Structural Design and Analysis of Flat LOFT Apartment with Large Aspect Ratio

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Abstract: This project is the building of LOFT system. Due to the high height and large width of the building, the structural design has been challenged. How to use a reasonable structure system on the premise of ensuring the safety of the structure to make the building and structure perfectly unified is the main goal of this engineering structure design. In this paper, according to the irregularity of the multiple structure, the author determined the corresponding seismic performance targets and analyzed the performance indexes of the structure in small earthquakes, medium earthquakes and rare earthquakes. The whole structure is calculated and analyzed, and the stress of the partial floor is calculated, so as to give the damage degree of each member of the high-rise building, and judge whether it meets the earlier development of the corresponding performance target. For this kind of high-rise building, it is an effective design idea to adopt performance-based seismic design method. According to the importance of components, corresponding seismic design methods and corresponding performance objectives are formulated and verified by appropriate analysis methods.

1. Introduction
This project is the construction of the LOFT system. Its total number of floors is 25, and its total number of floors is 47. The main structure is 145.6m high, in which the first floor is used for commercial purpose and the height is 5.5 meter respectively. The 9th and 17th floors are refuges with a height of 3.6 m. The rest are commercial service rooms with a height of 6.0 meters. Above the main roof is the machine room, and the height is 3.6 m. The plane size is 17.0m*65.9m (as shown in table 1). The standard layer height is 6.0m. The interlayer beams are set in the middle of the standard layer to tie the shear wall, and the interlayer beam height is 3.0m. The structure type is shear wall structure, and the fortification intensity is 7 degrees (0.1g). The earthquake groups designated as the first group, the site category is designated as class II. The fortification category belongs to class C (standard fortification class), the security level is level 2, and the site feature period is Tg=0.35s. Moreover, the average covering layer of the building site is greater than 20m, the soil type is overall medium soft soil, and the construction site type belongs to class II. The building site which is relatively flat belongs to non-karst areas, there are no geological disasters such as landslide, collapse and debris flow. On the whole, the site is in a stable area of geological structure, which is a stable foundation and suitable for the construction of the proposed structure. The specific structural appearance is shown in figure 1.

Table 1. structural parameters of building structure.

| Structural height | plane dimension | aspect ratio | aspect ratio of the tower |
|-------------------|-----------------|--------------|---------------------------|
| 145.2             | 17.0X65.9       | 3.88         | 8.54                      |
2. Elastic analysis of small earthquakes and medium earthquakes

According to the idea of architectural design, the author uses two kinds of software to compare and analyze the structural performance of the tower under small earthquakes. The vibration mode decomposition response spectrum method [1] is used in the analysis, and the elastic time history analysis is used for supplementary calculation. The calculation results by using the mode-superposition response spectrum method are shown in table 2. According to the calculation results in the table, combined with the requirements stipulated in the code and the seismic conceptual design theory of the structure, the following conclusions can be drawn: (1) the calculation results of the two software are similar, which indicates that the calculation results are reasonable and effective, and the calculation model conforms to the actual working status of the structure; (2) the cycle and vibration characteristics of the two directions of the structure are relatively close; (3) the inter-story displacement angle under small earthquakes and wind loads are all less than 1/800; (4) the shear-weight ratio of local floors in the lower part of the structure is less than 1.60%.

According to the code [2], the seismic shear force is amplified, and the rest of the floors meet the requirements of the Code 5.2.5. According to the overall response index of the structure under medium earthquakes, the shear wall and frame support frame of the strengthened area at the bottom are analyzed according to the calculation method of medium earthquakes elasticity. The results show that the base shear force of the structure in the X and Y directions is 2.65, 2.76 times of the base shear force of the medium earthquakes; The displacement Angle between floors X and Y on the whole layer is about 2.84 and 2.81 times of the displacement Angle between small earthquake layers, and the maximum displacement Angle is less than the specified limit. It can be preliminarily determined that the structure meets the requirements of the seismic performance objectives [3] of medium earthquakes.

3. Analysis of elastic-plastic dynamictime history under rare earthquake

3.1. Performance Objective

The tower is an over-limit high-rise structure with a structural height of 145.20 m, which exceeds the maximum limit of A-level height of 25.20 m. It is in the 7-degree intensity zone, and the height and width are relatively large. What’s more, there are many structural irregularities. In order to ensure the safety of the structure under strong earthquake and verify the seismic performance level of the structure [4], the author used the elastic-plastic dynamic time history analysis method to check and evaluate the seismic performance of the structure under "rare earthquake". The acceleration time history data of seismic wave
acceleration are directly applied to the structure in equilibrium state under the action of gravity, and the
elastic-plastic reaction of the structure at each moment is obtained through the method of step by step
integration. Finally, the whole process of the internal force and deformation of the structure member under
the action of earthquake changes with time is obtained.

| Seismic intensity | Small earthquake | Medium earthquake | Rare earthquake |
|-------------------|------------------|-------------------|----------------|
| Standard seismic concept | will not be damaged in the epicenter. | can be repaired in moderate earthquakes. | will not collapse in a major earthquake |
| Macropscopic damage degree | intact | Mild damage | Moderate damage |
| The possibility of continued use | can be used without repair | can continue to use after general repair | can continue to use, after repair or reinforcement |
| Story drift angle limitation | $1/800$ | — | $1/100$ |
| Calculation method | Analysis of elastic response spectrum and elastic time history | Elastic response spectrum | Elastoplastic time history analysis |
| The key components | Shear wall, frame supporting frame, floor slab at weak position and transfer floor in strengthening area at bottom | Small earthquakes remain elastic, bending earthquakes remain elastic, shear earthquakes remain elastic, bending earthquakes do not yield, shear earthquakes do not yield |
| Common vertical member | Non-bottom reinforced shear wall | Small earthquakes remain elastic | Unyielding in moderate bending; Shearing resistance remains elastic | Part of the bending earthquake can yield; Satisfying the control condition of shear section |
| Dissipative member | Coupling beams and frame beams | Small earthquakes remain elastic, some bending earthquakes can yield, shear earthquakes cannot yield, most bending earthquakes can yield, meet the shear section control conditions |
| Others | Other parts of floor slab | Small earthquakes elastic | Bending of the earthquake will not yield, shear of the earthquake will not yield | Part of the resistance to bending can yield; Meet the condition of shear section control |

3.2. Material Model
In this paper, considering the real contribution of structural members to the overall stiffness of the structure, the dynamic hardening model of steel adopts the bilinear dynamic hardening model. In the cyclic process, there is no stiffness degradation, and the Bauschinger Effect is considered. The strength ratio of steel is set to 1.25, and the ultimate plastic strain corresponding to ultimate stress is 0.025. As shown in the figure 2-1. The elastoplastic damage model is adopted in the concrete material model, which can consider the difference of tensile and compressive strength, the degradation of stiffness and the stiffness recovery of tensile and compressive cycles. The standard values of axial compressive strength and axial tensile strength are adopted according to Appendix C of Code for Design of Concrete Structures GB50010-2010[5]. Details are shown in Figures 2-2 and 2-3.

In the elastoplastic analysis model, the fiber bundle model is used in the one-dimensional elastic-plastic model of the rod. The two-dimensional shear wall and the floor elastic-plastic model adopt the elastoplastic shell element. In order to improve the ductility of shear wall under earthquake action, hidden beam or internal diagonal brace are set at the end of shear wall. The hidden beam and the hidden support are simulated by a one-dimensional element, which is a linear interpolation element with two nodes and is coupled to the node of the shear wall element.
3.3. Structural Analysis

In this project, three groups of seismic waves, namely artificial wave 1, natural wave 1 and natural wave 2, are selected for the elastoplastic time history analysis of the structure. A total of six working conditions were analyzed, and a combination of two-way seismic wave time history was used. The author divided the experiment into X direction: $X_1+0.85Y_1$, $X_2+0.85Y_2$, $X_3+0.85Y_3$; Y direction: $0.85X_1+Y_1$, $0.85X_2+Y_2$, $0.85X_3+Y_3$. The three response spectra were compared with the standard response spectra, as shown in figure 3.

Under the action of large earthquakes, the maximum base shear in the X direction is 33202.4kN, which is 4.83 times of the base shear (6871.756kN) obtained from the elastic time-history analysis of small earthquakes; the maximum base shear in the Y direction is 48601.04kN, which is 4.817 times of the base shear (10088.19kN) obtained by the time-history analysis of small earthquake elasticity; the maximum inter-layer displacement Angle in the X direction is $1/156$; the maximum inter-layer displacement Angle in the Y direction is $1/273$, both of which are less than the standard limit.

Under rare earthquake, the maximum displacement in X direction is 0.561m, and the maximum displacement in Y direction is 0.331m; the peak acceleration in X direction is 2.08218 m/s$^2$, and the peak acceleration in Y direction is 2.9537 m/s$^2$; the maximum base shear in the X direction is 33202.4kN, which is 4.83 times of that in the elastic time history analysis of small earthquakes (6 871.756kN); the maximum base shear in the Y direction is 4 8601.04kN, which is 4.817 times of that in the elastic time history analysis of small earthquakes (1 088.19kN). The statistical details of the peak value of structural response time interval under the strong earthquake are shown in the following table.
Table 4. Base shearing force of rare earthquakes and small earthquakes.

|                     | The X direction | The Y direction |
|---------------------|-----------------|-----------------|
|                     | X1+0.85Y1       | X2+0.85Y2       |
| Bottom shear of rare | 32175.1         | 33202.4         |
| earthquakes (kN)     | X3+0.85Y3       | 30088.9         |
|                      | 0.85X1+Y1       | 48601.04        |
| Small shock bottom   | 43530.16        | 43274.08        |
| shear (kN)           |                 |                 |
| Ratio of bottom      | 4.76            | 4.83            |
| shear force          | 4.17            | 4.817           |
|                     | 4.640           | 4.655           |
| Bottom bending       | 3244890.0       | 2695960.0       |
| moment (kN*m)        | 4025570.0       | 3710180.0       |
|                     | 3437020.0       | 3518480.0       |
| The top floor        | 0.561112        | 0.552366        |
| displacement (m)     | 0.468093        | 0.311908        |
| Interlayer drift     | 0.304393        | 0.331163        |
| angle (°)            | 1/165           | 1/156           |
|                      | 1/189           | 1/281           |
|                      | 1/298           | 1/273           |

Figure 4-1. maximum inter-layer displacement Angle.  
Figure 4-2. maximum floor shear.

Figure 5. Structure damage cloud diagram.

In order to verify that the floor can satisfy the requirement of normal use and ultimate state of bearing capacity, and ensure that the floor can transfer horizontal load effectively as well as coordinate the
deformation of the structural members effectively under earthquake, the author makes a detailed finite element analysis of the stress state of the floor[6], and aims at the weak parts of the floor. Therefore, these methods ensure that the floor slab will not appear large cracks and lead to severe stiffness degradation, so as to achieve the seismic performance of the floor. In this paper, the stress analysis of elastic floor slabs is carried out and the shell element is used to simulate the elastic floor slabs. At the same time, considering the out-of-plane and in-plane stiffness of the floor slabs, the author analyzed the floor stress under the combined action of seismic response spectrum, and determined the maximum seismic influence coefficient according to the code.

Through the calculation and analysis, the steel bar unyielding under the large earthquake of the floor slab in the weak part of the stress area is checked. The results meet the requirements of seismic performance targets.

Figure 6. damage cloud map of floor under compression.

3.4. Calculation and analysis conclusions

3.4.1. The general conclusion of rare analysis
1) The maximum peak displacement of the structure is 0.561m in X direction and 0.331m in Y direction under the action of strong earthquake, and it can remain upright eventually, which meets the requirement of "no collapse during strong earthquake".
2) The maximum elastic-plastic inter-story displacement angle of the main structure under seismic wave action is 1/156 in X direction and 1/273 in Y direction, which meets the requirement of 1/100 standard limit.
3) The maximum base shear of elastic-plastic time-history analysis is 3-5 times of that of elastic time-history analysis.

3.4.2. Conclusion of column beam analysis
At the end of earthquake shaking, there is no serious compression damage to the concrete of frame column under the action of earthquake. The maximum compression damage occurs at the bottom layer. The concrete of frame beam has some compression damage, the maximum compression damage factor is 0.37, and a few parts of frame beam yield.

3.4.3. Analysis Conclusion Of Shear Wall And Coupling Beam
Under the action of rare earthquake, the shear wall structure mainly concentrates on connecting beams, not present obvious compressive injury in the limbs of shear-wall. The shear wall at the bottom of the strengthened area reaches the maximum slight damage, which can meet the performance target of bending resistance and not yield. Most of the other shear walls reach below the slight damage and some reach the severe damage, which can meet some performance of bending yield, and there is no obvious shear type compressive damage on the whole wall. The limbs of shear-wall don’t yield. In conclusion, we can draw the following conclusions. Under the action of rare earthquake, the shear wall at the bottom of the strengthened area can satisfy the performance targets of bending and non-yielding under strong earthquakes; the other wall limbs can satisfy the partial performance targets of bending and yield; the shearing section can meet the requirements; the coupling beams can satisfy most performance targets of yielding under strong earthquakes.
4. Conclusion

(1) In view of the Transfinite situation of the project, the stirrup ratio of the coupling beam should be strengthened to make it reach the failure mechanism of Bending Yield and no shear yield according to the relevant specifications, calculation and structural requirements. The oblique cross-bracing and double-coupling beam structure should be set up for the coupling beam with large depth to span to ensure the safety and reliability of the structure.

(2) Small earthquakes elastic time history analysis of the structure is carried out to compare the relationship between the peak value of response and the results of mode decomposition response spectrum analysis and to check whether the results meet the requirements of Seismic Design Code GB 50011-2010 in order to determine the validity of seismic wave time history analysis results.

(3) Through the stress analysis of the floor slab, the reinforcement near the large opening of the floor slab is appropriately increased, and the thickness and additional reinforcement of the floor slab in the weak area are carried out.

(4) The dynamic elastoplastic time history analysis of the structure under the action of large earthquake was carried out to analyze the deformation form of the structure under the action of large earthquake, the plasticity and damage of the components, as well as the tension of the joints, and the vertical reinforcement ratio of shear wall was appropriately strengthened according to the calculation results.

(5) Special analysis is carried out according to the actual requirements of the project.

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