-overlapping layer, setting the joint enclosure to ensure the upper load can completely transfer to the lower new concrete section in the joint height range, and to ensure the reinforcement effective (Mago, 2016; Jin, 2016).

In the concrete filled steel tubular column (CFT), the joint action of steel pipe and concrete core has excellent bearing resistance performance without external protection (Xu, 2016; Jin, 2017). This feature encourages the use of CFT columns in conjunction with their positive properties at ambient temperatures, especially in high-rise buildings. In the past few years, as designers are increasingly interested in using this column to achieve the right bearing performance, the number of studies on the simulation of concrete filled tubular column bearing capacity has increased (Lin, 2017; Lu, 2015).

Due to these studies, several model proposals have been developed. In the literature, three-dimensional numerical models can be found, which can reproduce anomalous nonlinear behavior of CFT columns at high temperatures, such as advanced models proposed which considers several realistic considerations neglected by other researchers, and accurately estimates the bearing time, and accurately captures the overall response of the column along the bearing exposure time.

Although the trend of most authors is to develop three-dimensional numerical models, the fact is that these models are computationally time-consuming and inefficient when analyzing the entire structure. The numerical model based on beam column element is an effective method to simulate the performance of CFT column bearing because they are simpler because the material constitutive model is one-dimensional, even if the element itself is three-dimensional and its nonlinearity is distributed on its length. In this field, it simulates a composite column by combining a beam column element representing different cross sections. The thermal analysis is performed by finite difference method, although the gap conductance at the interface is neglected. This model proves a good estimation of bearing resistance time, but even if the slip between steel and concrete is considered, the whole response is not accurately reproduced (Han, 2016; Jin, 2017).

Finite element analysis (FEA) method has become one of the most important structural analysis methods because of its wide applicability and accurate simulation. At present, a lot of analysis and research are carried out on composite members, such as reinforced concrete columns, reinforced concrete beam column joints, shear wall structures and concrete structures, which are carried out on ABAQUS. All of these studies provide successful experiences in nonlinear analysis.
In addition, the researchers proposed a fiber heat transfer element with three nodes, can be used in commercial software in order to analyse the thermal mechanical coupling element using the available software, but they are not focused on the development of behavior model of CFT column by column model despite several attempts to analyze the development of fiber bundles the CFT column, but did not find any fiber finite element model in the literature, which provides accurate bearing resistance and time accurate reproduction of the overall response to the CFT column (Liu, 2016; Yao, 2016).

2. THE FRAMEWORK

In the previous work, the authors proposed the bearing response of the CFT column by three-dimensional model, showing the evolution of axial displacement of the column with time. As shown in Fig. 1, four stages can be clearly identified. At present, the research on the connection of concrete filled reinforced concrete column and reinforced concrete beam shows that the concrete filled steel tubular column is continuous along the whole length, and the floor is connected with the pipe from its side. In order to transfer the moment of the beam, the annular plate is used to reinforce the continuous steel bar or reinforced concrete ring beam. Shear transfer depends mainly on the support or shear reinforcement ring. The above nodes have complicated details and inconvenient construction. In reference, the connection between concrete filled reinforced concrete column and discontinuous column beam is presented, as shown in figure 2-4. In order to verify the feasibility of this type of joint, the axial and eccentric mechanical behavior was studied, and two groups of experiments including 41 samples were carried out. The construction method of this joint is similar to that of common reinforced concrete column beam joints. The experimental results show that this type of joint has higher compressive bearing capacity.

The experimental results show that the mechanical behavior of this type of connection zone is similar to the mechanical behavior of concrete members under local compression. Because the joint height is low, when the ultimate strength is reached, this kind of joint will not have a complete cutting cone. The three horizontal fracture modes of the side expansion scheme of the specimen are shown in figure 5.

Some have no horizontal cracks, and others have one or two cracks.

Stage 1. In the first stage of the bearing, the steel tube expands faster than the concrete core due to its higher thermal conductivity and direct exposure to the bearings. Two the axial displacement rate of the components are separated, and steel - concrete gap at the interface, resulting in concrete sandwich plate separation, steel began to bear the load imposed all.

Stage 2. The steel tube reaches the critical temperature, and the local yield occurs and begins to shorten, which makes the bearing plate contact with the concrete core.

Stage 3. At this time, the specific core is to display more resistance elements. The bearing plate has been exposed to the concrete core, and the load of the steel pipe gradually transfers to the concrete core as the column shortens.

Stage 4. Finally, the final failure occurs when the concrete core loses its strength and stiffness completely after a considerable reduction of its mechanical properties for a considerable period of time.

Therefore, the appropriate simulation of the relative sliding and separation between the two components is crucial for the accurate reconstruction of the overall response of the CFT column in the bearing, because this phenomenon is the main reason for the bearing capacity and response of the composite column.

Figure 1. Axial displacement versus time
Some other considerations, such as the effect of steel concrete gap, or the complete slip between concrete and steel tube, are not considered in other researchers. It is covering a wide range of concrete: ordinary, high strength reinforced concrete and reinforced concrete. In order to verify the fiber finite element model proposed in this paper, the simulation results are compared with the results of the three-dimensional model, and the experimental fire data and the validation of the fire response simulation accuracy.

The basic algorithm is shown as following:
Set \( \omega_f = Y \), \( \omega_f = X \), then the basic equation of the proposed equation is shown in equation (1) (Moustafa, 2016; Zhang, 2016):

\[
X = 2\pi k + \pi - \alpha_i - \pi M \sin Y
\]
The double Fourier series of function $u_p(X, Y)$ is given:

$$u_p(X, Y) = \begin{cases} 
0 & X < 2\pi k + \pi - \alpha_1 - \pi M \sin Y \\
\frac{E}{6} & X \geq 2\pi k + \pi - \alpha_1 + \pi M \sin Y 
\end{cases}$$

The double Fourier series of function $u_p(X, Y)$ is given:

$$u_p(X, Y) = \frac{A_{00}}{2} + \sum_{n=1}^{\infty} (A_{mn} \cos nX + B_{mn} \sin nY) +$$

$$\sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \left[ A_{mn} \cos(mX + nY) + B_{mn} \sin(mX + nY) \right]$$

In the above formula

$$A_{mn} + jB_{mn} = \frac{2}{(2\pi)^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} u_p(X, Y)e^{i(mX + nY)}dXdY$$

$$\varphi_j(\mu_i) = \exp \left( - \frac{(\mu_j - C_{ji})^2}{b_{ji}} \right), \text{for } i = 1, 2, \ldots, H$$

In this space, the $m$th multidimensional receptive field function is defined as

$$\Phi_m(\mu) = \prod_{j=1}^{L} \varphi_j(\mu_j), \text{for } m = 1, 2, \ldots, N$$

**Figure 5.** Three types of horizontal crack patterns of the side face expansion plans of the specimens

The function can be written in a vector notation as
\[ \Phi(\mu, C, b) = [\Phi_1, \Phi_2, ..., \Phi_N]^T \]  

(7)

The weight memory space with N components can be expressed in a vector as

\[ W = [W_1, W_2, ..., W_N]^T \]  

(8)

The activated weights in weight memory space, which can be written in a vector form as

\[ y = W^T \Phi(\mu) \]  

(9)

The state variables and the desired values can be defined as follows:

\[ z_1 = x_1 - y_d \]  

(10)

and

\[ z_2 = x_2 - \alpha_1 \]  

(11)

The following tracking error dynamics is shown as:

\[ \dot{z}_1 = \dot{x}_1 - \dot{y}_d = x_2 - \dot{y}_d = z_2 + \alpha_1 - \dot{y}_d \]  

(12)

3. EXPERIMENT AND ANALYSIS

In this work, the developed model is based on the proposed platform, and the Matlab toolbox is used for nonlinear analysis of the structure. The thermal analysis model of CFT circular section is implemented with the mechanical model considering temperature. The main parameters of the model are column length (L), outer diameter (D), steel tube thickness (T), end condition, axial load level (MU), and thermal and mechanical properties of the material. It consists of three parts: concrete core, steel tube and connectors connected to the former two.

Therefore, the model developed here is a complete circular CFT hollow section column. The clear origin of the clear thaw discussed above is a steel concrete column composed of two simple columns in parallel. As shown in Fig. 6 (a), these columns are modeled by finite element connections of longitudinal and transverse fiber connections. The link is located at the node point of single degree of freedom unit, knot steel and concrete column. The transverse link element has high stiffness to ensure that the two simple columns have the same deformation shape.

However, vertical link elements work in different ways. The inner longitudinal connecting rod reproduces very low friction between the steel tube and the concrete core. The top longitudinal connecting rod is designed to show higher stiffness in the compression state. On the contrary, when the longitudinal link is in tension, its stiffness is practically zero, so the behavior of trying to imitate the whole composite column is attempted. When the load is applied and the connection is compressed, the steel tube transfers the load to the concrete core. Once loaded and under fire, the longitudinal expansion of the steel tube is faster than the concrete core, so that the connectors acting in the direction are in tension and cannot transfer any load to the concrete column.

After sensitivity analysis, it was observed that four elements were used in each column to obtain high accuracy, and the results reduced the computation time. Beam column element for modeling two simple columns with a mixed interpolation iterative scheme for CO rotational expressions. Because the numerical solution process is more robust, the hybrid formula of beam element is very convenient.

![Figure 6. (a) Parallel model scheme; (b) Discretization of the section](image)

The scheme shown in Fig. 6 (b) is used to discretize the cross section. Perform mesh calibration to ensure sufficient accuracy, with the least number of fibers in each case. 16 fibers are used in circumferential direction. In the radial direction, the hollow steel section is assumed to be a fiber. For concrete cores, the number of fibers is varied to obtain the size of the unit close to 20mm, which is the typical size used in other models and the minimum size recommended for thermal analysis. Considering the lack of accuracy of the column due to its
own manufacturing process, the shape of the first buckling mode of the column with sinusoidal shape is considered by simulating the shape of the pinned column. For straightness, the L / 1000 value is used because it is usually used by researchers, and has been proved to be accurate in other models that exist in the literature.

After this study, it is found that the fully coupled thermal stress analysis is not worthwhile, because in these cases, the coupled thermal stress analysis gives accurate results. Therefore, in this work, a simple sequential coupled orbital stress analysis is carried out. The two analysis steps are different: thermal analysis and mechanical analysis. First, thermal analysis is performed to calculate the temperature field of the column, and then mechanical problems are solved to obtain structural response. Figure 7 shows the comparison of the skeleton test curves for each component.

Figure 7. The comparison of the test curves of the skeleton of each component

Taking the model with ring beam width b = 200 as an example, Figure 7 shows the relationship between the strain distribution and the height (H) at the center (x = 0) and the edge (x = R + b), with different joint heights. X = 0, x = R + B, y = 0, y = h correspond to the position of the axis, the outermost position, and the bottom position (the central position of the overall model), respectively. The results show that with the increase of the model height, the vertical strain (Ey) at x = R + B gradually increases from the tensile strain of the whole model to the tensile strain at the top and the compressive strain at the bottom. The calculated results are in agreement with the experimental ones. When the specimen height is low, the horizontal ring seam will not appear. When the joint height increases, a horizontal annular crack appears in the middle of the model with the maximum strain reaching. When the joint height increases to a larger value, two horizontal annular cracks appear in the upper and lower parts of the model, and the maximum tensile strain appears.
4. CONCLUSION

Finite element method is used to analyze the mechanical behavior of connections between concrete filled steel tubular column and axial compression column. In order to analyze the load distribution and bearing capacity of concrete RC columns, the nonlinear finite element method is adopted in this paper. A three-dimensional finite element model of reinforced concrete columns under cyclic loading is presented in this paper.

Some main conclusions are as follows.

(1) When the joint height is small (H = 100), the main compressive stress is mainly transferred to the local compression region, and the transmission is less through the ring beam. When the joint height is large (H = 800), the main compressive stress in the vector direction extends to the ring beam direction.

(2) When the width of the ring beam reaches a certain value, the ring beam and the core concrete of the joint remain the same constraint. There is no need to use too large ring beam width for joints.

(3) Vertical strain induced horizontal annular ring beam side of the crack. With the increase of height, the vertical strain at x = R + B changes from the tensile strain of the whole model to the tensile strain at the top of the model and the compressive strain at the lower part. There are three types of vertical strain distribution, 1) there is no tensile strain at the whole height of the joint; 2) there is only one maximum tensile strain at the middle height of the joint; 3) there are two maximum tensile strains at the top and bottom of the joint. This phenomenon is consistent with the experiment that annular cracks do not appear, or only one or two cracks appear with the increase of joint height.

The experimental results show that the finite element calculation results of ultimate bearing capacity and stress-strain curve agree well with the test results, and can be used in engineering practice.

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References


