Out-of-Codes Seismic Analysis on a Science Museum under Rare Earthquake

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Abstract. Take the example of a science and technology museum where the upper part is a steel structure and the lower part is a concrete shear wall structure. The performance-based design goals of the structure under rare earthquake are put forward. The performance of the structure under rare earthquake is analyzed considering the joint work of steel and concrete structure. Results show that the structure can meet the performance goals, the structure is safe, and some seismic strengthening measures of the structure are given based on the results.

Keywords. Out-of-codes structure, performance-based design, time history analysis, seismic strengthening measures.

1. Introduction
With the improvement of economic and social aesthetics, various structures have emerged, but the current structural design specifications only target more regular structures [1, 2]. For structures with high heights, irregular planes or verticals, or complex shapes, the current technical level is difficult to make a confident judgment on their performance under strong earthquakes, but their destruction or collapse will cause greater social and economic impacts [3-5]. Therefore, it is necessary to conduct a detailed analysis of its performance under earthquake action [6-8]. China’s “Code for Seismic Design of Buildings” stipulates that at least three sets of seismic waves similar to the response spectrum and seismic response spectrum should be used in the elastic and elastic-plastic time history analysis, and the envelope value of the result shall be taken [9]. This structure is designed and analyzed in accordance with Chinese standards and the results of time history analysis under rare earthquake are given.

2. Project Overview
2.1. Structure Overview
The space function requirements of the museum and the architectural modeling characteristics of this project form the following main structural geometric mechanical characteristics: the plane is spliced by several sectors, the main column network is 8 m×9 m, and the maximum column network is 15 m×11 m. The east and west sides are connected as a whole through the basement, 10.500 m floors, 24.000 m and 34.000 m floors and steel roof structure. The maximum span of frame beams is 26.2 m; there are split-level structures on some floors; and there are large openings on some floors. The main body adopts the reinforced concrete frame shear wall structure, the streamlined roof and the wall are connected as a whole, the large-span spatial truss steel structure is connected with the internal main structure, and the dome theater roof adopts a single-layer steel reticulated shell structure.
The architectural rendering is shown in figure 1 and the overall calculation model of the structure is shown in figure 2.

![Figure 1. The architectural rendering](image1)

![Figure 2. Overall FEA model of the structure](image2)

### 2.2. Irregularity of the Main Structure
Reverse irregularities: Some floors do not meet the requirements of Article 3.4.2 of the "Code for Seismic Design of Buildings (2016 Edition)" of China: The ratio of the maximum horizontal displacement and inter-story displacement of the vertical members of the floor to the average horizontal displacement and inter-story displacement of the floor should not be greater than 1.2. But the maximum value is less than 1.4.

Irregular flat surface: The plane is asymmetric, and the ratio of the protruding length of the north side area to the length in this direction is greater than 0.3.

Partially discontinuous floor: The east and west areas on the 24.000 m and 34.000 m floors are only connected by a span of beam slabs and the effective floor width is less than 50% of the typical width of the floor slabs. The elastic floor slabs is used for analysis and calculation and structural enhancement, and the nonlinear layered shell model is used to calculate the elastoplastic performance of the floor under the action of rare earthquakes.

### 3. Seismic Performance Design Goals and Seismic Analysis Parameters for Rare Earthquake

#### 3.1. Seismic Performance Design Goals for Rare Earthquake
According to the overrun conditions of this project, the seismic performance target of this project is selected as Grade C [10]. The corresponding seismic performance level under the estimated rare earthquake is level 4. The specific performance targets of each stage are shown in table 1.

| Code basic fortification goals | Does not collapse | Key concrete components (Cline column) | First-grade plastic hinge is allowed |
|--------------------------------|--------------------|----------------------------------------|-------------------------------------|
| Minimum seismic performance requirements | level 4 | Ordinary concrete vertical component (Ordinary column) | Secondary plastic hinge is allowed |
| Allowable story drift ratio | 1/100 | Floor truss, transition truss and cantilever ring truss | First-grade plastic hinge is allowed maximum story drift ratio 1/50 |
| Key concrete components (Cline wall) | Allow local concrete tensile stress to yield; steel bar stress is not greater than the standard value of strength; compressive stress of concrete is not greater than the standard value of strength | Complex area floor | Allow local concrete tensile stress to yield; Concrete compressive stress ≤ Concrete compressive stress standard value |

Table 1. Specific performance targets for rare earthquake.
3.2. Seismic Calculation Parameters
The seismic fortification intensity is 8 degree, the design basic seismic acceleration value is 0.2 g, the design earthquake is grouped into the third group, the site category is III, and the site characteristic period $T_g=0.65$ s.

The structural damping ratio is taken as $\zeta=0.05$ in the analysis of rare earthquakes. When the damping ratio is 5%, the earthquake influence coefficient is $\alpha_{max}=0.93$.

For the time history analysis of rare earthquake, the seismic parameters selected are: $T_g=0.70$ s, $\alpha_{max}=0.93$ and peak ground acceleration value 404Gal.

When selecting seismic waves, we fully consider the three factors of earthquake reflecting the damage effect of ground motion on the structure: effective peak ground motion acceleration, Spectrum characteristics and duration. Three seismic waves for calculation and analysis are selected including 2 sets of natural waves and 1 set of artificial waves: Westmorland wave (1981), Coalinga wave (1983) and artificial waves provided by earthquake safety evaluation report.

The input methods of seismic waves include: one-way horizontal and vertical input; three-way input, the acceleration peak value X: Y: Z is adjusted according to the ratio of 1:0.85:0.65. The time history analysis results take the envelope values of all waves for structural design.

Comparison of seismic time-history wave response spectrum curves and standard response spectrum curves are shown in figure 3.

![Figure 3](image)

Figure 3. Comparison of seismic time-history wave response spectrum curves and standard response spectrum curves under rare earthquake.

4. Rare Earthquake Time History Analysis (Performance level 4)

4.1. Material and Component Nonlinear Constitutive Relationship

4.1.1. Material Nonlinear Constitutive Relationship. The elastic-plastic time history analysis of structures under rare earthquakes uses a three-dimensional finite element model to consider the nonlinear hysteresis and constitutive behavior of structural members. The steel adopts the reinforced type ($\beta>0$) double-line hysteresis model considering the Bauschinger effect, as shown in figure 4; the concrete adopts the ability to simulate the cracking of the concrete structure and the stiffness degradation after yielding. The three-fold line model is shown in figure 4(b).

![Figure 4](image)

(a) Steel hysteresis characteristics  
(b) Concrete hysteresis characteristics

Figure 4. Material hysteresis model.
4.1.2. Component Nonlinear Constitutive Relationship. The line element component is simulated by the plastic hinge model; the column element considers the interaction between the bidirectional bending and the axial load, and uses the compression (tension) bending plastic hinge (P-MM hinge), and the position of the plastic hinge is at both ends. The beam element uses irrelevant axial force and bending hinges (P hinge and M hinge), and the position of the plastic hinge is at both ends. The strut unit adopts axial hinge, assuming that the plastic hinge appears in the middle of the rod.

There are mainly two simulation methods for concrete surface element components (such as shear walls and floor slabs). For the simpler core tube, the simplified line element model can be simulated by "equivalent thin-walled columns + rigid arms"; for the difficult complex shear wall structure simplified by "equal generation thin-walled column + rigid arm" is suitable to be simulated by a nonlinear layered shell using a fiber model.

Perform modal analysis on the simplified model and compare it with the original structure. The first three-order structural modes are shown in table 2. It can be seen from the table that the dynamic characteristics of the simplified model are close to the original model.

**Table 2. Modal period comparison table.**

| Mode | Period of original model (s) | Period of simplified model (s) | Error |
|------|----------------------------|-----------------------------|-------|
| 1    | 0.963                      | 0.936                       | 2.80% |
| 2    | 0.741                      | 0.744                       | -0.35%|
| 3    | 0.671                      | 0.667                       | 0.55% |

4.2. Story Drift Ratio of Concrete Structure and Vertical Displacement of Cantilever End of Steel Structure

Under the action of various seismic wave conditions of rare earthquakes, extract the story drift ratio of the concrete structure and the vertical displacement of the cantilever end of the roof steel structure.

As it can be seen in figure 5 and table 3, the story drift ratio between concrete structure and the vertical displacement of the cantilever end of the roof steel structure can meet the requirements of performance target level 4.

![Figure 5: Story drift ratio curve under various seismic wave conditions caused by rare earthquakes.](image)

**Table 3** shows the maximum vertical displacement of the cantilever end of the steel structure under various seismic wave conditions of rare earthquakes.
Table 3. Maximum vertical displacement of the cantilever end of the steel structure.

| Load condition       | Vertical displacement (mm) | Displacement / Cantilever length |
|----------------------|-----------------------------|----------------------------------|
| Westmorland-45 degree| 310.5                       | 1/90                             |
| Westmorland-X direction | 359.4                     | 1/78                             |
| Coalinga-45 degree   | 382.7                       | 1/73                             |
| Coalinga-X direction | 401.5                       | 1/70                             |
| Artificial wave-45 degree | 406.7                   | 1/69                             |
| Artificial wave-135 degree | 369.3                  | 1/76                             |
| Artificial wave-X degree | 350.6                    | 1/80                             |
| Artificial wave-Y degree | 338.7                    | 1/83                             |

4.3. Plastic Hinge Development

Reinforcing bars adopt HRB400, ordinary beams have a reinforcement rate of 1.5%, beams connected to shear walls and scientific research rooms have a reinforcement rate of 2%, ordinary columns have a reinforcement rate of 3%, and steel structures are connected with a roof column that is 4%. The reinforcement rate of the equivalent-generation thin-walled column is 1%.

4.4. Nonlinear Analysis of Shear Walls and Complex Floor Slabs

Taking into account the complexity of the structure, especially the discontinuous floor slabs, partial retracting, etc., it is advisable to use nonlinear shells to simulate the surface elements such as shear
walls and floor slabs with complex forces. In this section, SAP2000 is used to check the structure under rare earthquakes, and the shear walls and discontinuous floors are simulated by nonlinear layered shell elements.

4.4.1. Plastic Development Status of Shear Wall. The tensile and compressive stresses of concrete and the stress of steel bars are shown in figure 7 and figure 8. From figure 7 and figure 8, we can conclude that:

- Under the action of rare earthquakes, most of the shear walls are in compression, and do not exceed the standard value of the concrete axial compressive strength, and the tensile stress in the middle part of some shear walls reaches 3 MPa. In the seismic performance-based design target, under the action of rare earthquakes, cracks in the concrete of the shear wall are allowed, and the shear wall can achieve the seismic performance-based design target.
- Under rare earthquakes, the longitudinal reinforcement stress of the local bottom shear wall is relatively large, but the yield strength is not reached 400 MPa, and the reinforcement stress of the upper shear wall is relatively small, achieving the design goal of seismic performance.

4.4.2. Plastic Development Status of Floor Slabs. Under rare earthquakes where artificial waves are mainly X-direction, the seismic response of the overall structure is relatively large. Therefore, artificial waves are selected and the X-direction is used to analyze the stresses of the overall structure floor concrete and internal steel bars.

The tensile and compressive stresses of concrete are shown in figure 9 and figure 10. From figure 9 and figure 10, we can conclude that:
Under the action of rare earthquakes, the maximum compressive stress of each floor slabs does not exceed the standard value of C30 concrete axial compressive strength of 20.1MPa, and it will not be crushed. Earthquake resistance could achieve Performance-based design goal Level 4.

Under the action of rare earthquakes, the tensile stress of concrete floor slabs in some areas reached 3MPa, and the concrete slabs appeared cracks. The seismic performance target allows the concrete tensile stress to yield, the converted tensile stress of the steel bar does not reach the yield stress which can achieve the seismic performance design target (level 4).

4.5. Seismic Performance-Based Design of Important Components for the Cline Columns

Under the action of earthquake, due to the lack of restraint between the jump layers, the lateral stiffness of cline columns is relatively small, and the seismic force absorption is relatively small, but the horizontal deformation is relatively large. The concrete at the root of the columns may crack and occur large plastic deformation. Under the action of rare earthquakes, the horizontal deformation is shown in Table 4.

Table 4. Story drift ratio of the cline columns in the X-direction of artificial waves in rare earthquakes.

| Floor | Height(m) | X direction | Y direction |
|-------|-----------|-------------|-------------|
| 8-10F | 10        | 1/183       | 1/270       |
| 4-8F  | 13.5      | 1/239       | 1/236       |
| 2-4F  | 10.5      | 1/329       | 1/462       |

Under the X-direction of artificial waves in rare earthquakes, the story drift ratio of the key components of the cline columns is below 1/183, which is less than one-third of the collapse performance target of 1/50, and there is no lower plastic hinge in thermocline columns. Level 1 plastic hinges occur in top layer columns. So we can know that the cline columns could meet the requirement of rare earthquake.

5. Conclusion

Through the analysis of rare earthquake, the following conclusions can be drawn:

- Under the action of rare earthquake, the story drift ratio of the structure is below 1/200, and the maximum displacement of the cantilever end is 1/69 of the cantilever length, which can meet the performance goal of the structure.
- Under rare earthquake, the maximum compressive stress of each floor and shear walls does not exceed the standard value of C30 concrete axial compressive strength. The floor and shear wall concrete tensile stress of some parts reaches 3 MPa, and the concrete appears cracked, but the seismic performance targets allow concrete tensile stress to yield. The stress of the steel bars, does not reach the yield stress.
- The story drift ratio of the key component cline column is below 1/183, which is more than three times the collapse performance target 1/50, and the lower cline column is still in an elastic state without plastic hinge. Because of the top-layer cline column is connected to the steel structure, level 1 plastic hinges appear due to its influence, but it can still ensure safety under rare earthquake.

On the whole, the structure can meet the performance goals and ensure safety under rare earthquake.

In view of the calculation results, some suggestions for seismic fortification measures are also given for this structure:

- Increase structural redundancy (for example, install energy dissipation components in structurally weak areas), and reasonably set structural yield and energy dissipation mechanisms;
According to the results of elastoplastic time-history analysis of concrete structure, where there are more plastic hinges, the reinforcement ratio of the relevant beams and columns can be appropriately increased, and the plate thickness or wall thickness can be appropriately increased for the parts with higher tensile stress on the floor slabs or shear walls.

References
[1] Wang D S and Bao L J 2019 Development and prosperity of structural design of super tall buildings in China Building Structure 49(19) 11-24.
[2] Fu J, Wang L, Chen H and Sun H B 2020 Discussion on seismic analysis and design of out-of-code tall building structure Building Structure 50 (12) 84-88, 99.
[3] Guo C H 2020 Performance-based structural seismic method in high-rise building design Proc. Int. Conf. on Electronic, Electrical and Computer Applications (Osaka) 1578 p 012190.
[4] Bai Y T 2016, Permanent damages of structural components in existing high-rise steel buildings subjected to rare earthquakes Iabse Symposium Report 106(10) 386-393.
[5] Cheng X Y, Xue Y T and Liu Z H 2008 Comparison of the rc structures with the results provided by nonlinear static push-over and dynamic analysis Earthquake Resistant Engineering and Retrofitting 05 8-13.
[6] He Z W and Chen G X 2018 Super high-rise structural design and seismic performance analysis in Guiyang Guangdong Architecture Civil Engineering 25 (07) 24-27.
[7] Chen Z P, Feng D C and Wu G 2020 Seismic Performance and design process majorization of a reinforced concrete grid frame wall Journal of Earthquake Engineering 3 1-30.
[8] Li W and Li Q N 2012 Performance-based seismic design of complicated tall building structures beyond the code specification Structural Design of Tall & Special Buildings 21(8) 578-591.
[9] Mohurd 2016 Code for Seismic Design of Buildings Beijing: China Construction Industry Press.
[10] Mohurd 2010 Technical Specification for Concrete Structures of Tall Building Beijing: China Construction Industry Press.