Research on the Collapse-Resistance Capacity of Typical Prefabricated Frame Structures in Seismic Zone 8

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Abstract. In the milieu of rapid urbanization, prefabricated frame struc-tures, owing to their superior construction efficiency and quality control benefits, have garnered extensive application within the realm of architecture. Nonetheless, in regions prone to frequent seismic activity, the safety per-formance of such structures has ascended to the forefront of engineering and scholarly inquiry. To study the vulnerability and collapse resistance of pre-fabricated frame structures with seismic systems, this paper takes a typical multistory reinforced concrete frame structure as the analytical model in an 8 degrees, 0.2g seismic region. The PKPM software was utilized to design the seismic system model of the prefabricated frame structure. 23 commonly used natural earthquake waves were selected as dynamic inputs, and the IDA analysis method was employed. The ETABS finite element analysis software was used to conduct vulnerability analysis on the prefabricated frame struc-ture's seismic system, while the collapse resistance of the seismic system was evaluated using the CMR method. The research shows that the seismic system of the prefabricated seismic frame structure exceeds a probability of more than 50% under four performance levels, with corresponding PGAs of 0.13g, 0.31g, 0.54g, and 1.01g respectively. The corresponding safety reserve factors under rare earthquakes are 2.53, which are close to the recommended safety reserve factors. Furthermore, the collapse resistance reserve factor under extremely rare earthquakes is 1.8, indicating that the prefabricated frame structure's seismic system has a good resistance to collapse.

Keywords: Prefabricated seismic structure; IDA analysis; Vulnerability analysis; Collapse resistance capacity

1 INTRODUCTION

With the increasing demand for sustainable and low-carbon development in China, prefabricated construction has been increasingly valued for its efficiency and green features. However, the development of prefabricated construction in China started relatively late, and due to its single construction mode and lack of a comprehensive design system, it cannot meet the needs of specific architectural designs, especially in

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earthquake-prone areas of China. Since 2008, China has further raised the seismic performance requirements for buildings, which has restricted the development of prefabricated construction in some regions. It is urgent to find a building structure that can reduce the damage to buildings and personnel caused by earthquakes and enhance the energy-saving and environmental performance of buildings in urban construction.

In recent years, frequent earthquakes and shallow earthquake sources in China have led to the destruction of old buildings and a large number of casualties. The specific quantitative indicators of the three levels of structural design need to be further improved and enhanced. The seismic resilience assessment of precast con-crete structures, which extensively use component connection techniques, still de-pends on cast-in-place design at the component level. Thus, evaluating their capacity to endure real earthquakes is crucial. Experts and scholars have begun to pay atten-tion to the seismic performance of prefabricated concrete structures[1-2]. A large number of seismic performance issues of components have been addressed, but the research on modular structures at the overall structural level is relatively limited.

In assessing the seismic performance of structures, nonlinear dynamic analysis[3], which was once limited by computational costs, is now being increasingly applied to the analysis of prefabricated structures[4-7].

In light of the above-mentioned issues, this article establishes an 8-degree typical prefabricated frame structure seismic system based on standards[8-13]. Using IDA analysis, it discusses the structural capability of withstanding earthquakes and analyzes the seismic vulnerability and anti-collapse capacity of the structure. Finally, it introduces the Collapse Mitigation Ratio (CMR) as a safety reserve coefficient to quantitatively evaluate the anti-collapse capacity of the structure. By employing this structure-level seismic performance assessment method, we can obtain a more comprehensive evaluation of the structural performance, providing an important theoretical basis for the promotion and application of prefabricated buildings in earthquake-prone areas.

2 FINITE ELEMENT SIMULATION

In order to obtain a reasonable model for the prefabricated seismic structure, this study used PKPM software to design the prefabricated structure according to the specifications. The building type was set as Type C, site category as Category II, seismic design group as Group II, with a design earthquake intensity of 8 degrees and a design seismic acceleration of 0.2g. The upper structure was treated with one degree of reduction. Finally, an equivalent prefabricated seismic reinforced concrete frame model was obtained.

The height of the first floor of the structure is 3.9m, while the height of the rest of the floors is 3.6m. The upper structure consists of 6 floors with a height of 21.9m, and the lower supporting pier has a height of 2.2m, resulting in a total structural height of 24.1m. The seismic structure plan and elevation can be seen in Figure 1 and Figure 2. According to the specifications, the load settings for each functional area are as follows: the standard value for the floor dead load is 2kN/m2, the standard value for the room live load is 2.5kN/m2, the standard value for the corridor live load is 3kN/m2, the standard value for the roof dead load is 4.5kN/m2, the live load on the roof is 2kN/m2, and the standard values for the frame-supported shear wall and partition walls are 10kN/m and 9kN/m respectively, while the standard value for the parapet wall is 4.5kN/m.

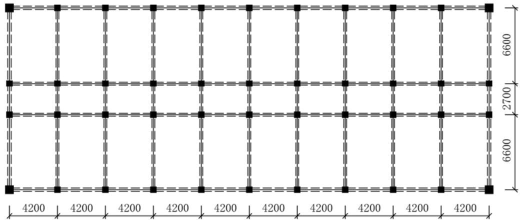

Fig. 1. Floor plan

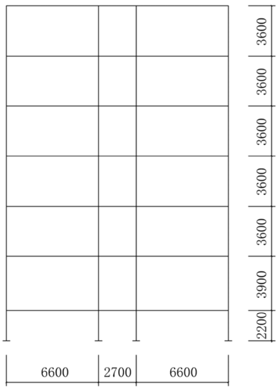

Fig. 2. Elevation layout

After obtaining the model designed by PKPM and applying the loads, this paper uses the ETABS finite element analysis software to assign M3 hinges to structural beams and P-M2-M3 fiber hinges to columns[14], thereby imparting non-linear properties to the beams and columns. This allows for non-linear dynamic time-history analysis of the structure. To ensure the validity of the finite element model, comparisons are made between the total mass and period parameters of this structure, and the model parameters established by PKPM. The difference in mass is 0.6% and the maximum difference in period is 2%, indicating consistency.

3 PERFORMANCE LEVELS CLASSIFICATION

The seismic performance of structural structures is usually described by indicators such as ductility, displacement, energy dissipation, and damage. This paper adopts inter-story drift angle as the performance evaluation indicator for prefabricated structures. According to the latest "Code for Seismic Design of Buildings", for rein-forced concrete frame structures, the limit values of inter-story drift angle under design, rare, and extremely rare earthquake actions are 1/550, 1/100, and 1/50 re-spectively. This paper adopts these limit values and corresponds them to the perfor-mance levels of Operationally Perfect, Immediate Occupancy, Life Safety and Col-lapse Prevention as defined in the code. As for the immediate occupancy perfor-mance level, the code does not provide corresponding design level indicators. Refer-ring to the statistical analysis of a large amount of experimental data from domestic and international scholars [15-16], the drift angle design standard for repairable in-ter-story drift in frame structures is determined as 1/200. Finally, the division and corresponding relationship of the four performance levels are shown in Table 1.

Table 1. Structural performance level

Damage Level	Abbreviation	θ
Safe	SF	θ＜1/550
Operationally Perfect	OP	1/550≤θ≤1/200
Immediate Occupancy	IO	1/200≤θ≤1/100
Life Safety	LS	1/100≤θ≤1/50
Collapse Prevention	CP	θ＞1/50

4 IDA ANALYSIS

Incremental Dynamic Analysis (IDA) is a reliable analytical method capable of meas-uring the earthquake resistance performance of structures. By applying pro-gressively increased seismic forces, IDA obtains the elastic-plastic feedback of structures. This analysis method reveals the relationship between the seismic inten-sity parameter IM and the structural damage parameter DM. The seismic intensity parameter IM and damage parameter DM vividly demonstrate the impact of seismic activity on struc-tures. In this paper, after assigning plastic hinges to structures through ETABS, an elastic-plastic model is obtained, thereby considering the non-linearity of building structures and materials, as well as the destructive charac-teristics of seismic forces on structures. The prefabricated structural model based on the PGA IDA curve is shown in Figure 3.

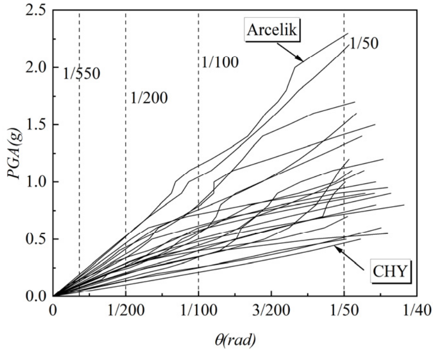

Fig. 3. IDA curve

In this figure, dashed lines represent the limits for the four different limit states: basically intact, immediately habitable, life safety, and near collapse. When the PGA is less than 0.5g, the curve is essentially a straight line, indicating the structure is in the elastic stage. Afterwards, the curve exhibits irregular transitions as the structure shifts from the elastic to the elasto-plastic stage. It is worth noting that despite hav-ing the same acceleration intensity, different seismic wave spectra result in different outcomes for the IDA curve.

5 VULNERABILITY ANALYSIS

The key characteristic of seismic motion is its randomness. By inputting different seismic waves under the same earthquake intensity, the dynamic response of the structure follows a log-normal distribution [17]. Through probability statistical analysis of the exceedance probability of structural performance levels, a smooth fragility curve can be obtained to predict the probability of structural collapse [18]. Based on the probability statistical analysis of the data, a fragility curve for precast assembly structures based on the peak ground acceleration (PGA) can be obtained, as shown in Figure 4.

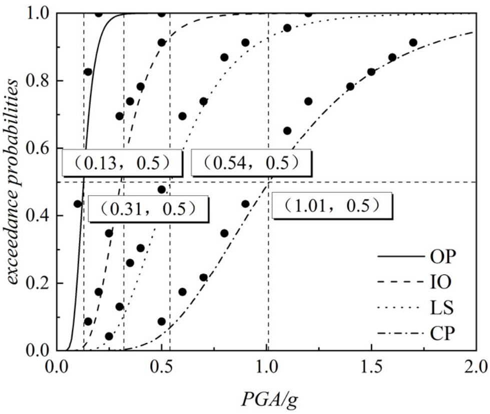

Fig. 4. Fragility curve

From Figure 4, it can be observed that the exceedance probabilities corresponding to the four performance levels are as follows: from OP to CP, they are 0.13g, 0.31g, 0.54g, and 1.01g. Under a rare earthquake with a PGA of 0.4g, the exceedance probabilities from OP to CP are 99.96%, 75.73%, 23.52%, and 1.43% respectively. According to the recommendations in American standard ATC-63, the collapse probability corresponding to a seismic intensity of 0.4g is 10%. However, the collapse probability of this structure is only 1/7 of that, indicating its excellent anti-collapse capability. The strength of building structures designed according to precast assembly specifications can withstand higher seismic intensities, resulting in a lower probability of collapse.

6 CALCULATION OF CMR

The seismic collapse resistance factor is used to assess the ability of a building structure to withstand an earthquake without collapsing. A higher CMR value indicates a stronger seismic resistance of the structure, making it an important indicator for seismic design and evaluation. This paper refers to ASCE7-10[19] which incorporates extremely rare earthquake events into structural seismic design and calculates the collapse safety reserve coefficient for such events, for reference purposes. The formula is as follows:

$$CMR = \frac{PGA_{50\%}}{PGA_{major\ earthquake}} \tag{1}$$

The symbol PGA50% in the equation represents the corresponding seismic intensity at which the structure collapses under 50% of the seismic wave input.

PGA major earthquake refers to the first-period response spectrum value of the structure under a rare earthquake, as recommended by the seismic design code.

The peak ground acceleration under rare earthquakes is defined as 0.4g, and under extremely rare earthquakes, it is defined as 0.6g. The corresponding collapse-resistant safety margin factor for rare earthquakes is calculated to be 2.53, and for extremely rare earthquakes, it is 1.8. Indicating that the typical prefabricated structure established in this paper has good anti-collapse performance under rare earthquakes. Additionally, it also possesses a certain collapse-resistant safety margin capacity under extremely rare earthquakes.

7 CONCLUSION

The typical assembly structural framework seismic system model was established based on the "Code". The model was endowed with elastoplasticity through finite element analysis using ETABS software. Nonlinear dynamic incremental time-history analysis method was adopted to analyze the collapse mode, seismic vulnerability, and collapse resistance of the assembly structural framework. Finally, the reliability was assessed using the collapse resistance safety reserve coefficient, and the following conclusions were drawn:

1) The analysis of the IDA curve showed significant differences in structural response caused by different types of seismic waves under the same PGA conditions, indicating that the use of a certain number of different seismic waves for IDA analysis is of great significance.

2) Through vulnerability analysis, it was found that the probability of collapse for the structure under an extremely rare earthquake with an amplitude of 0.4g was 1.43%, which is only 10% of the acceptable value specified in the American stand-ard ATC-63, indicating that it has excellent collapse resistance.

3) The collapse resistance safety reserve coefficient of the assembly structure under an extremely rare earthquake is 2.53, and under an extremely rare earthquake, it is

1.8, demonstrating its good collapse resistance safety reserve capability in the event of a major earthquake.

4) By adopting IDA-based vulnerability analysis and fully considering the complexity of earthquakes, it provides important guidance for enhancing the seismic performance of prefabricated buildings in seismic design, contributing to the development and optimization of prefabricated building technology, and ensuring the safety of people's lives and properties.

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