Dynamic Performance Analysis of Composite Frame with Concrete-filled Steel Tubular Columns Based on Nonlinear Beam-column Fiber Element

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Abstract. The three-dimensional elements method is imperfect in computational efficiency to simulate the behavior of structural systems based on elastoplastic theory. A finite element model (FEM) using beam element was performed to simulate the composite frames with concrete filled steel tubular (CFST) columns, and the separate modulus approach and the uniform modulus approach were used to the beam elements, respectively. The results from the two methods are verified with the experimental results of the CFST members and the numerical curves, respectively. The two validated models were used to perform the model analysis and elastic dynamic time history analysis under three different frequent earthquake waves for a 13 story composite frame with CFST columns, respectively. The top story displacement and acceleration-time history responses, the relative story drifts and the maximum dynamic magnification coefficients of the frame were contrasted with different two models. The results shown that the separate and uniform modulus approach are similar generally for the dynamic characteristics of composite frame under frequent earthquake.

Introduction

Concrete-filled steel tubular structures have been widely used in practical structure due to the favorable composite characteristics of steel and concrete materials which providing the merits of higher strength and stiffness, higher earthquake resistant behavior due to favorable ductility and large energy absorption capacity[1]. Concrete filled steel tubular columns to steel beam composite frame with RC slabs is one of the most common form of composite structures, which has been widely used in high-rise structures and super high-rise structures. So it has important theoretical significance and practical value to investigate the seismic performance of concrete filled steel tubular structure subjected to earthquake. Using the three-dimensional numerical simulation of unit modeling method to calculate the elastoplastic analysis on the performance of the structural system will need the huge unnecessary computing workload and difficult to obtain a reasonable balance between computational efficiency and results. Lu et al.[2] introduced the method of using different element model to analyze the elastoplastic behavior of building against earthquake. The results indicated that the beam-column fiber element was a effective finite element method to analyze the elastoplastic behavior of structures.

The composite effects of steel tube and concrete needed to considered when using the beam-column fiber element theory to study the mechanical performance of CFST structures, especially the constraint effect of steel tube on core concrete. There are mainly two kinds of methods to consider the constraint effect of steel tube, The earlier proposed a method of concrete filled steel tube is regarded as a composite materials of the steel and concrete and mechanical performance changed with the physical parameters and geometric parameters of composite material and cross section shape of CFST. The change is continuous, related and computing is unified, so it called
uniform modulus method [3]. Ding et al. [4] developed a finite element model to analyze the seismic behavior of concrete filled steel tubular frame under lateral cyclic load based on the uniform modulus theory and the core concrete considering the restraint effect of steel tube. Another method is considered the steel tube and core concrete, respectively, which considering the restraint effect of steel tube without considering the interface bond-slip, so it called the separate modulus approach. Liang. [5] Analyzed the strength and ductility of high strength concrete-filled steel tubular beam-columns. Wang et al. [6] used the separate modulus approach to study the hysteretic relationship of concrete filled steel tubular columns and steel beam planar frames. Valipour et al. [7] reported the nonlinear static and cyclic analysis of concrete-filled steel columns based on the separate modulus approach. Wang et al. [8] reported the seismic response of composite frame with CFST columns under far-field ground motion. Li et al. [9] analyzed the seismic performance of CFST column to steel beam joint with RC slab used the separate modulus approach. Dong et al. [10]

Reported the analysis of seismic behavior of structure with CFST columns and deep steel plate beam. Nie et al. [11] reported the development and application of steel concrete composite fiber beam model in ABAQUS platform. This paper presents a finite element model to calculate the elasto-plastic performance of composite frames with CFST columns using the separate modulus approach and the uniform modulus approach based on the ABAQUS software. The nonlinear time history analysis of composite frame under frequent earthquake was conducted to compare the calculation results between separate modulus approach and the uniform modulus approach.

Separate Modulus and Uniform Modulus Approach

This paper developed a finite element model to study the dynamic performance of composite frame with concrete-filled steel tubular columns based on nonlinear beam-column fiber element using ABAQUS software. How to deal with the constraint of the steel tube and core concrete is the key problem to calculation results. The paper present two kinds of methods to deal with the constraint of steel tube and core concrete, the separate modulus approach and the uniform modulus approach. The steel tube and core concrete were used the merge connection method in the finite element model.

The separate modulus approach

The separate modulus is the method which added the integral points in the column cross section to simulate core concrete and the outer steel tube, respectively. Integral points position were determined by the local coordinates of the concrete-filled steel tube cross section and the number of the integral points were calculated by the equivalent area of the steel tube and core concrete. The material properties of integral points were defined by the separate materials of steel and core concrete using the separate modulus method, respectively. The stress - strain relationship of steel and core concrete were given in Han [12]. The typical stress – strain relationship curves of steel can consist of five stages and the typical stress – strain relationship curves for confined concrete is shown as follows:

Concrete filled circular steel tube:

\[
\begin{align*}
y &= 2x - x^2 \quad (x \leq 1) \\
y &= \frac{1 + q \cdot (\xi^{0.12} - 1)}{\beta \cdot (x - 1)^2 + x} \quad (\xi \geq 1.12) \\
y &= \frac{x}{\beta \cdot (x - 1)^2 + x} \quad (\xi < 1.12) \\
\end{align*}
\]

Concrete filled square steel tube:

\[
\begin{align*}
y &= 2 \cdot x - x^2 \quad (x \leq 1) \\
y &= \frac{x}{\beta \cdot (x - 1)^2 + x} \quad (x > 1)
\end{align*}
\]
in which $x = \epsilon/\epsilon_o = \sigma/\sigma_o$, $\epsilon$ is the compression strain of core concrete and $\sigma$ is the compression stress. $\zeta$ is confined coefficient of steel tube.

**The uniform modulus approach**

The uniform modulus is the method which deal with the steel tube and core concrete of concrete filled steel tubular column as a single composite material. The composite material property was defined at the integral points in the beam element cross section. This paper presented a finite element model to study the elastic analysis and calculation of dynamic characteristics of composite frame with CFST columns under frequent earthquake and did not discuss the elastic-plastic performance. The elastic modulus $E_{sc}$ of composite material can be expressed as follows:

$$E_{sc} = \frac{f_{p}^p}{\epsilon_{p}^p}$$

in which $f_{p}^p$ is the proportional limit strength, $f_{p}^p=(0.192 \cdot f_y/235 + 0.488) \cdot f_{y}$. $\epsilon_{p}^p$ is the proportional limit strain, $\epsilon_{p}^p = 0.67 \cdot f_y/E_s$. $f_{y}$ is the value of compressive strength standard, $f_{y} = (1.212+b \cdot \zeta + c \cdot \zeta^2) \cdot f_{ck}$, in which $\zeta$ is confined coefficient of steel tube, $\zeta = \alpha \cdot f_y/f_{ck}$, $f_y$ is the strength of steel tube and $f_{ck}$ is the concrete strength of column.

Concrete filled circular steel tube:

$$EI = E_s I_s + 0.8 E_c I_c$$  \hspace{1cm} (4)

Concrete filled square steel tube:

$$EI = E_s I_s + 0.6 E_c I_c$$  \hspace{1cm} (5)

in which $E_s$ is the elastic modulus of steel tube, $E_c$ is the elastic modulus of core concrete, $I$ is cross section inertia.

**Finite Element Model of Composite Frame with CFST Columns**

According to relevant design codes, This paper designed 13 story of composite frame with concrete filled square steel tubular columns (S-CFST). The bottom floor is 4.2m, the standard floor is 3.3m, the total high of frame is 43.8m. Seismic intensity is 7 degrees, the basic earthquake acceleration is 0.15g, construction site category is II. The strength of steel is $f_y=345\text{MPa}$, the strength of core concrete is C40. The depth of floor is 120mm. The composite frame model is shown in Fig.1.

The Selection of Seismic Waves

This paper chosed three common seismic waves to analyze the elastic behavior of dynamic time history of composite frame according to the site conditions, the spectrum characteristics of seismic
waves, the amplitude characteristics of seismic waves and the time duration of seismic waves. The seismic waves were shown in Fig.2, such as Taft wave (W-E), El-Centro wave (N-S) and Tangshan wave (W-E). The input direction of seismic waves were parallel to the short span of composite structure. The duration time of each wave is 15s. According to the illustration of Code for Seismic Design of Building (GB50011-2010) [13] that the maximum peak acceleration of elastic time history under frequent earthquake is 55gal to amplitude modulation. The maximum time increment step is the time interval for all kinds of seismic acceleration time history curve, such as the maximum time increment step of El-Centro wave (N-S) and Taft wave (W-E) is 0.02s and Tangshan wave (W-E) is 0.01s.

Analysis Results

The results of modal

The finite element model (FEM) using beam element was performed to simulate the elastic performance of composite frames with concrete filled steel tubular (CFST) columns under different earthquake waves, and the separate modulus approach and the uniform modulus approach were used to the beam elements, respectively. The first 10 order frequency and periods were shown in Tab 1. As is seen, the eigenvalue and frequency drawn through separate modeling method are slightly smaller than the unified approach for modeling at the first seven order modals, however, the last 3 order modals have slightly different results, but on the whole, the difference between the two kinds of modeling methods is small.
Table 1. The calculation results of frequency ($f$) and period ($T$).

<table>
<thead>
<tr>
<th>order</th>
<th>separate modulus approach</th>
<th>uniform modulus approach</th>
<th>separate modulus approach</th>
<th>uniform modulus approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.51</td>
<td>0.53</td>
<td>1.96</td>
<td>1.89</td>
</tr>
<tr>
<td>2</td>
<td>0.52</td>
<td>0.54</td>
<td>1.92</td>
<td>1.85</td>
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<td>0.59</td>
<td>1.72</td>
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<td>1.48</td>
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<td>1.48</td>
<td>0.68</td>
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<td>1.64</td>
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<tr>
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<td>2.80</td>
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<tr>
<td>10</td>
<td>3.60</td>
<td>3.55</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Structure displacement response analysis

Of concrete filled steel tubular frame in the elastic time history response analysis under severe earthquakes, the vertex displacement time history curves of the top floor are shown in figure 3. The diagrams suggest that in the condition of the same input seismic waves, using separate modeling method and unified modeling method can almost get the same vertex displacement time history curve shape of the top floor.

Figure 4 shows the maximum displacement envelope of each layer of the concrete filled steel tubular frame structure under three kinds of seismic waves. Visibly, the maximum displacement of each layer calculated by using unified modeling way is slightly greater than the separation modeling method, the difference of Tangshan wave is maximum, El-Centro is the second and Taft wave is minimal. Structural maximum displacement of layers under the action of Tangshan wave occurs at the 10th floor and in the negative direction. When obtained by using the uniform modulus theory, the maximum displacement of layers is 5.96 mm, and the drift is 1/554, as to the separation modulus theory, the maximum displacement of the layers is 4.31 mm, and the drift is 1/766; Under the action of El Centro - wave (navier-stokes), the maximum layers displacement of structure occurred at the 9th layer and in the positive direction, When obtained by using the uniform modulus theory, the maximum displacement of layers is 5.63 mm, and the drift is 1/586, the maximum displacement of the layers is 4.52 mm, if using the separation modulus theoretical, the drift is 1/730; Under the action of Taft wave (navier-stokes), the maximum layer displacement of structure occurs at the 11th floor, By using modulus unified theoretical, the maximum displacement of layers occurs in the positive direction, which is 4.33 mm, and the drift is 1/762, if the separation modulus theoretical is adopted ,the maximum displacement of layers happens in negative direction, and the value is 4.58 mm, and the drift is 1/721.

![Displacement-time history curves](image)

(a) Taft(W-E,PGA=55gal)  (b) El-Centro(N-S,PGA=55gal)  (c) Tangshan(W-E,PGA=55gal)

Figure 3. Displacement-time history curves.
Concluding

(1) Finite element method is used in this paper for the analysis of composite frame with CFST columns. A comparison of results calculated using this modelling shows good agreement with those of the test results2)

(2) The calculation results of modal response are similar for the two kinds of different methods. The elastic dynamic analysis results show that the displacement response of composite frame of CFST columns which used the uniform modulus method is slightly larger than used the separation modulus method. The elastic interlayer displacement angle of structures used two kinds of method can meet the relevant standards.

(3) The typical envelope curves of the maximum dynamic magnification coefficient are analyzed. It is found that the shapes of the maximum dynamic magnification coefficient envelope curves are different under different earthquake waves and the shape of envelope curve is C+S. The change of dynamic magnification coefficient with the structural height is relatively slow.

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References


