Analysis of performance-based seismic design method for super high-rise frame-supported shear wall structure

Yuhong Ling1,2, Anqi Li1, Rui Liu2,3*
1 School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong, 510641, China
2 State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, Guangdong, 510641, China
3 Architectural Design and Research Institute of SCUT, Guangzhou, Guangdong, 510640, China
*Rui Liu’s e-mail: 873164170@qq.com

Abstract. In this paper, the advanced performance-based seismic theory is introduced, and combining with the seismic codes and high-rise building codes, a performance-based seismic design approach is established for high-rise frame-supported shear wall structure. Firstly, the performance objective is determined, and then calculation under frequent earthquakes, fortification earthquake and rare earthquake is carried out, finally, the performance analysis is carried out to see whether it achieves the predetermined performance objective. Then taking a high-rise frame-supported shear wall structure as an example, based on the performance-based seismic design method, YJK and ETABS software were used to carry out the performance-based seismic design under the action of frequent earthquakes and fortification earthquakes. Next, Perform3D software was used to analyze dynamic elastic-plastic time-history analysis under the action of rare earthquakes. In addition, the analysis of transfer component performance were conducted for quantitative control of the bearing capacity and deformation of reinforced concrete structures and structural members. The calculation results show that relevant parameters can meet code requirements and the seismic performance of the whole structure and components can reach the expected performance objectives. Finally, we present a summary of the proposed seismic strengthening measures and make suggestions for the whole structures, by which the structure can meet the seismic fortification code requirements and be safe and reliable.

1. Introduction
The classification criteria of fortification for A, B, C, D put forward in the code for seismic design of buildings[1]. In the code, the objective of seismic performance “frequent earthquake is not bad, fortification earthquake can be repaired, rare earthquake do not fall” reflects the performance-based seismic theory. However, the “three-level, two-stage” design method with empirical factors makes it difficult to quantitatively evaluate structural performance at different seismic levels. The performance-based seismic design method is to make the structure achieve different predetermined performance objectives under the earthquake action of different intensity levels during the design life.

At present, the performance-based seismic design method is used in the seismic codes of various countries, which means that seismic design is transferred from the qualitative goal in the code to the specific objectives in the specific project. Based on this, more stringent seismic requirement than the
code can be put forward. If the height exceeds the requirements of the code, or the structural system and type exceed the applicable type of the present code, the performance-based seismic design method can better adapt to the special requirements of super high-rise building. Finally, the corresponding structural performance objectives can be determined according to the actual situation and degree of structural scheme and the design requirements that are different from traditional design.

In the reference[2], taking the north tower of Wuxi Sunning Plaza as example, Perform3D software is used to analyze elastic-plastic time-history response analysis but no seismic strengthening measures are put forward. In the reference[3], through analysis of forces that destroy structures under continuous vibration, the experiment results show that the new method can help avoid building damage but the accuracy of the method has not been verified by the analysis of different magnitudes. In the reference[4], the seismic analysis of the super high-rise frame-supported shear wall structure is carried out, the reinforcement measures are taken in the weak parts but do not analyze the dynamics of the structure.

According to the above problems, this paper firstly describes the performance-based seismic analysis method for the super high-rise frame-supported shear wall structure, and then takes the actual engineering project as an example, finally gives the structural seismic measures and suggestions.

2. Methods

2.1. Determination of performance objectives
The performance objectives should be determined by many factors such as the height, regularity, structural type, seismic fortification standard, site conditions, post-earthquake loss, reconstruction cost and the difficulty after the damage. The technical specification for concrete structures of high-rise buildings code[5] puts forward the seismic performance objectives A, B, C and D, requiring the structure to satisfy the elastic design in the case of the frequent earthquakes, but the performance requirements for fortification earthquakes and rare earthquakes are different.

2.2. Analysis of different leveling earthquakes

2.2.1. Performance analysis of frequent earthquakes. When the elastic calculation of B level high-rise building structure is carried out under the frequent earthquakes, at least two different structural analysis software should be used to calculate the mode decomposition response spectrum, and the calculation parameters such as story drift, drift, shear gravity ratio and so on are expected to be compared. Then the elastic time history analysis method is used to supplement it, and take the larger value between the calculation results of the two methods as the final design. For the super high-rise frame-supported shear wall structure, it should also be judged whether the stiffness ratio of the upper and lower structures of the transfer story conforms to the requirements of appendix E of the technical specification for concrete structures of high-rise buildings code[5].

2.2.2. Performance analysis of fortification earthquakes. In the elastic calculation of fortification earthquake, the partial coefficient of load action, the partial coefficient of material, the partial coefficient of seismic bearing capacity and the material strength are the same as those in the analysis of frequent earthquake, the internal force adjustment coefficient of earthquake is set to 0.85.

In the non-yield calculation of fortification earthquake, the internal force adjustment coefficient of earthquake, the partial coefficient of load action, the partial coefficient of material and the partial coefficient of seismic bearing capacity are all set to 1.0, and the material strength adopts the standard value.

2.2.3. Performance analysis of rare earthquakes. In the high-rise buildings code 5.1.13[5], B level high-rise building structures and complex high-rise building structures such as structure with transfer story are generally using the static or dynamic elastic-plastic analysis method to analyze the weak parts and seismic performance. The static elastic-plastic method is also called pushover analysis, and the loading
is carried out in two steps. First, the representative value of the gravity load is applied and remains constant during the subsequent application of the horizontal load. Second, the horizontal load in which the vertical distribution mode is inverted triangle is gradually applied, without considering the damage accumulation and stiffness change. Finally, the calculation can only analyze the overall performance of the structure. The dynamic elastic-plastic analysis method directly inputs the time-history wave data of the ground motion acceleration into the structural model. The whole process of the internal force and deformation of structural components changing with time under the earthquake is obtained. In addition, the dynamic characteristics and the three key points of strong earthquakes are considered[7].

The quantitative assessment criteria for different damage for various components are determined by reference to the United States ASCE41 code, as shown in table 1 and figure 1 below.

| Structural component | Description object | Degree of damage |
|----------------------|--------------------|------------------|
| Concrete beam        | Plastic corner     | Minor damage     | Mild damage    | Moderate damage | Severe damage |
|                      |                    | 0.00<θ<0.0025    | 0.0025<θ<0.005  | 0.005<θ<0.01   | 0.01<θ<0.02   |
| Column, wall         | Compressive strain of concrete | ε₁<ε≤ε₂ | ε₂<ε≤ε₃ | ε₃<ε≤ε₄ | ε₄<ε≤ε₅ |
|                      | Tensile strain of steel bar | 0.002<ε≤0.004 | 0.004<ε≤0.006 | 0.006<ε≤0.008 | 0.008<ε≤0.01 |

Figure 1. Sketch of degree of loss of concrete.

2.3. Selection of seismic waves
For the dynamic elastic-plastic time-history analysis, the seismic acceleration time history curve should satisfy the requirements of three key points: effective acceleration peak, spectral characteristics and the duration of ground motion. A group of seismic waves should contain not less than two artificial waves and no less than five natural waves. The effective duration of each group of waveforms is generally not less than 5 to 10 times of the basic period of the structure. Compared with the seismic influence coefficient adopted by the mode decomposition response spectrum method, the difference should not be more than 20% at each periodic point.

3. Actual project
3.1. Project overview
The height of the structure is 115.3 m, 35 floors above ground and the transfer story is set in 5 floors. The structural type is frame-supported shear wall structure. The transfer story and the next floor plan are shown in figure 2.
3.2. Out-of-code situations
By reference to the codes, the out-of-code situations of this project are as follows:

- The height exceeding the code: the structural height is 115.3 m which exceeds the maximum applicable height in the code.
- Torsion irregularity: the torsional drift considering accidental eccentricity is greater than 1.2.
- Irregular lateral stiffness: in order to meet the requirements of shops, part of the shear wall does not fall to the ground but is converted by a five-story frame supported.
- Partial discontinuity of the floor: the ratio of the effective floor width to the typical floor width is 23.5% which is less than the 50% required by the code.

3.3. The seismic performance objective of the structure
The seismic performance objective of the structure is set as C-grade. In the frequent earthquake, the structure should achieve the requirement of performance level “1” and the limit story drift is 1/800. In the fortification earthquake, the structure should achieve the requirement of performance level “3” and the limit story drift is 1/400. In the rare earthquake, the structure should achieve the requirement of performance level “4” and the limit story drift is 1/120.

3.4. Results

3.4.1. Modal analysis. The modal analysis results of each software are shown in table 2, which verifies the accuracy of the model.

| Analysis software | YJK          | ETABS       | PERFORM-3D |
|-------------------|--------------|-------------|------------|
| T1/s              | 3.16         | 3.09        | 3.11       |
| T2/s              | 2.97         | 2.92        | 2.97       |
| T3/s              | 2.40         | 2.35        | 2.38       |
| T3/ T1            | 0.76         | 0.77        | 0.77       |

3.4.2. Elastic analysis of frequent earthquakes. From table 3, the calculation results of the YJK and ETABS software are close, so the performance objectives under the frequent earthquake are satisfied.

| result                          | YJK          | ETABS       |
|---------------------------------|--------------|-------------|
| Modal participating mass ratios | 97.71% (X direction) | 95.80% (X direction) |
|                                 | 96.85% (Y direction) | 94.05% (Y direction) |
| Shear gravity ratios            | 1.66% (X direction) | 1.70% (X direction) |
|                                 | 1.60% (Y direction) | 1.70% (Y direction) |
|                                 | 1/1185 (X direction) | 1/1201 (X direction) |
| Maximum story drift             | 1/1008 (Y direction) | 1/1048 (Y direction) |
| Maximum drift                   | 1.14 (X direction) | 1.16 (X direction) |
|                                 | 1.29 (Y direction) | 1.29 (Y direction) |
| Lateral stiffness ratio between transfer story and adjacent upper story | 0.736 (X direction) | 0.725 (X direction) |
|                                 | 0.826 (Y direction) | 0.885 (Y direction) |
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The structural elastic time-history analysis under seven groups of seismic waves are shown in table 4.

| Method                  | Based shear force (kN) | X direction | Y direction |
|-------------------------|------------------------|-------------|-------------|
| CQC method              | BASED SHEAR FORCE (K)   | 7442.166    | 7384.537    |
| Natural wave GM1        | BASED SHEAR FORCE (K)   | 8310.816    | 7055.920    |
| Natural wave GM2        | BASED SHEAR FORCE (K)   | 7919.374    | 7526.718    |
| Natural wave GM3        | BASED SHEAR FORCE (K)   | 6430.842    | 6756.600    |
| Natural wave GM4        | BASED SHEAR FORCE (K)   | 7354.284    | 6579.820    |
| Natural wave GM5        | BASED SHEAR FORCE (K)   | 7854.850    | 7267.334    |
| Artificial wave AT1     | BASED SHEAR FORCE (K)   | 8471.463    | 8285.832    |
| Artificial wave AT2     | BASED SHEAR FORCE (K)   | 7440.624    | 7692.492    |
| Average value           | BASED SHEAR FORCE (K)   | 8805.22     | 7309.25     |

3.4.3. Elastic analysis of fortification earthquakes. YJK is used to check the seismic elasticity of beams, columns, walls and other components, the results show that the maximum story drift in the X and Y directions are 1/502 and 1/443 is less than 1/400 to meet the requirements. According to the calculation, the reinforcement ratio of the horizontally distributed bars is increased to 1.3% to ensure the strength. And the stress analysis of the frame supported floor achieves the elastic performance goal.

3.4.4. Elastic-plastic analysis of rare earthquakes.

1) Energy dissipation distribution

In the process of Perform3D calculation, taking the GM1 (in the X direction) condition as an example. From figure 3(a), the dissipated inelastic energy accounts for about 25% of the total energy consumption, so the structure is basically in a moderately nonlinear state. From figure 3(b), frame beam and coupling beam account for about 90%, shear wall accounts for about 10% and columns basically do not participate in energy dissipation, so the beam is the main energy dissipation component.

2) Overall calculation

The maximum elastic-plastic story drift of X and Y directions under the rare earthquakes are 1/139 and 1/136, which less than the limit value of 1/120 under the rare earthquakes.
3) Seismic performance of structural components
Taking the GM1 (in the X direction) condition as an example. From figure 4(a), the weak bending part of the shear wall is mainly concentrated on the adjacent floors of the transfer floor. The steel bar is slightly damaged, and the maximum tensile and compressive strain is about 0.002 which is less than 0.01. The maximum compressive strain of concrete is about 0.0005 which does not reach the compressive strength. From figure 4(b), the frame column is basically in elastic state under the rare earthquake. From figure 4(c), most of coupling beams are in the state of moderate damage due to flexural yield, and a small part also has shear plastic hinges. As a result, the performance of structural components can meet the requirements of the rare earthquake.

![Figure 4. Component performance in the GM1 (X direction) condition.](image)

3.5. Performance analysis of components in transfer story
Taking the GM1 (in the X direction) condition as an example, the flexural bearing capacity of the transfer floor component is reviewed. From figure 5(a) and (b), neither the frame beam nor the column has entered the yield performance state which can meet the requirements. From figure 5(c) and (d), most of the frame beams and columns are in the shear elastic state to meet the requirements.

![Figure 5. Analysis of transfer component performance.](image)
3.6. Structural technical measures

According to the out-of-code conditions and the analysis results, the corresponding structural technical measures are taken to ensure the safety and reliability of the structure [11-12], as follows:

- YJK and ETABS are respectively used to carry out the elastic analysis of frequent earthquakes, and the calculated results are basically similar. Therefore, the final design is carried out according to the most unfavorable situation. Besides, the action of earthquake is enlarge to enable the structural reinforcement to envelop time-history analysis results.

- The reinforcement ratio of boundary columns in the ground walls meet the tensile requirements, and the partial walls tend to increase the horizontal distribution reinforcement ratio. Based on the analysis results of the frame supported beam, that is, the upper longitudinal steel bar is all pulled through and the anti-torsion steel bars are strengthened. The frame-supported slab is used as the main force-transmitting component, the thickness of the slab is increased to 180 mm. In addition, the double-layer two-way steel bar is pulled through to ensure that the shear force of the non-ground shear wall can be effectively transmitted to the ground wall.

- In view of the torsion irregularity and the discontinuous design of the slab, the measures for increasing the thickness of the slab and the reinforcement of the ribs are taken for the parts with large floor stress. What is more, the bearing capacity of the frame component is strengthened to improve the torsional stiffness of the structure.

4. Conclusions

In this paper, the performance-based seismic design method is summarized, and the actual project is taken as an example to analyze the performance under frequent earthquake, fortification earthquake and rare earthquake. The following conclusions are drawn: 1) under the frequent earthquake, the respectively use of YJK and ETABS eliminates the one-sidedness and limitation of single software analysis. The correctness of the model is verified by the comparison of the structural dynamic characteristics. The first-story frame columns with large axial compression ratio are expected to increase the limit value of the axial compression ration by setting the composite columns and the seismic reinforcement of the whole building is enlarged to envelope the time-history analysis results. 2) Under the fortification earthquake, the measures are taken according to the analysis results, for example, the horizontal distribution reinforcement ratio of the wall limb is increased to ensure that the shear capacity meets the performance goal. 3) Under the rare earthquake, Perform3D elastic-plastic analysis is used to judge the performance level and increase the hoop ratio of frame-supported columns and transfer beams to verify that the structure can achieve the fortification goal.

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