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A "Three-index" Seismic Performance Evaluation Method Based on Sino-US Seismic Code

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Abstract: The Code for Seismic Design of Buildings (GB50011-2010) in 2016 and the method of seismic performance-based design for high-rise buildings in the Guide for Performance-based Design of High-Rise Buildings (TBI2017) are compared. In view of the characteristics and limitations of the seismic performance index set by the Sino-US seismic code, a "three-index" performance index system and evaluation process considering the displacement angle of the structural interlayer, the plastic damage degree of components and the plastic strain of material is put forward; combining the example of time-history analysis of a out-of-code high-rise building under the rare earthquakes is verified. The results show that the method of seismic performance evaluation by using deformation control index in Sino-US seismic code is relatively simple; however, both are lacking in the setting of specific components and the whole structure level respectively. The "three-index" system can comprehensively and quantitatively evaluate the seismic performance of out-of-code high-rise buildings.

Keywords: Seismic performance evaluation, seismic performance index, out-of-code high-rise buildings, rare earthquakes, time-history analysis.

1 Introduction

Seismic performance-based design is the design method based on the importance and use of the building to determine its performance objectives, and according to the objective to put forward different seismic performance indicators in order to let the buildings have intended function in the further earthquake. It realizes the transition from the macroscopic qualitative objective to the specific objective, and the designer can choose the performance objective for an individual structure and get rid of the limitation on the height and regularity of the building in the early specification [Dai, Han and Lin (2011); Karbassi, Mohebi, Rezaee et al. (2014); Martins, Silva, Marques et al. (2015)].

The performance-based seismic design theory was first proposed by American engineering field in 1990s, and the authoritative scientific research institutions of the country have promulgated many guide specifications for seismic performance-based

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design [Xu and Dai (2005); Naeim (2001)]. ATC-40 [Applied (1996)] marked a comprehensive study on the performance-based engineering theory and specified the implementation of the model in detail. It suggested that the capacity spectrum method was used for seismic design of reinforced concrete structures. FFMA 273 [Federal (1997)] provided a feasible guide for the seismic reinforcement and reconstruction of existing institutions. It suggested that the elastic static and elastic-plastic time-history analysis methods be adopted in the analysis and design. It also recommended that the performance level of structural and unstructured components was defined by the vertex displacement of the building. TBI2010 [Pacific (2010)] required evaluating the structural performance objectives in SLE and MCE level. The corresponding acceptance criteria are given on both the whole structure and the component level according to the deformation control and bearing capacity control. This specification is a complete set of performance-based seismic design guidelines, which produced a great impact on the appearance of the subsequent seismic design specifications and standards. TBI2017 [Pacific (2017)] was the promotion of TBI 2010, which summed up the experience and lessons of the previous version of the standard and integrated the new knowledge, new technology and practical achievements of the current project. Since 2010, China has put forward the seismic performance evaluation system for the whole structure, structural components and accessory components in GB50011-2010 (2016 Edition) (hereinafter referred to as GB50011) [Ministry (2016)] and JGJ3-2010 [Ministry (2010)], and gives the performance objective and indexes dominated by interlayer displacement and bearing capacity. However, in view of the limitation of using the nonlinear analysis method of structure under the strong earthquake action, it is suggested that it is conservative in the selection of structural performance objective s and the necessity of deep study.

In this paper, the similarities and differences of seismic level, seismic performance objective s and performance indexes in GB50011 of China and TBI 2017 of US are compared in detail. The performance evaluation system of “three-index” considering the interlayer displacement angle, the plastic damage degree of component and the plastic strain of material is put forward in this paper. In view of the dynamic time-history analysis of a certain high-rise building in China under the action of rare earthquakes, the deformation of the structure and plastic damage degree of components are analyzed, and the "three-index" system is used to evaluate the attainment of its seismic performance objective. The practical results of the study will provide a reference for improving the performance-based seismic design theory of high-rise buildings in China.

2 Comparison of seismic performance-based design methods in Sino-US

2.1 Seismic performance-based design in GB50011

The seismic performance-based design of structure should include the selected ground motion level, performance objective and specific performance index. GB50011 adopts the design method of “three-level and two-stage”. The three-level includes multiple earthquakes (50-year surpassing probability 63.2%), fortified earthquake (50-year surpassing probability 10%) and rare earthquake (50-year surpassing probability 2-3%); two-stage analysis includes multiple seismic elastic analysis and rare earthquake elastic-plastic analysis. Seismic performance objectives based on seismic levels are shown in Tab. 1.

Table 1: Seismic performance objective of GB50011-2010

Seismic level	Performance 1	Performance 2	Performance 3	Performance 4
Frequent earthquakes	Perfect	Perfect	Perfect	Perfect
Fortified earthquakes	Perfect, normal use	Basically perfect, continue to use after overhaul	Minor damage, continue to use after simple repair	Slight to medium damage, deformation <3[ΔU_e]
Rare earthquakes	Basically perfect, continue to use after overhaul	Minor damage, continue to use after simple repair	Its destruction needs to be strengthened and continued to use	Close to serious damage and continue to use after a major repair

Seismic performance index usually involves structural deformation and bearing capacity index, both of them are expounded in GB50011. However, the definition of bearing capacity indexes is vague and not easy to control quantitatively. The structural layer displacement angle $\theta = \Delta u / h_i$ as the representative of the deformation index is a detailed control, which has been widely used in the performance level classification of high-rise structures. In the case of rare earthquakes, time-history analysis method can be used on the structure to analyze the interlayer deformation and the seismic performance evaluation to determine whether it meets the desired performance objectives. In this code, the maximum interlayer displacement limits for multi high-rise structures under different performance levels are shown in Tab. 2.

Table 2: The maximum inter-layer displacement angle limits under different performance levels in GB50011

Structure type	Elastic interlayer displacement angle	Different damage state				Elastic-plastic interlayer displacement angle
		Perfect	Minor damage	Moderate damage	Serious damage	
Reinforced concrete frame structure	1/550	1/550	1/250	1/120	1/60	1/50
Reinforced concrete seismic wall, tube-in-tube	1/1000	1/1000	1/500	1/250	1/135	1/120
Reinforced concrete	1/800	1/800	1/400	1/200	1/110	1/100

frame-seismic wall and slab column seismic wall, frame-core tube						
Reinforced concrete frame	1/1000	1/1000	1/500	1/250	1/135	1/120
Steel structure	1/250	1/250	1/200	1/100	1/55	1/50
Steel frame-concrete core wall, steel reinforced concrete frame-concrete core wall	1/800	1/800	1/400	1/200	1/110	1/100

2.2 Seismic performance-based design in TBI 2017

TBI2017 is a newly issued guide designed based on seismic performance by the Pacific seismological Engineering Research Center. It sets two kinds of seismic performance objectives that are Minimum Performance Objectives and Enhanced Objectives [Wu, Jiang, Yang et al. (2015)]. Both of them need meeting the performance requirements of two seismic levels: (1) Service-Level Evaluation (The exceeding probability in 30-year is 50%, which is close to the frequent earthquakes in China) can verify whether the structure can maintain elastic and finite damage; (2) Maximum Considered Earthquake Evaluation (The exceeding probability in 50-year is 2%, which is close to the rare earthquake in China) can verify whether the load-bearing capacity of the structure is lost, the plastic deformation of serious degenerated strength happens; excessive residual deformation or un-stability of the whole structure appears. From the whole structure and component level, the standard pointed the minimum performance objectives respectively aiming at the interlayer displacement angle, the component demand and capacity ratio, the limit strain, the strength degradation of the material and more shown in Tab. 3. Among them, the performance indexes for deformation are more convenient to analysis and comparison. No specific requirements for enhanced performance objectives are required, and high-level performance indexes should be determined through negotiation among designers, owners and experts.

Table 3: Seismic performance index in TBI2017

Seismic level	Whole structure		Component	
	Deformation	Bearing capacity	Deformation	Bearing capacity
SLE	Maximum interlayer displacement angle 0.005	—	—	When the response spectrum is analyzed, the ratio of demand and capacity is ≤1.5 with analysis of response spectrum.

				The earthquake action is less than or equal to the material design strength in the nonlinear time-history analysis.
MCE	The maximum instantaneous interlayer displacement angle of 0.03 should not exceed 0.045; The maximum residual displacement angle 0.01 should not exceed 0.015.	The loss of bearing capacity of any layer is not more than 20%.	Limit strain δ_u-When the ultimate strain of unconstrained concrete reaches 0.003, the strength degradation can reach 50%; When the limit strain of confined concrete is 0.015, the strength degradation can be up to 20%, and the strain hardening will occur when the tensile strain of the longitudinal reinforcement reaches 0.05.	Components meet the demand of bearing capacity

2.3 Comparison of seismic performance index

It is found that the seismic performance indexes of the existing codes in Sino-US for deformation control are clearer and more detailed. The two codes limit the interlayer displacement angles under different seismic levels in the whole structural layer. The TBI2017 specification is more general and the specific structural types are not divided. The displacement limits under the SLE and MCE levels are also more relaxed than those many and rare earthquakes in GB50011. However, in the related component displacement control index of TBI2017, the limit variables related to concrete and steel and involving the problem of strength degradation under the limit strain state of concrete, whose index points are more abundant. The two existing codes set the performance indicators from the whole structure and the specific component level, and each has its own emphasis. In order to evaluate the seismic performance of high-rise buildings more comprehensively and reliably, this paper proposes that the interlayer displacement angle limit is used as the whole performance index of out-of-code high-rise structure under the rare earthquakes, and controls the plastic damage degree of the concrete and the plastic strain of the steel in the component layer; the "three index" evaluation system is established [Bradley (2013)].

3 Characteristics of concrete and steel

3.1 Plastic damage characteristics of concrete

3.1.1 Plastic damage model of concrete

The plastic damage model of concrete is first proposed and improved by Lubliner et al. [Lubliner, Oliver, Oller et al. (1989); Lee and Fenves (1998)], which can accurately simulate the non-recoverable plastic deformation and crack of concrete under earthquake and other cyclic loads, which eventually leads to the characteristics of plastic damage and stiffness degradation of the material. In Fig. 1, when the concrete is transferred from the tension state to the compression state, the cracks change from separation to contact closure, and the stiffness of concrete begins to recover. When the pressure is transferred to the tension state, the original cracks are turned from closure to separation, and the stiffness of the concrete cracks is not provided. In the finite element software, the plastic compression damage factor d_c and tensile damage factor d_t are commonly used to indicate the plastic damage degree of concrete under cyclic loading. The paper adopts the uniaxial tension and compression constitutive relation of the damage factor considered in GB50010-2010(2015 Edition) [Ministry (2015)] to determine the damage model of concrete[Su and He (2012); Al-Nimry, Resheidat and Qeran (2015); Bradley (2013); Huang and Kwon (2015)].

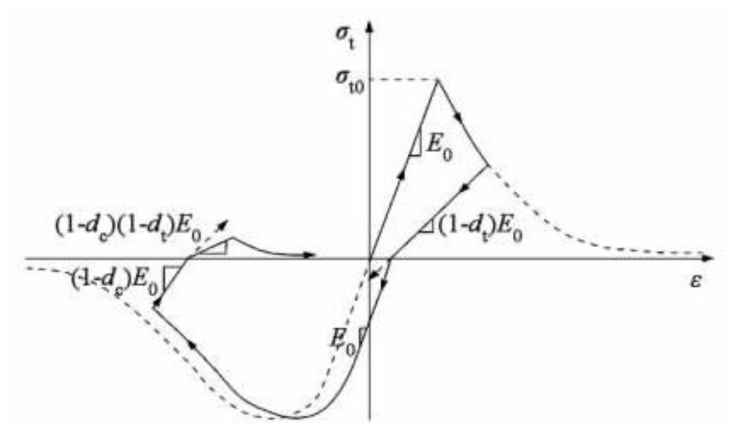


Figure 1: Tension and hysteresis curve of concrete

The uniaxial tensile stress-strain relation of concrete is as follows:

$$\sigma_t = (1-d_t)E_0\varepsilon \tag{1}$$

$$d_t = \begin{cases} 1-\rho_t\left[1.2-0.2x^5\right] & x \le 1 \\ 1-\dfrac{\rho_t}{\alpha_t(x-1)^{1.7}+x} & x > 1 \end{cases} \tag{2}$$

$$x = \frac{\varepsilon}{\varepsilon_{t,r}}; \quad \rho_t = \frac{f_{t,r}}{E_0\varepsilon_{t,r}} \tag{3}$$

Where d_{t} is the single axis tensile damage factor of concrete; α_{t} is the concrete parameter in descending section of uniaxial tensile stress-strain curve; $f_{\mathrm{t,r}}$ is the standard value of the uniaxial tensile strength of concrete; $\varepsilon_{\mathrm{t,r}}$ is the peak tensile strain of concrete corresponding to $f_{\mathrm{t,r}}$.

The stress-strain relationship of uniaxial compressive stress of concrete is as follows:

$$\sigma_{\mathrm{c}} = (1-d_{\mathrm{c}})E_0\varepsilon \tag{4}$$

$$d_{\mathrm{c}} = \begin{cases} 1-\dfrac{\rho_{\mathrm{c}} n}{n-1+x^n} & x \le 1 \\ 1-\dfrac{\rho_{\mathrm{c}}}{\alpha_{\mathrm{c}}(x-1)^2+x} & x > 1 \end{cases} \tag{5}$$

$$x = \frac{\varepsilon}{\varepsilon_{\mathrm{c,r}}}; \quad \rho_{\mathrm{c}} = \frac{f_{\mathrm{c,r}}}{E_0\varepsilon_{\mathrm{c,r}}}; \quad n = \frac{E_0\varepsilon_{\mathrm{c,r}}}{E_0\varepsilon_{\mathrm{c,r}} - f_{\mathrm{c,r}}} \tag{6}$$

Where d_{c} is the uniaxial compression damage factor of concrete; α_{c} is the concrete parameter in descending section of uniaxial compressive stress-strain curve; $f_{\mathrm{c,r}}$ is the standard value of uniaxial compressive strength of concrete; $\varepsilon_{\mathrm{c,r}}$ is the peak pressure strain of concrete corresponding to $f_{\mathrm{c,r}}$.

3.1.2 Plastic damage factor of concrete

The damage factor of concrete is taken as the judging index of its failure state. When the material is in tension and compression, the damage factor is 0. With the production and development of plastic deformation, the number of damage factors increases. When the damage factor is close to 1, the whole section of the component gradually enters the complete failure state. By quantifying the interval of damage factors, we can determine the seismic failure state of members, as shown in Tab. 4. The seismic performance objective of the structure can be determined by the ratio of the number of components under different failure conditions [Alembagheri and Ghaemian (2013); Zhang (2010)].

Table 4: Range of plastic damage factor of concrete members related to damage state of components

State of destruction	Description of destruction condition of component	Compression damage parameter	Compression damage parameter
Complete	Non-plastic	0	0

elasticity	deformation		
Basically perfect	There are tiny cracks in the individual parts, which can be used after minor repair.	0-0.25	0-0.10
Minor damage	Part of the internal and external penetration cracks are easier to repair	0.25-0.50	0.10-0.50
Medium damage	Most serious cracks or partial cracks expand and are difficult to repair.	0.50-0.80	0.50-0.90
Severe damage	Steel yield, partial complete destruction	0.80-0.97	0.90-0.95
Complete destruction	Failure of full section and loss of bearing capacity	>0.97	>0.95

Note: individual refers to less than 5%, part refers to less than 30%, and most refers to more than 50%.

3.2 Plastic strain of steel

The yield stress of steel with obvious yield point is the ratio of yield strength to elastic modulus, and then enters a long plastic strain state, and its limit strain is controlled to about 0.025, which is lower than the limit strain limit of 0.05 in TBI2017.

4 Seismic performance analysis procedure of out-of-code high-rise buildings under rare earthquakes

Based on the "three-index" evaluation method, the concrete steps for the seismic performance analysis of out-of-code high-rise buildings under rare earthquakes are as follows: (1) According to the out-of-code situation of the building, its seismic performance objectives are formulated; (2) The time-history analysis parameter is determined according to the area and soil condition of the out-of-code buildings and then the time-history analysis of the structure under the action of rare earthquakes is carried out to calculate the structural response of the structure; (3) The displacement angle of building is analyzed from the whole structural level and seismic performance is evaluated on the basis of Tab. 2; (4) The plastic damage degree and plastic strain of concrete are analyzed from the aspect of component, and the seismic performance is evaluated on the basis of Table 3, table 4 and the ultimate strain value of steel bar; (5) It is determined whether the structure satisfies the standard of GB50011 and TBI2017 specification based on the deformation seismic performance index, the plastic damage of concrete and the plastic strain of steel, and then evaluates the rationality of its seismic performance objective[Luo, Wang, Li et al. (2011); Yang, Zhou, Chen et al. (2014); Zhang, Li and Li (2013); Huang, Liao, Li et al. (2012); Gobbo, Williams, and Blakeborough (2017)].

5 Engineering example

5.1 Engineering general situation and seismic performance objective

The core tube structure (Figs. 2-3) of a frame with 5 stories underground and 62 floors above ground; height of the main structure is 273 m, and the whole height containing the top tower is 309 m; The outer frame column adopts concrete filled steel tubular column, the maximum length of cross-layer concrete filled steel column reaches 18.8m, and the second and third floors has holes on one side. The core tube of the elevator shaft is biased on one side, and there are many openings in the core wall. The top two floors have transfer beam structures. According to GB50011-2010 (2016 Edition) and JGJ3-2010, the structure exceeds the height limit of class B building and is irregular along the vertical direction. It is necessary to study the interlayer displacement angle of the whole structure, the damage degree of the concrete component and the plastic strain of steel to ensure that the structure meets the requirement of GB50011 performance objective 3 and the MCE fortification level under the lowest performance objective in TBI2017.

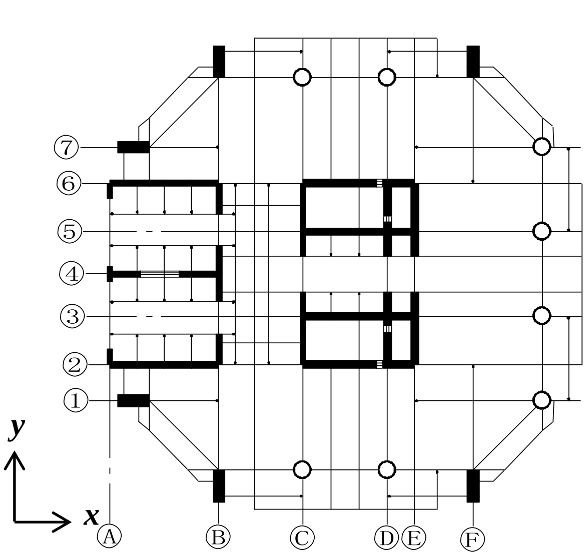


Figure 2: Structure plane layout

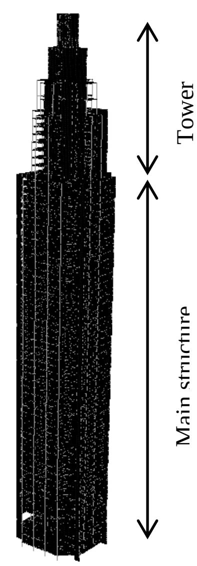
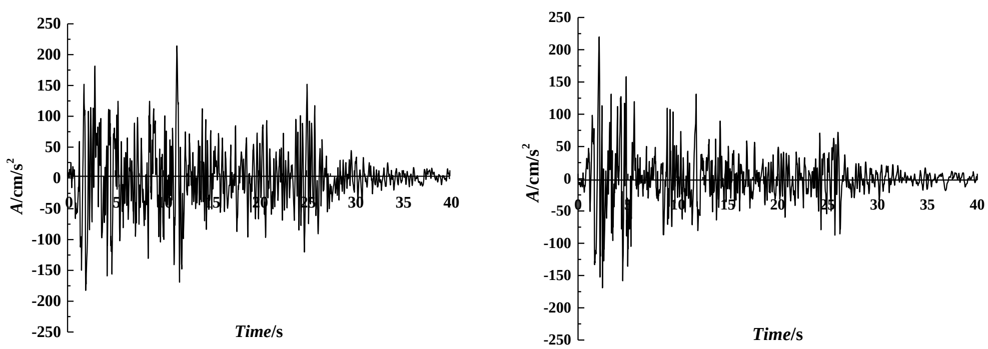


Figure 3: Structure integral model

5.2 Modeling and loading seismic waves

Large general finite element software ABAQUS is used to build the structural model and one dimensional elastoplastic rod element is used to simulate the beam and column, and the two dimensional elastic plastic shell elements is used to simulate the shear wall and the floor. A bilinear follow-up hardening model is adopted for the steel. The plastic damage model considering the tension and compression hysteresis is adopted in the concrete. The service life of the structure designed is 50 years and the area is 7 degree seismic fortification, 0.10 g, type II site soil. According to GB50011-2010 (2016 Edition), the Elcentro wave applied to the long period structure (1.5-5.5 s) of type II site soil (1.5-5.5 s) is selected from literature, and the time-history analysis of the structure under the action of double horizontal ground motion in the case of rare earthquakes is carried out [Lin and Wang (2014); Xian and Jia (2016)]. The main direction of seismic wave peak value is 1:0.85, the seismic wave duration is 40 s; the main direction of seismic peak acceleration is 220 cm/s^2, see Fig. 4 [Chomchuen and Boonyapinyo (2017); Sinkovič, Peruš and Fajfar (2016); Oyguc, Oyguc and Tonuk (2018)].



(a) Acceleration time-history in main direction (b) Acceleration time-history in secondary direction

Figure 4: Earthquake acceleration time-history of Electro wave in the two-directions

5.3 Interlayer displacement angle

It is known from the calculation that the structural dynamic response of seismic waves taking Y as the main direction is more obvious; therefore, the latter analysis results all take this loading condition as an example. The distribution of interlayer displacement angles under the action of bidirectional seismic waves is shown in Fig. 5. The maximum displacement angle of the main structure along X is 1/132, and the maximum displacement angle along y is 1/220, which appears at the top 63 positions of the main structure. The maximum displacement angle of the small tower along X is 1/211 and along y is 1/58, which appears in the 67 layers of the tower. The maximum displacement angle of the main structure along X meets the requirement that lower than 0.03 under the MCE level in Tab. 3, and it is judged by the corresponding index of the frame core tube structure in Tab. 2, which is between the medium damage (1/200) and the serious damage (1/110). The full height of the tower is 36m and has a severe whipping effect under the action of the earthquake, and increases rapidly along the Y direction. Although it is in line with the limit of MCE level in Tab. 3, it has greatly exceeded the limit of the maximum elastic-plastic interlayer displacement angle 1/100 in Tab. 2.

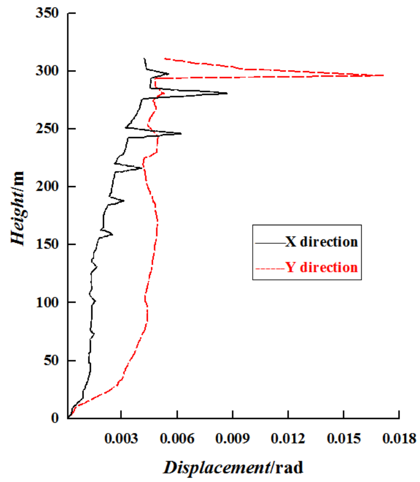
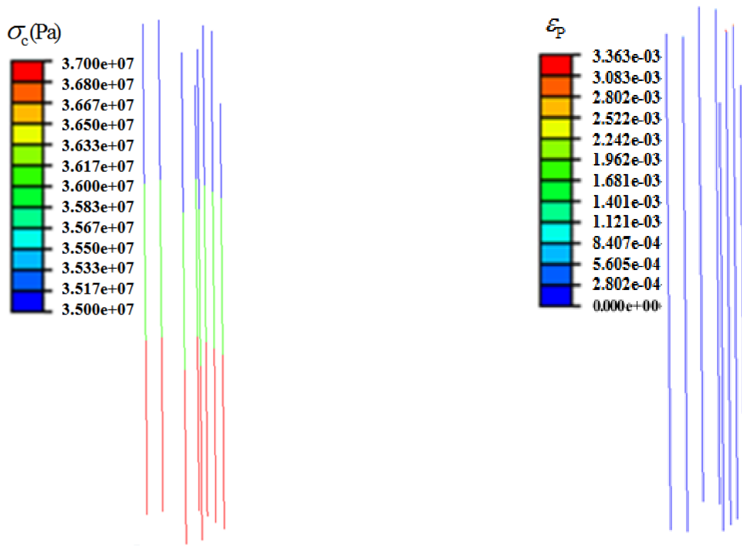


Figure 5: Interlayer displacement angle curve along X and Y

5.4 Deformation and damage of main components

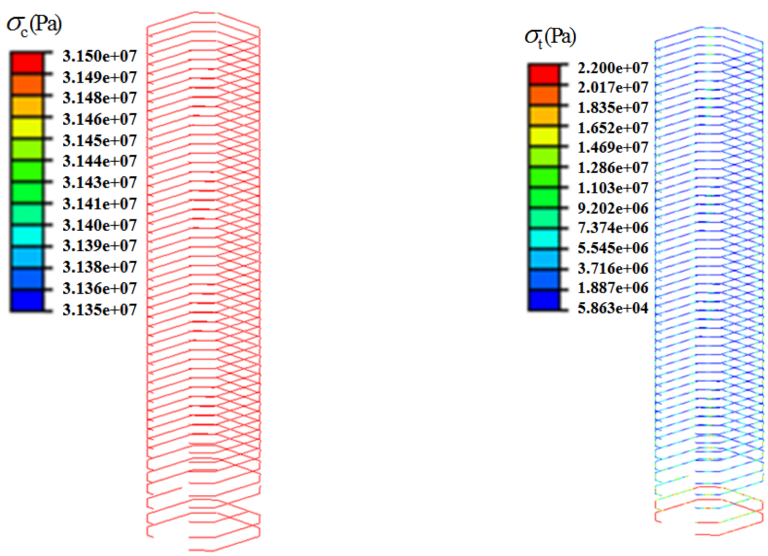
5.4.1 Outer frame

Fig. 6 is stress and strain of concrete filled steel columns of outer frame. Due to the larger structure weight, the outer frame column is mainly subjected to axial pressure even under the action of rare earthquakes. The compressive stress range of frame column concrete is basically in 35-37 MPa with no compression damage and the column retains elasticity. There is no plastic strain in most of the steel tube and the longitudinal stress bar; however, 0.0033 of the tensile plastic strain appears in the minimum area at the top of the column at the intersection of the transfer beam, whose total strain is far below the limit strain of 0.025. Fig. 7 is the stress and strain of the frame beam. There is no compressive damage to the concrete of frame beam, while the beam ends are subjected to tensile cracking under bending moment. There is no plastic yielding phenomenon in the reinforced bar and only 0.0006 slight plastic strain occurs at the end of the beam. The concrete filled steel tube column of the frame is kept well and the strength reserve is sufficient; the tensile damage of the frame beam is more obvious than that of the frame column with remarkable energy dissipation effect and the whole seismic ductility is perfect optimal.

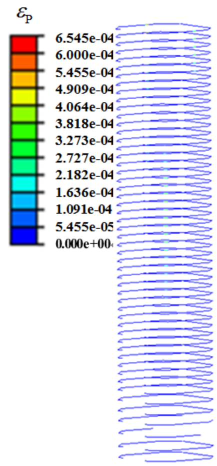


(a) Concrete compressive stress of frame column (b) Plastic strain of steel pipe and steel bar

Figure 6: Stress and strain of concrete filled steel tube columns



(a) Concrete compressive stress of frame beam (b) Tensile stress of concrete in frame beam

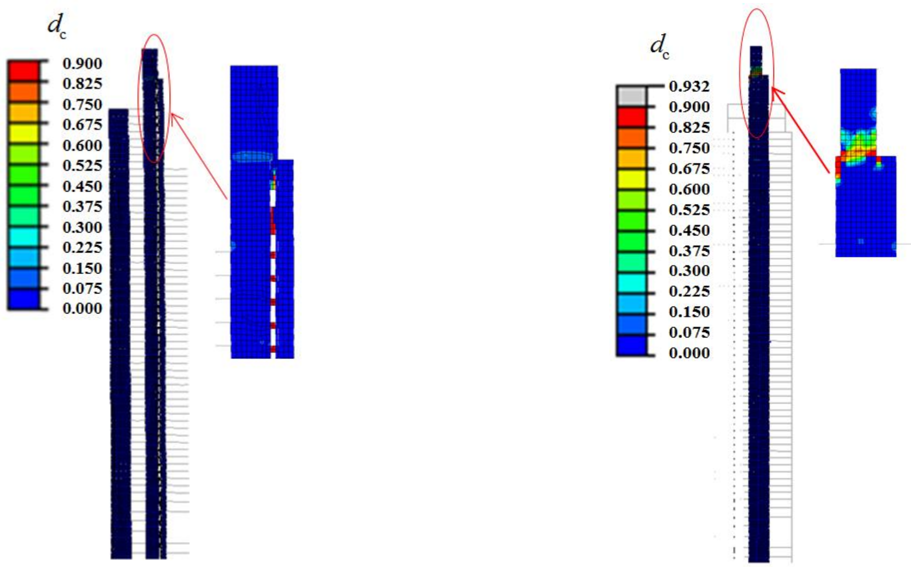


(c) Plastic strain of steel bar in frame beam

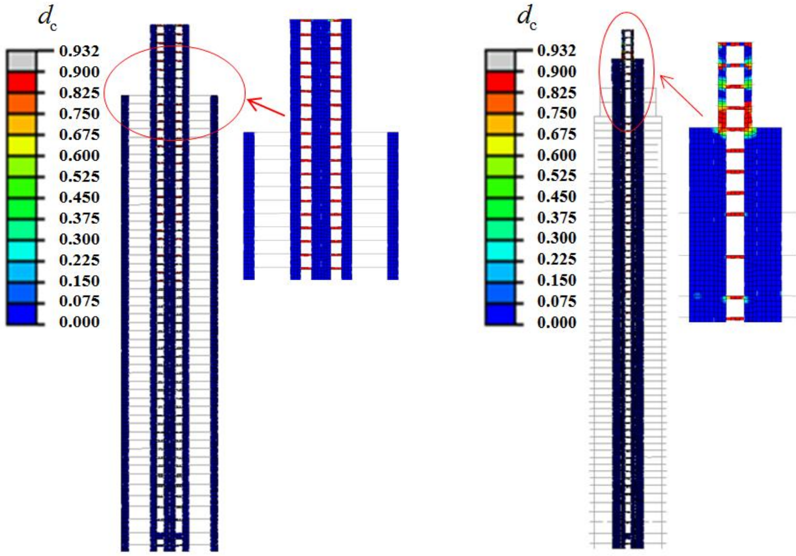
Figure 7: Stress and strain of frame beam

5.4.2 Shear wall

The analysis of concrete damage of shear walls of each axis under the influence of bi-directional earthquakes shows that the regions with relatively serious damage of shear walls are concentrated in axes ②-⑥ and Ⓑ-Ⓓ in Fig. 2. Taking the symmetry of the structural plane into account, the compression damage of concrete with respect to ②, ③, Ⓑ and Ⓒ is presented in Fig. 8. The damage of shear wall mainly presents as coupling beam damage. The damage of coupling beam is the most obvious in the upper 1/3 height range of the main structure, d_c is in 0.825-0.932 and enters a serious state of destruction, which has played a good energy dissipation effect. In addition to a slight damage within 0.375 of d_c for the main structure, the rest remained elastic. The indent size of the top small tower is larger; there is an obvious stress mutation with the connecting segment of the main wall limb, and the plastic damage area of d_c more than 0.5 is more concentrated, entering the middle damage or above damage state.



(a) Compression damage of wall limb in ②-axis (b) Compression damage of wall limb in ③-axis



(c) Compression damage of wall limb in Ⓑ-axis (d) Compression damage of wall limb in Ⓒ-axis

Figure 8: Plastic damage of main shear walls

5.4.3 Top tower

The core tube is indented two times vertically along the sixtieth and sixty-seventh layers, and the top sixty-seventh towers are completely indented into the top tower. A strong whipping effect is formed in the tower part, causing serious damage to the shear wall at its root as shown in Fig. 9. The wall is crushed from the corner and gradually spread to the root of the whole wall. The d_c values in the range are all over 0.5 and the maximum value is 0.932, entering the middle or above damage state. Therefore, increasing the amount of reinforcement at the ends of the columns of the shear walls of the tower columns or embedding steel into the concealed columns will be effective measures for improvement.

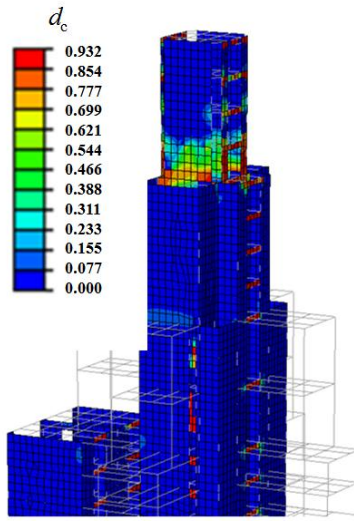
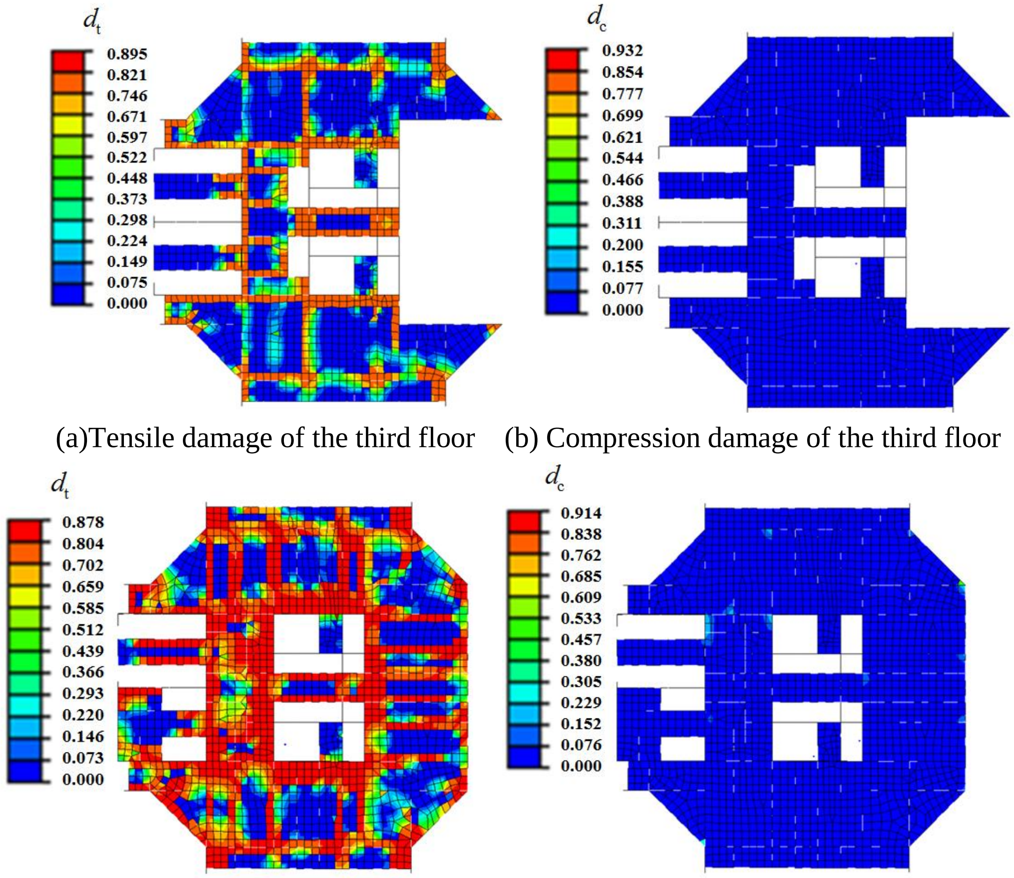


Figure 9: The compression damage of the shear wall of the top tower

5.4.4 Floor

Under the action of rare earthquakes, the floor is responsible for the distribution and coordination of the seismic forces between the various shear walls; concrete crack cannot be unavoidable. In Fig. 10(a), and in the large opening floor with three layers, there is a medium damage zone in some surrounding regions of shear wall and frame beam, whose 犽 is higher than 0.746. The cracking of the floor around the left side of the core tube is slightly lighter than that of the middle core tube, and the eccentricity located core wall has no effect on the floor. From Fig. 10(c), the tensile damage of the 20th floor is more serious, and more than 50% of the area reaches the medium damage zone with a value higher than 0.804. The tensile stiffness of the floor is greatly weakened after tensile cracking, and the seismic force is immediately unloaded from the floor without causing cracks for continue expansion. From Figs. 10(b) and 10(d), the compressive bearing capacity of the cracked floor has not been affected. Under the vertical load, there are no crushing conditions in all floors. The slab has a large area of compression elastic in addition to a few positions.



(a)Tensile damage of the third floor (b) Compression damage of the third floor

(c)Tensile damage of the 20th floor (d) Compression damage of the 20th floor

Figure 10: Plastic damage of main floors

5.5 seismic performance objective evaluations

The whole deformation of the overrun structure is between the moderate damage and serious damage of GB50011, meeting the requirement of deformation limit of MCE in TBI2017. There is no compression damage of concrete on the outer frame column, the frame beam exerts energy dissipation effect and the steel has micro plastic strain; the concrete of shear wall has slight compression damage and coupling beam exerts energy dissipation effect. The tower is damaged by medium or above and needs to be strengthened. The floor concrete is not subjected to compression damage, and appears above medium tensile damage. According to the deformation, damage and plastic strain of the integral structure and key components, the structure can be maintained after the rare earthquakes, which conforms to the characteristics of the medium damage to the serious damage interval of Chinese GB50011, and can be used again after the reinforcement of the tower and meets the requirement of the performance objective 3; At the same time, it also accords with the seismic performance index of MCE fortification level under the lowest performance objectives of TBI2017.

6 Conclusion

(1) The contents of seismic performance-based design of China GB50011 and British TBI2017 are compared. The two existing codes are different in terms of seismic performance objectives and performance indicators; However they are both verified by performance indicators of structural deformation and bearing capacity. In contrast, deformable performance indicators are simpler and easier to use. The criterion is limited to the interlayer displacement angle under different seismic levels from the whole structure layer. The structure type of GB50011 is more detailed, and the displacement limit under different seismic level is stricter than that of TBI2017. According to the displacement control index of the component, the plastic damage degree of concrete and the ultimate strain value of the steel bar involved in TBI2017 can be more practical according to the index point.

(2) The "three-index" seismic performance evaluation system and analysis steps for high-rise buildings are put forward. The whole deformation performance of the structure is evaluated based on the interlayer displacement angle limit of GB50011; the deformation properties of components are evaluated based on TBI2017, the plastic damage of concrete and the plastic strain of steel; the above indexes can judge the rationality of seismic performance objectives of the out-of-code high-rise buildings comprehensively and quantitatively.

(3) In view of the dynamic time-history analysis of an out-of-code high-rise building in China under the rare earthquakes, three main performance indexes of the whole structure and the detailed components are analyzed; the seismic performance objectives of the structure are evaluated, and the improvement measures are put forward. The analysis method is practical.

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