Research on Seismic Performance of Bottom Frame Structure Based on Pushover Method

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Abstract. To study the seismic performance and seismic capacity evaluation method of the bottom frame structure, this paper adopts a five-story bottom frame structure as an example, and uses SAP2000 finite element software to establish an analytical model on Pushover analysis. The results show that Pushover analysis is an effective method to evaluate the seismic performance of the structure. The impact on the bottom frame structure of the high-order vibration modes under the earthquake is negligible, mainly because the first-order vibration mode plays a controlling role, and the lateral force adopts the inverted triangle Load distribution mode loading is feasible, and the bottom frames structure after formal construction and design according to the specifications can meet the requirements of seismic performance.

1. Introduction
Pushover analysis method (also known as static nonlinear or static elastoplastic analysis method) can be used for structural seismic design and structural seismic performance evaluation, it was first proposed by Freeman, and later Krawwinkler[1], Saiidi[2], Fajfar[3] and other scholars have proposed the conversion theory of equivalent single degree of freedom system for multi-degree-of-freedom system, and improved and perfected Pushover method. Lawson[4] and Krawinker[5] conducted dynamic time history analysis and compared their results with the results obtained by Pushover analysis, and found that the two are not much different, proving that the first mode is mainly used and the period is 2s. The result of the Pushover analysis of the structure is correct. The basic principle of the Pushover analysis method is as follows: the lateral force according to a certain distribution mode (such as uniform distribution, inverted triangle distribution, exponential distribution, etc.) is applied to the structural model established by the finite element software to simulate the structure subjected to horizontal seismic forces When the structure stiffness changes, the lateral force is gradually adjusted. This continues until the structure reaches a specified limit state (loss of bearing capacity). Through this process, the load-displacement curves representing the structural capacity and the interlayer are obtained. Displacement angles to assess the seismic performance level of the structure. To perform the Pushover analysis, the structure of the multi-degree-of-freedom system has to be treated as a single degree of freedom structure. The ATC-40 capability spectrum method can be utilized to convert the external force action and structural response[6].
2. Basic principle of pushover analysis method

2.1 Equivalent single degree of freedom system

The general method of establishing an equivalent single degree of freedom system is to perform an equivalent conversion to the dynamic equation of a multi-degree-of-freedom system. The equivalent conversion process is as follows[7]:

The dynamic balance equations listed for the original multi-degree-of-freedom system subjected to earthquakes is:

\[
[M][\ddot{x}]+[C][\dot{x}]+[Q]=-[M][I]\ddot{x}_g
\]

In the formula, \([M]\) is the mass matrix of multi-degree-of-freedom system, \([C]\) is the damping matrix of multi-degree-of-freedom system, \([Q]\) is the resilience vector of structure, \([I]\) is the unit vector, \(\ddot{x}\) and \(\dot{x}\) are the represent the relative acceleration vector and the relative velocity vector of the structure, \(\ddot{x}_g\) is the ground motioned acceleration.

The relative displacement vector of the structure \(\{x\}\) can be transformed from the displacement of the structure vertex \(x_i\) according to formula (2):

\[
\{x\} = \{\Phi\}x_i
\]

Substituting equation (2) into equation (1), the equation can be transformed into:

\[
[M][\Phi]\ddot{x}_i+[C][\Phi]\dot{x}_i+[Q]=-[M][I]\ddot{x}_g
\]

Multiply both ends of equation (3) by \(\{\Phi\}^T\) simultaneous left multiplication, then the equation can be transformed into:

\[
\{\Phi\}^T[M][\Phi]\ddot{x}_i+\{\Phi\}^T[C][\Phi]\dot{x}_i+\{\Phi\}^T[Q]=-[\Phi]^T[M][I]\ddot{x}_g
\]

The corresponding displacement response \(x^*\) of the equivalent single degree of freedom system after the structure is transformed is:

\[
x^* = \frac{\{\Phi\}^T[M][I]}{\{\Phi\}^T[M][\Phi]}x_i
\]

Representing \(x_i\) the equation (4) with \(x^*\) according to equation (5), it can be expressed as:

\[
\{\Phi\}^T[M][I]\ddot{x}_i+\{\Phi\}^T[C][\Phi]\dot{x}_i+\{\Phi\}^T[Q]=-[\Phi]^T[M][I]\ddot{x}_g
\]

\[
M^* = \{\Phi\}^T[M][I]
\]

\[
C^* = \{\Phi\}^T[C][\Phi]\frac{\{\Phi\}^T[M][I]}{\{\Phi\}^T[M][\Phi]}
\]

\[
Q^* = \{\Phi\}^T[Q]
\]

Define the equivalent single degree of freedom system. Substituting equations (7) – (9) into equation (6), the dynamic equilibrium equation of an equivalent single degree of freedom system can be obtained.
\[ M^* \dddot{x} + C^* \dot{x} + Q^* = -M^* \ddot{x}_g \]  

(10)

Where \( M^* \) is the equivalent mass, \( C^* \) is the equivalent damping, \( Q^* \) is the equivalent resilience.

Through Pushover analysis of the multi-degree-of-freedom system, the relationship curve of base shear force and apex displacement at the yield point of the multi-degree-of-freedom system can be achieved. By converting from equations (11) to (13), the equivalent single degree of freedom system can be achieved. The relationship curve between the base shear force and vertex displacement is illustrated in Figure 1.

![Figure 1. Force-displacement diagram of multi-degree-of-freedom system and equivalent single degree of freedom system](image)

2.2 Establish the ability spectrum curve

Through the Pushover analysis of the structural model, the relationship curve between the base shear force and the vertex displacement of the structure can be obtained, which can be converted into the spectral acceleration (\( S_a \)) and spectral displacement (\( S_d \)) of the equivalent single degree of freedom system by formulas (11) to (14) Relationship lines.

\[ S_a = \frac{V}{G} \alpha_1 \]  

(11)

\[ S_d = \frac{\Delta}{\gamma_1 X_1} \]  

(12)

\[ \alpha_1 = \frac{\left[ \sum_{i=1}^{n} (m_i \psi_{i1})^2 \right]}{\sum_{i=1}^{n} m_i \left[ \sum_{i=1}^{n} (m_i \psi_{i1})^2 \right]} \]  

(13)

\[ \gamma_m = \frac{\sum_{i=1}^{n} (m_i \psi_{im})}{\sum_{i=1}^{n} (m_i \psi_{im})^2} \]  

(14)

In the formula, \( V \) is the base shear, \( G \) is the representative value of total equivalent load, \( \alpha_1 \) is the first vibration mode quality participation coefficient, \( \Delta \) is the vertex displacement, \( \gamma_1 \) and \( \gamma_m \) are the respectively the first and m-th vibration mode participation coefficients, \( X_1 \) is the peak amplitude of the first mode, \( m_i \) is the quality of the i-th layer, \( \psi_{im} \) is the amplitude of the m-th vibration mode in the i-th layer, \( n \) is the number of structural layers.
2.3 Establish demand spectrum curves

China's "Code for Seismic Design of Buildings" (GB 50011 2010)[8] through statistical and numerical fitting of a large number of actual seismic records data, we have obtained a response spectrum curve that conforms to the design of the Chinese code, as shown in Figure 2. Through a series of The transformation process will transform it into ATC-40 design response spectrum, as shown in Figure 3.

3. A bottom frame structure example based on Pushover analysis

3.1 Project Overview
This calculation example is a bottom frame structure, the seismic fortification intensity is 7 degrees (0.1g), the site category is category II, and the seismic design is classified in the second group. The cast-in-place beam slabs and columns from the top of the foundation to the first floor are C30. Masonry is made of MU10 red brick. The mortar grade is M7.5. The height of the bottom frame is 4 meters. The height of the upper masonry is 3 meters. The height is 16 meters, and the plan view is illustrated in Figure 4 and Figure 5.

3.2 Results of analyses
According to the calculation results, the structural deformation value at the performance points can be obtained, and then the inter-layer displacement angle of each layer can be obtained, and the performance level can be determined according to the previous division criteria, as shown in Table 1.

| Floor | 7 degrees frequent earthquake | 7 degrees rare earthquake |
|-------|-------------------------------|--------------------------|
|       | Interlayer displacement angle | Performance level | Interlayer displacement angle | Performance level |
| 1     | 1/685                         | Normal use               | 1/238                      | Life safety       |
| 2     | 1/2763                        | Normal use               | 1/1093                     | Moderate damage   |
| 3     | 1/2816                        | Normal use               | 1/1125                     | Moderate damage   |
| 4     | 1/2874                        | Normal use               | 1/1179                     | Moderate damage   |
| 5     | 1/3218                        | Normal use               | 1/1247                     | Moderate damage   |
According to the results in Table 4-8, it can be seen that the interlayer displacement angle of the bottom frame shear layer is 1/685, which is less than the 1/500 interlayer displacement angle limit of the normal use level under the action of 7 degrees of frequent earthquakes. It falls within the "normal use" level. The interlayer displacement angle of the upper masonry layer is lower than 1/2000. It falls within the "normal use" level. It can be seen that the structure is intact or slightly damaged, but the structure is still in the elastic stage; Under the rare earthquake of 7 degrees, the interlayer displacement angle of the bottom frame shear layer is 1/238, which is less than 1/150 of the interlayer displacement angle limit of the life safety level, which belongs to the "life safety" level, the upper layer of the masonry layer The inter-displacement angles are all less than 1/900, which belongs to the "moderate damage" level. At this time, the structure has suffered serious damage, but it will not collapse and endanger life, meeting the performance indicators of life safety. In general, the project example meets the three-level requirements of my country's seismic design: "small earthquakes are not bad. Medium earthquakes are repairable, and large earthquakes are not falling".

4. Conclusion

(1) Pushover analysis is an effective method to evaluate the seismic performance of the structure. The impact of the bottom frame structure on the high-order vibration modes under the earthquake is negligible, mainly because the first-order vibration mode plays a controlling role, and the lateral force is inverted Triangular load distribution mode loading is feasible.

(2) For an example of a four-story brick wall building with a frame shear layer at the bottom and a brick wall at the top, the SAP2000 finite element software was used to establish an analytical model for Pushover analysis to determine the spectral displacement of this example under the action of 7-degree frequent earthquakes and rare earthquakes According to the curve of the spectral acceleration, the intersection point of the capability spectrum and the demand spectrum is obtained as the performance point, and then the interlayer displacement angle at the performance point is obtained. According to the proposed performance level division standard, the seismic performance of the structure is evaluated to determine that the structure meets the seismic code requirements.

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