Seismic Vulnerability Analysis of High-Rise Composite Frame Concrete Tube Composite Structure

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Abstract. In order to study the possibility of structural failure of high-rise composite frame-concrete tube structure under different earthquake intensity, seismic vulnerability analysis of the structure is carried out based on IDA principle, and its seismic performance is evaluated. Taking 30-storey high-mixing structure as an example, eight seismic records are selected. After amplitude modulation, non-linear dynamic time history analysis is carried out. PGA, PGV and Sa are selected as seismic intensity parameters, and the maximum inter-storey displacement angle is selected as structural performance index. IDA curve clusters are obtained. Quantile curve method is used to analyze and analyze the results. It is concluded that PGA strength index is more effective. The seismic performance of this kind of structure is evaluated effectively, and then the vulnerability curve and vulnerability matrix are obtained. The analysis results show that the hybrid structure can meet the requirements of “three-level” seismic response and has good seismic performance under 8-degree frequent, basic and rare earthquakes.

Keywords. Hybrid structure, incremental dynamic analysis, vulnerability curve, seismic performance.

1. Introduction
High-rise composite frame-concrete tube hybrid structure is a hybrid structure system with steel reinforced concrete columns and steel beams in the periphery and reinforced concrete core tube in the interior [1-2]. Composite frame concrete tube hybrid structure system is widely used in high-rise and super-high-rise buildings in China, and part of it is constructed in high seismic fortification area [3-4].

Incremental dynamic analysis, also known as IDA analysis, is a relatively new method for analyzing dynamic parameters of elastic-plastic seismic response of structures [5-6]. It studies the whole process of seismic response of structures from elasticity to plasticity and finally to collapse through a series of dynamic elastic-plastic analysis of structures. Seismic vulnerability describes the degree of structural failure. It analyses the possibility of structural failure under different earthquake intensity from the perspective of probability [7]. Some scholars have studied the seismic vulnerability of hybrid structures in combination with specific projects [8-11].

In this paper, IDA analysis of composite frame concrete tube hybrid structure is carried out to study the dynamic response process of this kind of hybrid structure under different seismic intensity parameters, and seismic vulnerability analysis is carried out by selecting appropriate seismic intensity indexes, and the seismic capacity and damage of this kind of hybrid structure under different seismic levels are investigated to evaluate its seismic performance.
2. Seismic Vulnerability Analysis

2.1. Incremental Dynamic Analysis Method
The basic steps are as follows: to establish a correct structural analysis model and select several ground motion records representing the site of the building; to select the intensity index IM and the structural performance index DM, to define the damage level and the quantitative index limit of the structure; to conduct the non-linear dynamic time history analysis of the structure after the amplitude of the ground motion is adjusted, and to extract the necessary conclusions Structural performance index: Draw IDA curve cluster, deal with it according to certain statistical methods, and evaluate the seismic performance of structures under different earthquake action.

2.2. Seismic Vulnerability Analysis Steps Based on IDA
The vulnerability analysis steps based on IDA are as follows: Statistical analysis of IDA curve clusters, using the defined limit state and the quantitative index of structural performance parameters to obtain the limit state; Semi-probability analysis method is used to solve the specific quantity corresponding to the given earthquake intensity index when the structural performance index exceeds each performance level. The probability of the quantified index, i.e. the limit value of the index expressed by the structural performance index, is as follows:

\[ p(L_{\text{Si}}|IM=x)=P(DM \geq d_{\text{mi}}|IM=x) \]  
\[ = 1 - P(DM < d_{\text{mi}}|IM=x) \]  
\[ = 1 - \Phi(\frac{\ln dm - \mu_{\ln DM|IM=x}}{\beta_{\ln DM|IM=x}}) \]  

Among them, the logarithmic mean of DM is A standard deviation B: extract the calculation results and fit the exceeding probability curve of the limit state. Analyse the vulnerability curve of different performance levels to evaluate the seismic performance of the structure.

3. Seismic Vulnerability Analysis of Hybrid Structures

3.1. Typical Structure Overview
In the background of document [12], a typical 30-storey composite frame-concrete tube structure is selected. The composite frame is used in the periphery and the reinforced concrete tube is used in the middle. The layout of the 1-30-storey structure is shown in figure 1. The story height is 3.3 m, the total height of the structure is 99 m, the column spacing is 7.5 m and 9 m, and the plane size of the middle concrete cylinder is 9 m*9 m. The frame column adopts cross shaped steel concrete column, and the frame beam adopts I-shaped steel beam. The frame beam and the core tube are articulated, and rigid connections are adopted between the frame beams and columns. The sectional dimensions and materials of components of model are shown in table 1.
The steel bars in the shear wall are arranged in two directions. The 1-6 storeys are 20@200, the 7-10 storeys are 18@200, the 11-30 storeys are 14@200, the 1-10 storeys are 8@600, and the 11-30 storeys are 6@600. The floor load is 4.5 kN/m² and the live load is 2.0 kN/m². The seismic fortification intensity is 8 degrees, the earthquake is divided into the first group, the site type is II, and the structural damping ratio is 0.04.

3.2. Establishment of Finite Element Model

Frame steel beam and concrete connecting beam adopt M3 hinges, whose positions are 0.1 and 0.9 of the relative positions of the elements. Self-defined PMM coupling hinges [13] are set at both ends of the steel reinforced concrete column. Shear walls adopt layered shell elements, in which the ideal elastic-plastic constitutive model is adopted for reinforcing bars and Ma is used for compression of concrete. Nder model considers the influence of stirrups and is used to simulate the confined concrete at the end of the wall. In addition, a simplified constitutive model of concrete under tension is adopted. The tensile strength of concrete is taken as 1/10 [14] of the compressive strength. The connection between the I type steel beam and the cylinder shear wall will release 3-3 axle moments to form a
hinge, assuming that the floor is rigid. Section of the steel reinforced concrete column is shown in figure 2, and the three-dimensional finite element analysis model of the structure is shown in figure 3.

![Section of steel reinforced concrete column](image1)

![Three-dimensional finite element analysis model](image2)

(a) Z1(950×950)  (b) Z2(650×650)

**Figure 2.** Section of steel reinforced concrete column.

3.3. **Selection of Ground Motion**

The site type is class II, and the ground motion input selects the actual seismic record and artificial analogue wave. Eight ground motion records are selected for IDA analysis according to site type, seismic fortification intensity and design earthquake grouping. Detailed information of ground motion records is shown in table 2.

3.4. **Ground Motion Intensity Index (IM)**

In this paper, three parameters of ground peak acceleration (PGA), ground peak velocity (PGV), and SA (T1, 4%) are selected as the index of ground motion intensity (IM), and the more suitable index of ground motion intensity for vulnerability analysis of this hybrid structure is determined.

**Table 2.** Selected ground motions information used in IDA.

| Serial Number | Earthquake Name         | Times | Time Interva (s) | PGA (cm·s⁻²) |
|---------------|-------------------------|-------|-----------------|--------------|
| E1            | EL Centro               | 1940  | 0.02            | 341.7        |
| E2            | TangShan EW             | 1976  | 0.01            | -65.94       |
| E3            | TangShan SN             | 1976  | 0.01            | 55.49        |
| E4            | LanZhou 2               | 1921  | 0.02            | 219.7        |
| E5            | LanZhou 3               | 1921  | 0.02            | 196.2        |
| E6            | WenChuan                | 2008  | 0.02            | 304.8        |
| E7            | TRA-TARZANA -00         | 1994  | 0.02            | 397.5        |
| E8            | Artificial wave         | —     | 0.02            | 450.5        |
3.5. Structural Performance Index (DM)
In this paper, the maximum interlayer displacement angle is chosen as the performance index DM of the structure. According to the five performance levels of the structure, the performance level and the quantitative index limit of the hybrid structure are determined by reference [10-11]. The specific values are shown in Table 3. The limit state point is determined according to the DM criterion, and the maximum interlayer displacement angle of 0.1 is chosen as the termination point of IDA analysis.

**Table 3.** Performance level and quantitative index in core-RC and composite frame hybrid structure.

| Level of performance | Displacement angle limit | Maximum interpass |
|----------------------|--------------------------|-------------------|
| Normal useLS₁        | 1/800                    |                   |
| Basically usableLS₂  | 1/400                    |                   |
| Can be used after repairLS₃ | 1/200                |                   |
| Life safetyLS₄        | 1/100                    |                   |
| Close to collapseLS₅ | 1/50                     |                   |

3.6. Analysis Results under Multiple Ground Motions
The IDA curve clusters of hybrid structures under multiple ground motions with PGA and PGV as the parameters of ground motions are obtained by using the index of ground motion intensity and the maximum interlayer displacement angle as the coordinate system, respectively, as shown in figures 4-6.

**Figure 4.** The IDA curves show by PGA-$\theta_{\text{MAX}}$.

**Figure 5.** The IDA curves show by PGV-$\theta_{\text{MAX}}$.

**Figure 6.** The IDA curves show by Sa-$\theta_{\text{MAX}}$.

**Figure 7.** IDA quantile curve show by PGA.
From the IDA curves of the three parameters in figures 4-6, it can be seen that with the enhancement of seismic waves, the slope of most IDA curves shows an irregular trend. When the earthquake intensity is small, the structure is in elastic state, and the discreteness of the three IDA curve clusters is small, but with the increase of the earthquake intensity, the discreteness of the curve clusters is also increasing.

In view of the uncertainties of the structural response under the action of multiple seismic waves, the quantile curve method is used to analyze the IDA curves. The mean values and natural logarithmic standard deviations of different earthquake intensity indices are obtained. The 16%, 50% and 84% quantile curves of IDA curves are obtained. The average and discreteness are shown in figures 7-9. The comparative analysis shows that the IDA curve obtained by using the ground peak acceleration PGA as the index of seismic intensity is relatively compact and better discrete. Therefore, the vulnerability study of the composite frame-concrete tube structure using PGA as the index of seismic intensity is more accurate.

3.7. Seismic Vulnerability Analysis Results

The seismic vulnerability curves of the hybrid structure are fitted by using PGA as X-axis and P as Y-axis, as shown in figure 10. It can be seen that under the action of small earthquake level, the slope of the probability curve of the hybrid structure in LS1 state is larger and the trend is steep. This shows that the maximum interlayer displacement angle is easier to exceed the limit value of the elastic interlayer displacement angle of 1/800 in the case of small earthquakes. With the increase of PGA, the slope of the probability curve of the other limit states decreases slowly, the trend is gentle, and the probability of exceedance decreases. When the structure enters the elastic-plastic state, the LS4 and LS5 state under the action of large earthquakes is relatively small, because the internal force redistribution occurs between the outer composite frame and the core tube shear wall, so that this kind of hybrid structure can maintain good ductility and anti-seismic capacity under larger earthquake intensity.

Figure 8. IDA quantile curve show by PGV.

Figure 9. IDA quantile curve show by Sa.

Figure 10. Exceeding probability show by PGA.
By analyzing the vulnerability curve of figure 10, the vulnerability matrix is obtained according to the probability of exceeding the limit state with PGA as strength parameter under different seismic levels, as shown in table 4.

**Table 4.** Vulnerability matrix of hybrid structure based on PGA.

| Earthquake standards          | PGA/g | Limit state probability /% | LS1  | LS2  | LS3  | LS4  | LS5  |
|------------------------------|-------|----------------------------|------|------|------|------|------|
| 8 degrees more than 0.07 g   | 0.07  | 12.51                      | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 8 degree basic 0.20 g        | 0.20  | 100.00                     | 82.53| 3.22 | 0.00 | 0.00 | 0.00 |
| 8 degrees rare 0.40 g        | 0.40  | 100.00                     | 99.98| 86.11| 8.73 | 0.01 | 0.01 |

From table 4, it can be seen that the probability of exceeding the normal service limit state is 12.51% when the 8 degree earthquake occurs frequently (PGA = 0.07 g), while the probability of exceeding the other four limit states such as basic service state is 0, which meets the seismic requirement of “small earthquake is not bad”. When the 8 degree earthquake occurs with basic intensity (PGA = 0.20 g), the probability of exceeding the normal service limit state is 3.22%. In this case, it will not endanger lives and meet the seismic requirement of “repairable under moderate earthquakes”. In 8 degree rare earthquakes (PGA = 0.40 g), the probability of the structure in the state of service and life safety after repair is higher, and the probability of approaching collapse is only 0.01%, which meets the seismic requirement of “no collapse under large earthquakes”.

4. Conclusion

(1) The IDA curve separation obtained by using PGA as seismic strength indicators is synthesized. The dispersion is better, and it can more effectively evaluate the seismic performance of the composite frame concrete cylinder hybrid structure.

(2) The composite frame-concrete tube structure can meet the three-level seismic requirements of “small earthquakes are not bad, medium earthquakes are repairable and large earthquakes are not collapsed” under 8-degree frequent, basic and rare earthquakes. It is shown that the composite frame concrete cylinder hybrid structure has good seismic performance.

References

[1] Wang Dasui, Zhou Jianlong. Development and Prospect of Steel-concrete Mixed Structures of High-rise Buildings in China [J]. Journal of Architectural Structure, 2010, 31 (06), 62-70.

[2] Xu Peifu, Wang Cuikun, Xiao Congzhen. Development and Prospect of China’s High-rise Building Structures [J]. Architectural Structures. 2009, 39 (09): 28-32.

[3] Bai Guoliang, Li Hongxing, Zhang Shuyun. Application and Problems of Mixed Structural System in Super High-rise Buildings [J]. Architectural Structures, 2006, 36 (08): 64-68.

[4] Wang Cuikun, Tian Chunyu, Xiao Congzhen. Progress in research and application of steel-concrete composite structures in high-rise buildings [J]. Architectural structures. 2011, 41 (11): 28-33.

[5] Vamvatsikos D, Cornell C. A. Incremental dynamic analysis [J] Earth quake engineering and Structural Dynamics, 2002, 31 (3): 491.

[6] Zhou Ying, Lu Xilin, Bu I. Application of incremental dynamic analysis in performance evaluation of high-rise hybrid structures [J].Journal of Tongji University (Natural Science Edition), 2010, 38 (02): 183-187+193.
[7] Zhu Jian. Structural dynamics and seismic vulnerability analysis [M]. Beijing: Science Press, 2014.

[8] Lucilin, Suning Powder, Zhou Ying. Seismic Vulnerability Analysis of Complex High-rise Structures Based on Incremental Dynamic Analysis [J]. Seismic Engineering and Engineering Vibration, 2012, 32(05):19-25.

[9] He Yibin, Li Yan, Shen Pusheng. Seismic vulnerability analysis of high-rise hybrid structures based on performance [J]. Engineering Mechanics, 2013, 30 (08): 142-147.

[10] Liu Yang, Shi Qingxuan, Wang Qiuwei, Wang Bin. Seismic vulnerability analysis of steel reinforced concrete frame-core tube hybrid structures [J]. Seismic resistance and reinforcement of engineering, 2014, 36 (06): 75-81.

[11] Zhang Lingxin, Xu Ziyang, Liu Jieping. Seismic vulnerability analysis of super high-rise hybrid structures based on incremental dynamic analysis [J]. Journal of Architectural Structures, 2016, 37 (09): 19-25.

[12] Xu Peifu, Xue Yantao, Xiao Congzhen et al. Experimental study on seismic behavior of high-rise steel reinforced concrete frame-tube hybrid structures [J]. Building Structures, 2005, 35 (05): 3-8.

[13] Zhang Shuyun, Bai Guoliang, Wei Hongyu. Nappe analysis of high-rise composite frame-concrete tube structure [J]. Journal of Huazhong University of Science and Technology (Natural Science Edition), 2012, 40 (9): 95-100.

[14] Zhao Wenwei, Research on Seismic Behavior of High-rise SRC Frame-RC Cylinder Hybrid Structures [D]. Xi'an: Xi'an University of Science and Technology, 2014:10-17.