Seismic Vulnerability Analysis of High-Rise SRCFrame-RC Core Tube Hybrid Construction

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Abstract. With the development of the modern building, the steel-concrete hybrid structure is more and more widely used. However, the study on the seismic behavior of steel reinforced concrete composite structures is not fully studied. Using a 30-storey steel reinforced concrete (SRC) frame-reinforced concrete core tube hybrid structure (RC) analyze the seismic performance and seismic fragility by theoretical analysis and numerical simulation methods. The PUSHOVER method is used to obtain the capacity spectrum curve, the seismic demand spectrum curve and the performance control points. According to the development of plastic hinge of typical structure, the limit value of quantitative index of structure and the division of structural failure grade is determined. According to the data obtained from finite element analysis, the fragility curve. Provide the basis for earthquake disaster prediction and evaluation.

Keywords: vulnerability, seismic demand spectrum, structural capacity spectrum, quantitative index.

1. Introduction
Earthquake, as one of the most severe disasters in nature, is highly destructive and extremely harmful to human and property. Seventy percent of China’s large cities are located in seismic regions with seismic intensity above 7 degree, meanwhile China’s seismic belt distribution area also has a wide distribution range, strong ground motion intensity, shallow depth of the source, etc. It has been an important issue that disturbs human’s life. With the continuous development of science and technology, the layers and height of high-rise buildings are constantly breaking through, the types and functions of buildings are becoming more and more complex, the structural system is more diverse as well.

In China, the main high-rise buildings systems mainly include steel structure, concrete structure and steel-concrete hybrid structure. Hybrid structure refers to the frame-cylinder structure composed of steel frame or steel reinforced concrete (SRC) frame with reinforced concrete core cylinder, or the tube in tube structure composed of outer and inner SRC cylinders. The SRC frame in the frame-cylinder structure may be a frame composed of SRC beams and columns (concrete-filled steel tube column). Besides the outer cylinder in tube in tube structure might be a frame tube, a truss tube or a cross grid tube.

The traditional seismic damage analysis is not suitable for the hybrid structure’ statistical analysis of vulnerability, meanwhile the data of which is insufficient in our country. Therefore, the analysis of the hybrid structure has stemmed from the shaking table experiment and software analysis. Although software analysis has a large workload, with the development and maturity of various theories and
software technology, its accuracy is getting better and better. Therefore, the seismic performance of complex structures is increasingly studied by software analysis. In the seismic performance analysis of the structure, this paper intends to analyze the vulnerability of such structures in earthquakes by Midas/Gen software on the basis of fiber beam element.

2. Structure Model

The typical model, in this paper, is the SRC frame-RC core tube hybrid structure, which is a 30-story SRC frame-concrete cylinder hybrid structure with a layer height of 3.3 m and same plane dimensions as showed in Figure 1. The column space of both directions are respectively 7.5 m and 9 m, and the intermediate tube has a plane size of 9 m × 9 m. For the detail of structure mode, the frame columns adopt a cross-shaped steel concrete columns, and the beams adopt an “I” shaped steel beam. The connection between frame beam and the core tube is hinged, and which of the frame beam and the column is rigid.

Considering the reality, C50 concrete is used in 1~10 layers of SRC frame-RC core tube hybrid structure, however, C40 concrete is used for 11~30 layers. The size of four prisms and the other middle columns are respectively 950mm×950mm and 650mm×650mm, and which of all cross-shaped steel and all I-shaped steel beam are respectively 2× (340×200×30×20) mm\(^4\) and 650×300×30×20 mm\(^4\). The shear wall’s thickness of the core tube mainly contains three types, such as the 1~6 storeys are 700mm, the 7~10 storeys are 600mm, and the 11~30 storeys are 400mm. The distributed rib of the cylindrical shear wall is shown in Table 1.

Using MIDAS/GEN FE analysis software is to establish the structure model. In the model, the steel beam and the core tube shear wall respectively adopt the 3D beam element and the 3D macro shear wall element provided by the software. Meanwhile plastic hinge adopts the FEMA constitutive model. SRC columns use fiber beam-column element, in which, the concrete adopts the modified Kent-Park model of Scott. B. D which ignores the tensile effect of concrete, as shown in Figure 2.

Through the improved Menegotto-Pinto model by Filippou et al, the stress-strain relationship has a good simulation effect on the nonlinear characteristics of steel under reciprocating load, and the model is more efficient in calculation, as shown in Figure 3.

| Floor | Horizontal distribution reinforcement | Vertical distribution reinforcement | Brace |
|-------|-------------------------------------|-----------------------------------|-------|
| 1-6   | A20@200                             | A20@200                           | A8@600|
| 7-10  | A18@200                             | A18@200                           | A8@600|
| 11-30 | A14@200                             | A14@200                           | A6@600|

Figure 1. 1~30 floors Structural layout plan. Figure 2. The stress-strain curve of concrete.
3. Control Point of Structural Performance

PUSHOVER analysis on the structure model was carried out. Since the layout of the model’s X and Y directions is exactly the same, the stiffness is equal, only the X direction will be considered. The increment was controlled by the maximum displacement of vertex. According to the specification, the elastoplastic interlayer displacement of the structural weak layer (part) should be satisfied: \( \Delta u_{\text{max}} \leq \theta_{r} h = 99000 / 100 = 990 \text{mm} \), so chose the 800 mm as the limited displacement of vertex. Based on the above control options, utilizing the capacity curve converted by the control displacement-base shear curve is shown in Figure 4 obtained by the PUSHOVER analysis. Then according to the model earthquake grouping, the fortification intensity, and seismic elastoplastic demand spectrum from the damping of 5% transformed from the site category, the two curves were put together to obtain the performance points of the structure.

4. Performance Level Classification

Referring to the domestic and international classification of structural performance levels, the paper stipulated the seismic performance levels of the structure includes four performance levels: normal use (NO), immediate use (IO), life safety (LF) and prevention of collapse (CP). The seismic performance of the structure is an attribute of the structure itself that can resist external load effects. According to different measurement criteria, including bearing capacity, deformation capacity, energy consumption etc. An index is named a quantitative index, which is used to define the failure state of a structure and indicate the seismic resistance of the structure. Besides the specific value of the quantitative index is the limit of the quantitative index.

In this paper, the inter-layer displacement was used as a quantitative index to establish the correspondence between structural damage level and performance level. According to the development of the structural plastic hinge, the displacement angle of the structure can be obtained, between the bottom layer with different failure state representative points, which is also called the structural quantization index limit: NO=LS1=1/500, IO=LS2=1/400, LF=LS3=1/250, CP=LS4=1/167. The state of the structure destruction was divided into: basically intact, slightly damaged, moderately damaged, severely damaged, and completely destroyed five levels.
5. Basic Principle of Vulnerability Analysis of Building Structures

The vulnerability curve of a building structure is the probability that the structural demand exceeds a certain performance level under the action of different strength earthquakes. According to the definition of structural performance level in the foregoing, the maximum interlayer displacement angle under the performance point was determined as its input parameter, and the cumulative lognormal distribution was used to indicate the conditional probability parameter that the structure reached or exceeded a certain failure state. The ground motion demand spectrum and the structural capability curve determined by the previous summary, were placed in the same coordinate system, to obtain the intersection corresponding to the maximum interlayer displacement angle. According to \( \delta \), the cumulative probability that the structure reaches a certain damage can be obtained by the following formula.

\[
P(\delta | PGA > LSi) = 1 - \Phi \left( \frac{\ln(\delta) - S_{\lnPGA}}{\beta_{\lnPGA}} \right)
\]

Where, \( P(\delta | PGA > LSi) \) represents the probability that the maximum interlayer displacement angle \( \delta \) of the structure under different PGAs exceeds the limit value \( LSi \); \( LSi \) represents the quantization index limit corresponding to the four kinds of performance levels of the structure. And \( S_{\lnPGA} \) and \( \beta_{\lnPGA} \) represent the logarithmic mean and logarithmic standard values corresponding to the structural demand of the different PGAs, and \( S_{\lnPGA} \) choose the logarithm of the inter-layer displacement angle in a certain failure state; \( \beta_{\lnPGA} \) took an value of 0.35 for the interlayer displacement angle for steel-concrete hybrid structure; \( \Phi(\bullet) \) is the standard normal distribution function.
The structural vulnerability curve was obtained, as shown in Figure 5 according to formula (1):

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{t^2}{2}} dt$$  \hspace{1cm} (2)$$

The structural vulnerability curve was obtained, as shown in Figure 5 according to formula (1):

![Figure 5. PGA-exceedance probability curve.](image)

It can be seen from Figure 5 that the vulnerability curve of structure emerges to be flat from intact to collapse. With the change of PGA, the corresponding response of the structure subsequently changes. When the peak acceleration reached 0.2g, the probability of each failure state of the structure respectively were that slightly damage: 17.6%; moderately damage 44.4%; severely damage 18.6%, collapse 3.3%. When the peak acceleration reached 0.4g, the probability of each failure state of the structure respectively were that slightly damage 0.8%; moderately damage 13.3%; severely damage 34.4%; collapse 51.3%. Consequently, the structure tends to increase the probability of danger with the increase of PGA.

It is feasible to use the method of this paper to calculate the seismic vulnerability curve of steel-concrete hybrid structures with different performance targets. It is possible to evaluate the ability of structures to achieve different performance levels under different earthquake intensity, and to more comprehensively understand and evaluate seismic performance of the structure.

6. The Influence of Different Factors on Vulnerability

There are many factors affecting the seismic vulnerability of building structures. This paper considers the influence on the structural vulnerability by changing the stiffness ratio and the axial compression ratio.

On the basis of typical model, by changing the dimensions of beams and columns of the outer frame and the thickness of the shear wall of inner core tube respectively, received totally nine hybrid structure models. K is used to represent the frame, and K08, K10, and K12 respectively indicate that the cross-sectional dimensions of the frame beams and columns were changed by 0.8, 1.0, and 1.2 times with respect to which of the typical structure model. The core tube shear wall is represented by T, and T08, T10 and T12 respectively indicate that the thickness of the core tube shear wall section were 0.8, 1.0, and 1.2 times with respect to which of the typical structure model.

Table 2 lists the structural stiffness characteristic value ratios of the nine hybrid structural models obtained by resizing the basic model.

PUSHOVVR analysis was performed on the above models to obtain the maximum interlayer displacement angle $\delta$ under different PGAs. The vulnerability curves of each model were obtained according to formula (1), and showed as Figures 6-9.
Through the comparison and analysis of the above figures, it could be obtained that the ultimate probability of the ultimate state of the structure decreases with the increase of the structural stiffness characteristic value, and the change of the outer frame size has a greater influence on the stiffness characteristic value than the change of the shear walls of core cylinder. At the same time, the transcendental probability also changes significantly.

Besides, on the basis of typical model, by changing the floor live load value under static load conditions, therefore four hybrid structure models with different axial compression ratios are obtained. L is used to represent the floor live load, then L02, L04, L06, L08 indicate the floor live load is 2kN/m², 4kN/m², 6kN/m², 8kN/m² respectively as shown in Table 3, finally the vulnerability curves were obtained as shown in Figures 10-13.

### Table 2. Stiffness ratio.

| Model  | K08T15 | K08T12 | K08T10 | K10T12 | K10T10 | K10T08 | K12T12 | K12T10 | K12T08 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $\lambda$ | 0.821  | 0.905  | 0.982  | 1.415  | 1.535  | 1.699  | 2.037  | 2.210  | 2.446  |

### Table 3. Load and axial compression ratio.

| Calculation model | L02 | L04 | L06 | L08 |
|-------------------|-----|-----|-----|-----|
| Live load (kN/m²) | 2   | 4   | 6   | 8   |
| Axial compression ratio | 0.302 | 0.357 | 0.421 | 0.484 |
From the comparison and analysis of the above figures, the influence of the axial compression ratio on the structural vulnerability is more and more obvious in the process of gradually becoming dangerous, and the probability that the structure as a whole tends to be safe with the increase of the axial compression ratio decreases, on the contrary, the probability which tends to danger increases. Overall, its vulnerability increases gradually.

7. Conclusion
The paper utilized MIDAS/GEN to conduct the FE analysis, in which, the unit was based on fiber unit, adopted PUSHOVER analysis method to obtain the performance control point of the structure. The seismic peak acceleration was used as the seismic parameter, and the interlayer displacement angle was used as the quantitative index to obtain the probability of structure under each failure state subjecting earthquake action. The probability of failure state. Further the vulnerability curve was conducted, and the influence of structural stiffness ratio and axial compression ratio on its vulnerability was studied, which provides a basis for the prediction and evaluation of earthquake disasters.

In the paper, the peak acceleration of the earthquake was selected as the ground motion parameter, besides other ground motion parameters such as spectral acceleration and peak velocity were used as the structural seismic intensity to change, the impact on the structural earthquake will also affect the structural vulnerability.
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