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Seismic design of reinforced concrete frame structure based on structural energy analysis

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Abstract: Different from the traditional seismic design method based on bearing capacity and displacement, the energy method can consider the cumulative plastic damage caused by earthquake duration, which is a relatively perfect seismic design method and has attracted wide attention. Based on the principle of energy balance, through the analysis of hysteretic energy consumption and its interlayer distribution, we can find out the weak parts of the structure and make an effective qualitative evaluation of the seismic performance of the structure. By calculating the inter-story damage index of the structure, the seismic performance of the frame structure can be effectively and quantitatively evaluated. Example analysis shows that the energy response distribution of the structure is closely related to the selection of damping model, and the seismic response and damage process of the structure are closely related to the energy absorption and dissipation process of the structure.

1. Introduction

With the accelerating pace of social and economic construction in China, the scale of urban construction has been further expanded, and the number of various large-scale construction projects is increasing day by day, which requires higher and higher quality of buildings. As a new building form, reinforced concrete frame structure has many advantages, such as good integrity, fast construction speed, flexible layout and light retaining wall, and is widely used in modern large-scale building projects [1].

In order to ensure the safety of structures under strong earthquakes, it is necessary to analyze the seismic performance of structures, especially for some complex structures, whose stress state and dynamic response under strong earthquakes are more complex than those of conventional structures, and more attention should be paid to their behavior under strong earthquakes [2-3]. Aiming at this problem, this paper makes a more in-depth study. In addition, the energy distribution law of each part of the structure during the earthquake is of great significance to the design method based on the concept of energy. This paper will study the energy distribution law of the structure during the earthquake and its influencing factors by analyzing the energy of an actual reinforced concrete frame structure.

2. Importance of seismic design of reinforced concrete frame structure

Earthquake can be said to be the main cause of building collapse, and the damage degree of buildings in earthquake can directly reflect the intensity of earthquake. Therefore, in engineering design, especially for building projects in earthquake zone areas, we should pay more attention to the earthquake resistance of reinforced concrete frame structures.

First of all, strengthen the seismic design of reinforced concrete frame structure, effectively improve the seismic performance of the structure, and ensure the stability and safety of the internal structure. In the event of an earthquake disaster, its internal force can support the weight of the whole building, thus providing more sufficient escape time and space for people and ensuring the safety of people's lives and property.

Secondly, strengthening the anti-seismic design of reinforced concrete frame structures can also reasonably lay out the internal facilities of construction projects, which can provide people with more reasonable and rapid escape routes when an earthquake occurs, reduce the losses caused by the earthquake in all aspects and ensure the minimum impact of secondary damage caused by the earthquake.

Finally, because the earthquake is extremely uncontrollable, strengthening the seismic design of reinforced concrete frame structures can also effectively monitor the earthquake disaster, thus achieving the role of earthquake prevention and minimizing casualties and property losses. It can be seen that the seismic design of reinforced concrete frame structure is extremely important for improving the construction quality of building engineering [4].

3. Seismic design of reinforced concrete frame structure

3.1 Structural energy response calculation

Most of the actual engineering structures are multi-degree-of-freedom systems with complex spatial relationships. Considering the various load distributions and the extremely complex nonlinear characteristics of reinforced concrete materials, it is quite difficult to accurately analyze the actual multi-degree-of-freedom spatial system [5]. Therefore, an important premise before the seismic response analysis of the structure is to obtain a structural calculation model which is convenient for theoretical analysis and does not lose the actual accuracy requirement.

The essence of energy analysis for building structures is to study the energy transfer and dissipation relationship between the structure itself and the ground under earthquake. When the energy dissipation capacity of the structure itself is greater than the total input value of the structure under earthquake, the structure can be considered safe.

The motion equation of multi-degree-of-freedom system under earthquake is:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[k]\{x(t)\}=-[M]\{\ddot{x}_g(t)\} \tag{1}$$

In the formula: $\{x(t)\},\{\dot{x}(t)\},\{\ddot{x}(t)\}$ ——For the displacement vector, velocity vector and acceleration column vector of the ground;

$\{\ddot{x}_g(t)\}$——Ground acceleration column vector;

$[M],[C],[k]$——They are the mass matrix, damping matrix and stiffness matrix of the structure. Usually, numerical integration method is used to solve the structural vibration differential equation.

In the process of concrete design, it is necessary to pay full attention to the problem of lithology protection in reinforced concrete frame structure houses, effectively limit the axial compression ratio in design and calculation, and effectively control the maximum matching ratio of longitudinal reinforcement, so as to effectively ensure the improvement of ductility of building components, reasonably adjust the compressive height of concrete, strictly control the building materials of reinforced concrete buildings, effectively improve the level of seismic design and ensure the optimization of seismic performance of reinforced concrete structure buildings.

3.2 Guarantee ductility

In terms of structural layout, the design according to the enlarged bending bearing capacity of the column end can theoretically reduce the possibility of column yielding and ensure the design principle of "strong column and weak beam". However, due to various reasons, such as the actual bending bearing capacity of the beam may increase, the high vibration mode will shift the bending point in the column and other comprehensive factors, it is difficult to completely avoid plastic hinges in the column. At the same time, in order to meet the requirements of "strong shear and weak bending" and ensure the local ductility of the plastic hinge area, certain structural measures must be taken to ensure the ductility of the structure.

Damping is a term used to describe a certain energy dissipation mode of a structure in the process of vibration. It is the dynamic characteristic of the structure and one of the important factors affecting the dynamic response of the structure. Although damping is an objective existence, its mechanism is quite complicated, so in engineering practice, damping is usually abstracted as a convenient mathematical model [6].

Rayleigh damping model is most commonly used in structural seismic response analysis. Rayleigh damping assumes that damping matrix is proportional to stiffness matrix and/or mass matrix, namely:

$$[C]=a[M]+b[K] \tag{2}$$

Where a,b is a constant. According to the orthogonal formation condition, the relationship between the undetermined constant a,b and the vibration damping ratio should be satisfied:

$$\xi_k=\frac{a}{2\omega_k}+\frac{b\omega_k}{2}(k=1,2,\cdots,n) \tag{3}$$

Specify the damping ratios ξ_i and ξ_j of any two modes, and then, the proportional constant can be determined according to the following formula:

$$a=2\left(\frac{\xi_i}{\omega_i}-\frac{\xi_i}{\omega_j}\right)/\left(\frac{1}{\omega_i^2}-\frac{1}{\omega_j^2}\right) \tag{4}$$

$$b=2(\xi_i\omega_j-\xi_j\omega_i)/(\omega_j^2-\omega_i^2) \tag{5}$$

The damping ratio of other modes is obtained by formula (2). When Rayleigh damping is applied to elasto-plastic time history analysis, the Rayleigh damping matrix can have many different forms because the system stiffness matrix $[K]$ changes with time [7], and its general expression is:

$$[C]=a[M]+b[K_t]+b_0[K_0] \tag{6}$$

Where $[K_t]$ is the instantaneous stiffness matrix of the structure; $[K_0]$ is the initial stiffness matrix of the structure; a,b,b_0 is the proportional coefficient, and b,b_0 does not appear in the equation at the same time.

Reasonable stress process can obviously improve the ductility of members. In order to realize the failure mode that the tensile steel bars yield first and the concrete in the compression area is crushed, and to improve the rotation ability of the plastic hinge area, the specification limits the axial compression ratio and the maximum reinforcement ratio of longitudinal bars, and at the same time puts forward corresponding requirements for the height of the concrete compression area.

In order to ensure the design principles of "strong joint", "strong column and weak beam", "strong bottom column bottom" and "strong shear and weak bending" and the local ductility of the plastic hinge area, it is necessary to encrypt the stirrup spacing in the plastic hinge area, which can not only improve the shear capacity of the column end, but also restrain the concrete in the core area, provide lateral support for the longitudinal reinforcement, and prevent the longitudinal reinforcement from buckling under large deformation, thus improving the local ductility of the plastic hinge area.

3.3 Seismic design of stairs

In stair structure, the most important form is slab, with stair slab, platform slab and platform beam as its main components. The ladder board has less stress bars and poor bearing capacity. When the earthquake occurred, due to the insufficient number of steel bars, the cracks gradually expanded and stretched continuously, and finally the stepped slab broke. The platform beam and the platform plate bear complicated pressure because they are connected to the ladder plate. The joint between the platform and the frame is subjected to a large internal force, which will be seriously damaged when an earthquake occurs.

The strength criterion is enough to solve the internal force of the structure by using the calculation method of structural seismic action stipulated in the code, and then design the bearing capacity of the structural members. When the designed structural resistance is greater than the actual load, the structure can be considered safe, otherwise the structure is unsafe. The criterion can be expressed as:

$$\sigma < [\sigma] \tag{7}$$

Where: $\sigma, [\sigma]$ is the strength of the component and the allowable strength specified in the specification respectively.

For the structure of stairs, it is not suitable to build stairs at the top corner of the house. Masonry structures need reliable components to support and connect stairwells. For the design of stair board, it is necessary to appropriately increase its thickness and pull through the negative reinforcement. Two-way and double-sided reinforcement should be realized for ladder boards and broken platforms of stairs. At the corner of the stair board, strengthen local structural measures. In order to avoid brittle failure of short column frame, diagonal reinforcement can be placed in the column body [8].

The failure criterion is to take the structural deformation as an index to measure the structural failure. It is considered that when the structural deformation under earthquake exceeds the specified limit, the structural failure will occur. The criterion can be expressed as:

Maximum elastic-plastic displacement means:

$$X_m < [X_m] \tag{8}$$

Or the maximum ductility coefficient indicates:

$$\mu_m < [\mu_m] \tag{9}$$

When the hysteretic energy dissipation of the structure reaches the limit of the energy dissipation capacity of the structure, the structure will be destroyed. One of the advantages of energy criterion is that the influence of earthquake duration can be considered. The energy failure criterion can be expressed as:

$$E_h < [E_h] \tag{10}$$

Where: $E_h, [E_h]$ is the hysteretic energy dissipation and energy dissipation capacity of the structure respectively.

In the seismic design of stairs in multi-story reinforced concrete frame structure, in order to reduce the damage of stairs in earthquake, the stair structure can be separated from the main structure, so that the pressure on the stair structure can be separated from the overall stress. This stair form not only reduces the bending moment and shear force of the ladder column, but also greatly reduces the damage degree of the ladder column, thus realizing the relative safety of the stairs.

4. Numerical example analysis

The equivalent single-degree-of-freedom system of the original structure is solved by mode decomposition method. Selecting E1-Cengo seismic wave as the ground motion input, the comparative results of hysteretic energy consumption time-history curves of equivalent single-degree-of-freedom system and original multi-degree-of-freedom system are shown in Figures 1 to 3.

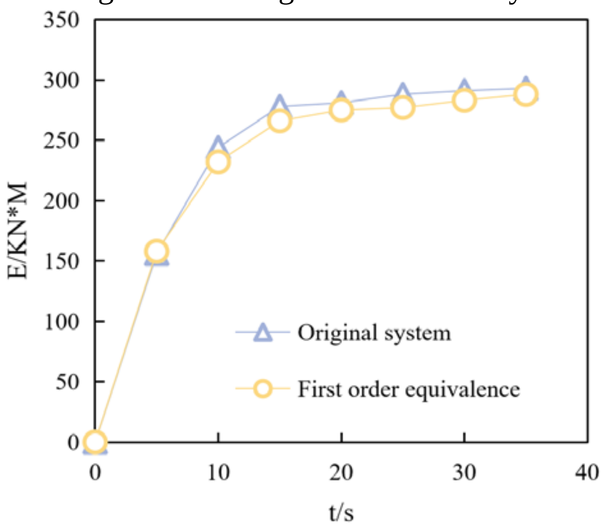

Figure 1: Comparison of first-order equivalent results

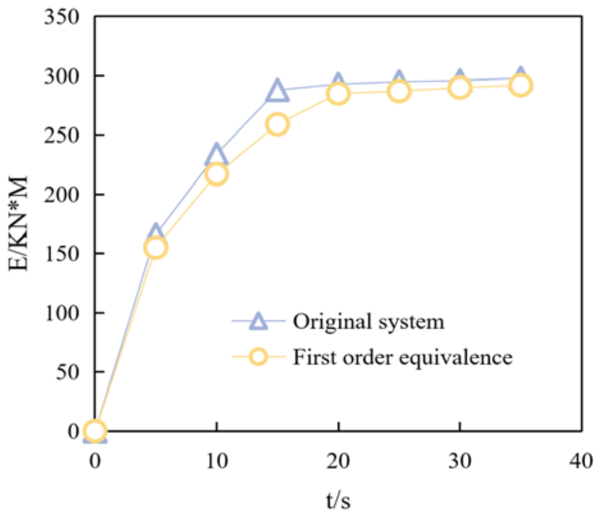

Figure 2: Comparison of second-order equivalent results

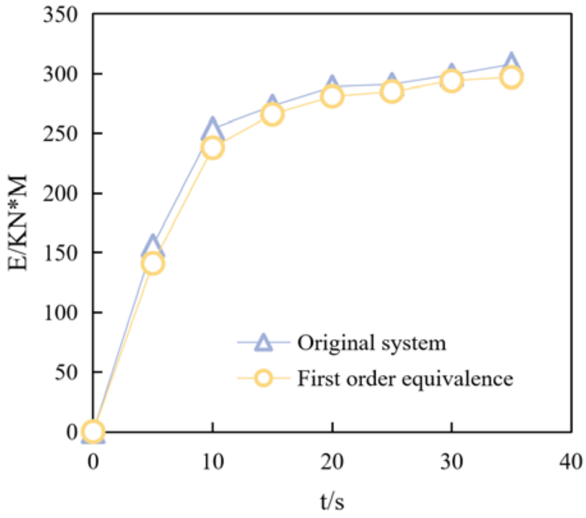

Figure 3: Comparison of third-order equivalent results

From Figure 1 to Figure 3, it can be seen that it is feasible to solve the hysteretic energy consumption of the original structure by using the mode decomposition method through the equivalent single free system. The variation law of the hysteretic energy dissipation curve of the equivalent single-degree-of-freedom system tends to be consistent with that of the original system. At the same time, it can be seen that there is little difference between the equivalent calculation results of the hysteretic energy dissipation of the structure and that of the original structure.

Before the earthquake, the hysteretic energy consumption of the structure increases continuously, and the hysteretic energy consumption tends to a constant value near the end of the earthquake. Compared with the first two-order errors, the first three-order calculation errors of the structure have little change. It can be concluded that the first-order equivalent result can be used when the number of structural layers is small. For a large number of stories, better accuracy can be obtained by using the combined value of the results of the first two steps, so as to simplify the calculation of structural energy response and provide convenient conditions for structural energy analysis and evaluation.

5. Summary

To sum up, seismic design of reinforced concrete frame structures can reduce the harm caused by earthquakes. In seismic design, designers should pay special attention to the reasonable setting of their own load capacity, and at the same time, they should accurately grasp the details of the construction, so as to ensure the quality and reliability of the building. Combining the results of the first two orders of the energy response of the equivalent single degree-of-freedom system of the structure can obtain a simplified calculation result of the energy response of the structure with higher accuracy. If there are more layers of the structure, the influence of higher-order vibration modes can also be considered, thus providing a simple and fast energy response calculation for the seismic performance evaluation of the structure. The seismic design method based on direct displacement has clear design concept and high feasibility, which can directly reflect the performance of reinforced concrete frame structure before earthquake action and effectively guarantee the safety of buildings.

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