NONLINEAR SEISMIC RESPONSE ANALYSIS METHOD OF REINFORCED CONCRETE CORE-TUBE

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ABSTRACT:

This paper gives a nonlinear seismic response analysis method of reinforced concrete core-tube, which is key lateral-force-resisting member of the steel-concrete hybrid structures. In this method, two key problems are solved. The one is to determine the reasonable nonlinear analysis model of concrete core-tube, and the other one is to select the nonlinear hysteretic model that can reflect true behavior of core-tube. At last, the corresponding analysis program is compiled on the basis of the large special computer program DRAIN-2D. And the program is proved to be reliable and effective by an example. The method in this paper can be used in steel-concrete core-tube structures and reinforced concrete frame-shear wall structures, and can be extended to use in reinforced concrete core structures and tube in tube structures.

KEYWORD: reinforced concrete core-tube, analysis model, hysteretic model, nonlinear, seismic response analysis

1. INTRODUCTION

At present, the steel-concrete hybrid structures have been applied to the tall buildings and super-tall buildings more and more widely in China. However, the study on seismic behavior of the structures is not perfect and does not meet the needs of its development speed. There are many different viewpoints on seismic behavior and mechanics analysis of this kind of structures at home and abroad [1]. Furthermore, there are not definite stipulations about the seismic design of the steel-concrete hybrid structures in *Code for seismic design of buildings (GB50011-2001)*. In order to ensure seismic safety, mitigate earthquake damage, it is urgent need to study systemically and deeply seismic behavior and design method of this kind of buildings. The reinforced concrete core-tube, which is key lateral-force-resisting member of the steel-concrete hybrid structures, bears a great of bending moment and shear force. So the study on reinforced concrete core-tube is an important part in the study on hybrid structures. This paper gives mainly a nonlinear seismic response analysis method of reinforced concrete core-tube. The method lays a foundation to research further the seismic behavior and seismic design method of the hybrid structures.

2. DETERMINATION OF NONLINEAR ANALYTICAL MODEL

In recent years, people have recognized more and more clearly that the effective analysis method of nonlinear response is very significant for seismic design and research of structures, because it can provide actual condition of the nonlinear response of structures. In nonlinear response analysis method, a key problem is to determine the reasonable nonlinear analytical model. Because the nonlinear behavior of reinforced concrete core-tube is very complicated, its nonlinear analytical model is not perfect.

By studying the analytical model and mechanics behavior of the concrete core-tube, we can find that they are

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similar to those of shear-wall. In the aspect of plane analytical model, the concrete core-tube is usually simplified as L-shaped, T- shaped and I- shaped etc. elements, which are similar to shear-wall element. In the aspect of mechanics behavior, the concrete core-tube and the shear-wall are both main lateral-force-resisting member, and bear a great of bending moment and shear force. They have very large lateral-force-resisting stiffness, not well deformation capacity, and high axial compression ratio. Their damages are caused by interaction of shear force, bending moment and axial force. The central axis of section will be moved during the process of damage. From the above analysis, it can be seen that the mechanics behavior of the concrete core-tube is similar to the one of shear-wall. Therefore, the nonlinear response analytical model of reinforced concrete core-tube is determined by connecting its mechanics behavior with current nonlinear analytical models of shear-wall.

The current nonlinear analytical models of shear-wall include equivalent beam model, equivalent brace model, column element model, three-vertical-line-element model, multiple-vertical-line-element model, two dimensional plate model, two-component model, and four-spring model etc.. Among these models, the multiple-vertical-line-element model shown in Fig. 1 is regarded as the most ideal macro model of shear-wall element, and can simulate mechanics behavior of the concrete core-tube very well. In this model, the two outside truss elements represent the axial stiffness of flange of core-tube. The central vertical truss elements represent the axial stiffness of the panel of core-tube. All vertical truss elements give the flexural stiffness of core-tube wall together. The horizontal spring in the height of 0.5h represents the shear stiffness of core-tube wall. This model can describe movement of the central axis of core-tube section, imbalance of internal force in two ends, and solve axial force-bending moment interaction. So in this paper, the multiple-vertical-line-element model is determined as the nonlinear response analytical model of reinforced concrete core-tube.

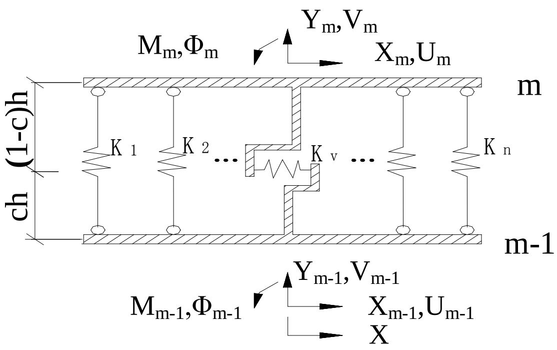


Figure 1. Multiple-vertical-line-element model

3. SELECTION OF HYSTERETIC MODEL IN NONLINEAR ANALYTICAL MODEL OF THE CORE-TUBE

Recently, the shear hysteretic and the axial stiffness hysteretic models used in the multiple-vertical-line-element model are generally given based on tests and experiential hypothesis. Some is too simple to reflect nonlinear hysteretic characteristic of core-tube well, and some is too complicated to use.

In order to describe rationally the axial stiffness hysteretic characteristic of vertical truss elements in multiple-vertical-line-element model of shear-wall, the reference [14] conducts axial cyclic loading tests of five reinforced concrete column specimens. Based on the experimental results, the axial force-deformation relationship for RC columns subjected to axial cyclic loading is studied, and an axial stiffness hysteretic model of RC columns is suggested. In this paper, this model is selected as axial stiffness hysteretic model of vertical truss elements in multiple-vertical-line-element model of core-tube, as shown in Fig. 2.

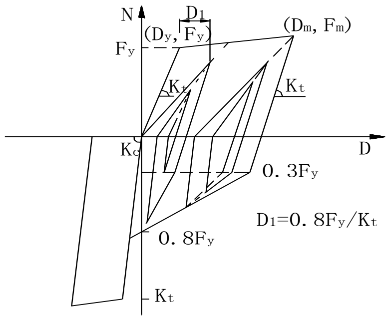
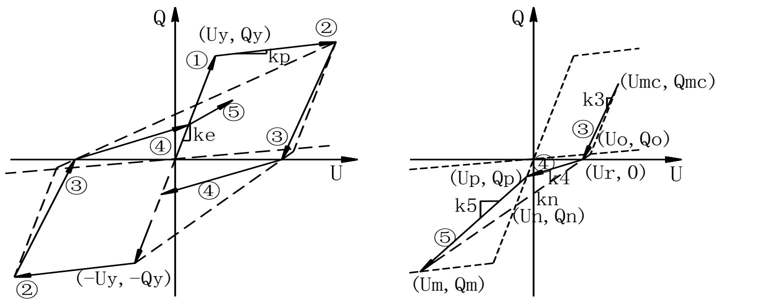


Figure 2. Axial stiffness hysteretic model

The reference [12] suggests selecting the revised Takeda model with pinch as the shear hysteretic model of the concrete core-tube and gives the detail hysteretic rules by comparing and evaluating the current hysteretic shear models used to the shear-walls and combining the results of current concrete core-tube tests at home and abroad. In this paper, this model is selected as shear hysteretic model of horizontal spring in multiple-vertical-line-element model of core-tube, as shown in Fig. 3.



(a) Hysteretic curve (b) Unloading and Reloading stiffness

Figure 3. Revised Takeda model

4. NONLINEAR SEISMIC RESPONSE ANALYSIS METHOD OF REINFORCED CONCRETE CORE-TUBE

The implicit direct integration method is used to core-tube element structures described by the multiple-vertical-line-element model. The nonlinear seismic response analysis method of reinforced concrete core-tube is given, and the corresponding analysis program is compiled on the basis of the large special computer program DRAIN-2D.

4.1. Element Stiffness Matrix of Multiple-vertical-line-element Model

As above mentioned, the multiple-vertical-line-element model is determined as the nonlinear response analytical model of reinforced concrete core-tube, as shown in Fig.1. In the model, the displacement vector in two ends of core-tube is as follows:

$$\{\delta\} = \{U_{m-1},\ V_{m-1},\ \Phi_{m-1},\ U_m,\ V_m,\ \Phi_m\}^T \tag{1}$$

Where, $U_{m-1}, V_{m-1}, \Phi_{m-1}$ represent the horizontal displacement, vertical displacement and rotation of end m-1, respectively; U_m, V_m, Φ_m represent the corresponding displacement of end m, respectively.

The end force vector of element is as follows:

$$\{R\} = \{X_{m-1}, Y_{m-1}, M_{m-1}, X_m, Y_m, M_m\}^T \tag{2}$$

Where, $X_{m-1}, Y_{m-1}, M_{m-1}$ represent the shear force, axial force, and bending moment of end m-1, respectively; the remaining components represent the corresponding end forces of end m, respectively.
The relationship of end force vector and displacement vector can be written:

$$\{R\} = [k_e]\{\delta\} \tag{3}$$

$$[k_e] = \begin{bmatrix} k_H & 0 & -\frac{h}{2}k_H & -k_H & 0 & -\frac{h}{2}k_H \\ & \sum k_i & \sum k_i x_i & 0 & -\sum k_i & -\sum k_i x_i \\ & & \frac{h^2}{4}k_H + k_\theta & \frac{h}{2}k_H & -\sum k_i x_i & \frac{h^2}{4}k_H - k_\theta \\ & & & k_H & 0 & \frac{h}{2}k_H \\ & symmetry & & & \sum k_i & \sum k_i x_i \\ & & & & & \frac{h^2}{4}k_H + k_\theta \end{bmatrix} \tag{4}$$

where, $[k_e]$ is the element stiffness matrix obtained in the case of c=0.5, $k_H = GA_s / h$ is the shear stiffness, G is shear modulus, A_s is the effective shear area, h is the element height, $k_i = E_i A_i / h$ is the axial stiffness of vertical element, E_i and A_i is the elastic modulus and section area of the vertical element i, respectively, $k_\theta = \sum_{i=1}^{N} k_i x_i^2$ is the rotation stiffness, x_i is the central coordinate of the vertical element i.

4.2 .Nonlinear Seismic Response Analysis Method

In order to meet with the large special computer program DRAIN-2D, the constant acceleration method in the implicit direct integration method is adopted to solve the equation of nonlinear dynamic equilibrium of structure.

The steps of nonlinear dynamic response of the whole structure are as follows:

(1) To choose nodal displacement as the basic unknown quantity.

(2) To disperse structure into elements, establish element stiffness equation, i.e. the relationship of force and displacement in the end:

$$\{\overline{F}\}^e = [\overline{k}]^e \{\overline{\delta}\}^e \tag{5}$$

where, $\{\overline{F}\}^e$ is the end force vector of element e, $\{\overline{\delta}\}^e$ is the end displacement vector of element, $[\overline{k}]^e$ is the stiffness matrix of element e.

(3) To establish the stiffness equation for assembled structure:

$$[K]\{\Delta\} = \{P\} \tag{6}$$

where, $\{\Delta\}$ is the nodal displacement vector of structure, $\{P\}$ is the nodal load vector of structure, $[K]$ is the stiffness matrix of structure, i.e. the stiffness matrix for assembled structure.

(4) To solve the equation (6) to obtain the nodal displacement $\{\Delta\}$ and the end displacement $\{\overline{\delta}\}^e$, and then to calculate each end force using equation (5).

In this paper, the program DRAIN-2D is selected to conduct the nonlinear seismic response analysis of concrete core-tube, in which there is not the multiple-vertical-line-element model. The revised work is done. Firstly, the subroutine of multiple-vertical-line-element model is compiled and added to the program DRAIN-2D as a new element. So the program of nonlinear seismic response analysis of the core-tube is given.

5. EXAMPLE

Owing to having little example of the reinforced concrete core-tube, this paper chooses a shear-wall, which mechanics behavior is similar to the one of core-tube, as an example to verify the reliability and effectiveness of the compiled program.

A seven-story shear-wall structure from references [13] is regarded as an example. Its section view is shown as Fig. 4. The length of wall is L=6.0m; its thickness is t=200mm; the size of columns in two end of wall is $a\times b=300\times 300mm^2$. The detail of the structure can be seen in references [13]. The above analysis model and program are used to the nonlinear analysis. The input earthquake motion is the El-Centro waves. The peak acceleration is adjusted to 220gal and 400gal.

In the analytical model, each story is regarded as an analytical element, and each element is simulated by the multiple-vertical-line-element model which consists of ten vertical springs and one horizontal spring.

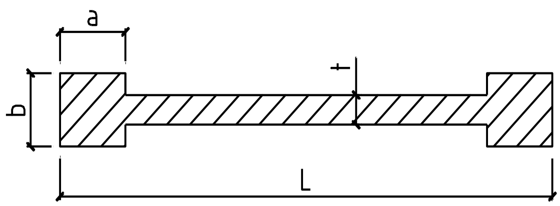


Figure 4. Section view of structure

Fig.5 and 6 shows the shear hysteretic curve and the axial stiffness hysteretic curve of the outside vertical element in the first floor subjected to the peak ground acceleration 220gal. Fig.7 and 8 shows the shear hysteretic curve and the axial stiffness hysteretic curve of the outside vertical element in the first floor subjected to the peak ground acceleration 400gal.

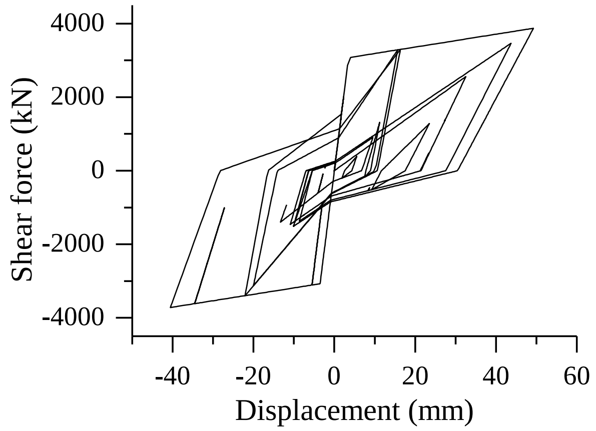


Figure 5. Shear hysteretic curve of the first floor subjected to the peak ground acceleration 220gal

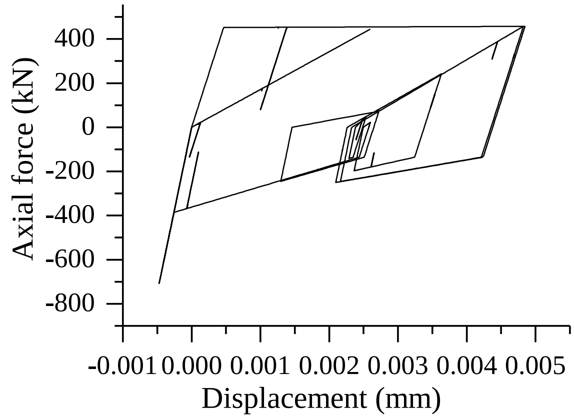


Figure 6. Axial stiffness hysteretic curve of the outside vertical element in the first floor subjected to the peak ground acceleration 220gal

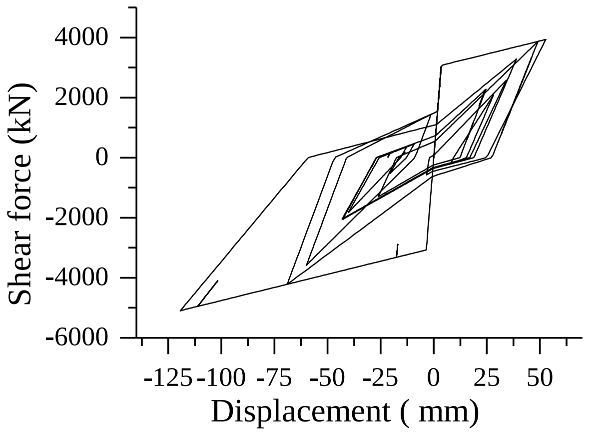


Figure 7. Shear hysteretic curve of the first floor subjected to the peak ground acceleration 400gal

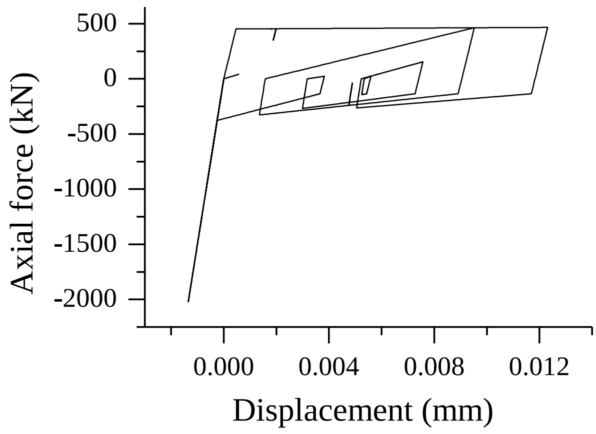


Figure 8. Axial stiffness hysteretic curve of the outside vertical element in the first floor subjected to the peak ground acceleration 400gal

From the Fig. 5 and 7, we can see that the shear hysteretic curves of the first floor subjected to different peak ground acceleration follow the rule of the revised Takeda model with pinch. From the Fig. 6 and 8, we can see that the axial stiffness hysteretic curves of the outside vertical element in the first floor subjected to different peak ground acceleration also follow the rule of the axial stiffness hysteretic model. So the program is proved to be reliable and effective by the example.

6. CONCLUSIONS

In this paper, a nonlinear seismic response analysis method of reinforced concrete core-tube is given. In order to give a reasonable and effective method of nonlinear seismic response analysis, two key problems are solved. The one is to determine the reasonable nonlinear analytical model of concrete core-tube, and the other one is to select the nonlinear hysteretic model that can reflect true behavior of the core-tube. At first, the mechanics behavior of the concrete core-tube is analyzed. It is found that its mechanics behavior is similar to the one of shear-wall. Therefore, by considering its mechanics behavior and analyzing current nonlinear analysis models of shear-wall, the multiple-vertical-line-element model is determined as the nonlinear response analytical model of reinforced concrete core-tube. Secondly, the hysteretic models of horizontal and vertical springs in the multiple-vertical-line-element core-tube model are chosen. By analyzing the results of current concrete core-tube and some shear-wall tests at home and abroad, the features of shear hysteretic model of the core-tube are given. Compared with the current shear hysteretic models, the revised Takeda model with pinch is selected as the shear hysteretic model of the concrete core-tube. By analyzing current axial-stiffness hysteretic models of concrete structures, the axial-stiffness hysteretic model given based on test results by Jiang Jinren is selected as the axial-stiffness hysteretic model of concrete core-tube. At last, the nonlinear seismic response analysis method of the core-tube is given by using the analysis model, and the corresponding analysis program is compiled on the basis of the large special computer program DRAIN-2D. The program is proved to be reliable and effective by example. The method in this paper can be used in steel-concrete core-tube structures and reinforced concrete frame-shear wall structures, and can be extended to use in reinforced concrete core structures and tube in tube structures.

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