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Research paper

Resilience-based seismic design method for reinforced concrete structures

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Abstract: As high-rise buildings gradually increase, their seismic performance has become a focus in the engineering field. To improve the functional recovery ability and economy of buildings after earthquakes, a resilience-based seismic design method for reinforced concrete structures is proposed. An indicator system that can reflect the functional loss of buildings after earthquakes is developed. A seismic design strategy based on functional recovery indicators is proposed to improve the seismic performance and economy, while shortening the recovery time after earthquakes. The research results indicated that the average inter story displacement of the standard seismic method for reinforced concrete structures was 168 mm. The inter story displacement of the seismic resistance method for reinforced concrete structures based on resilience objectives was 192 mm. The repair time for standard seismic method of reinforced concrete structures was 33 days. The repair time for the seismic resistance method of reinforced concrete structures based on resilience was 24 days. The resilience-based seismic design method is superior to traditional methods in controlling structural damage, reducing repair cost, and shortening repair time. The designed method proposed in the study not only enhances the seismic resilience of the structure, but also has significant economic and social benefits, providing a new perspective and practical tools for the seismic design of high-rise buildings.

Keywords: earthquake resistance, functional recovery indicators, reinforced concrete, repair cost, resilience

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1. Introduction

Reinforced concrete structures have become a common form of building structure due to their excellent load-bearing capacity and ductility. However, traditional seismic design methods may not fully consider the resilience performance of structures under extreme seismic actions. Resilience refers to the ability of a structure to withstand, adapt to, and quickly recover from damage in the event of extreme events such as earthquakes. With the deepening understanding of earthquake disasters, resilience-based seismic design methods have gradually become a new trend in seismic design. Seismic resilience is defined as the ability of a building structure to maintain or restore its function under the influence of earthquakes, which is crucial for improving the overall performance of engineering structures [1, 2]]. In order to enhance this ability, numerous researchers have conducted extensive research work, and the seismic design of reinforced concrete structures has attracted widespread attention [3, 4].

Leyva et al. conducted a comparative study on seismic optimization design between traditional reinforced concrete buildings and three-dimensional structures equipped with anti buckling braces using multi-objective non dominated sorting genetic algorithm. Compared with traditional buildings that relied solely on anti-bending moment frames, buildings with added anti-buckling supports exhibited higher economic benefits while maintaining the same structural performance [5]. In the field of structural design, performance-based design methods have not yet become widespread. Padalu and Surana conducted an in-depth analysis about the differences between traditional specifications and performance-based design approaches. The application value and implementation strategies of performance-based design in seismic design were discussed. The research showed that performance-based design allowed designers to conduct seismic design based on established performance goals [6]. Sattar et al. conducted a detailed analysis of multiple standards and guidelines for seismic design to reveal differences in performance regulations in different documents. This study helped relevant committees recognize the differences in existing documents, explore the root causes of their differences, and seek consensus in future revisions [7]. Zakian and Kaveh comprehensively analyzed structural seismic design optimization, including commonly used solving strategies, optimization problem types, and objectives. Among numerous structural loads, seismic loads had a particularly significant impact on structural design [8]. The results indicated that using non prismatic beams not only met the structural height requirements, but also optimized economic cost and environmental impacts [9]. Hidayat et al. established finite element models of non ductile concrete columns, beam column nodes, and three story buildings to address design deficiencies of existing reinforcement standards. The research results confirmed that finite element analysis could accurately predict the performance and failure mode of reinforced concrete structures under earthquake action [10].

In summary, although existing seismic design codes have played an important role in improving structural safety, they often overlook the rapid recovery ability of building functions after earthquakes. The lack of this ability may lead to huge economic losses and social impacts. Therefore, the study proposes a resilience-based seismic design method to optimize the seismic performance and economy through optimized design, while shortening the recovery time after earthquakes, in order to provide practical tools for seismic design of building structures. The innovation and contribution of the research lies in the reverse operation method, which deduces the corresponding engineering requirement parameters through the target repair cost, providing a new perspective for seismic performance evaluation. Simplifying the structure into a single degree of freedom system model, the study can calculate key parameters such as equivalent displacement, equivalent mass, and equivalent damping ratio of the structure, providing a more accurate and simplified method for seismic design.

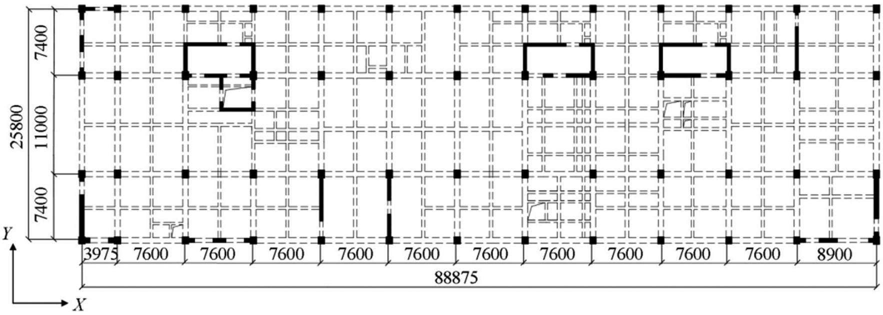
2. Methods and materials

The study first identifies crucial evaluation criteria in elastic seismic design strategies. That is, an indicator system is developed that can be applied in the design phase and reflect the functional loss of buildings after earthquakes. Subsequently, a seismic design strategy is proposed to achieve resilience demand. Finally, a design method for reinforced concrete structures with functional recovery as the core is proposed.

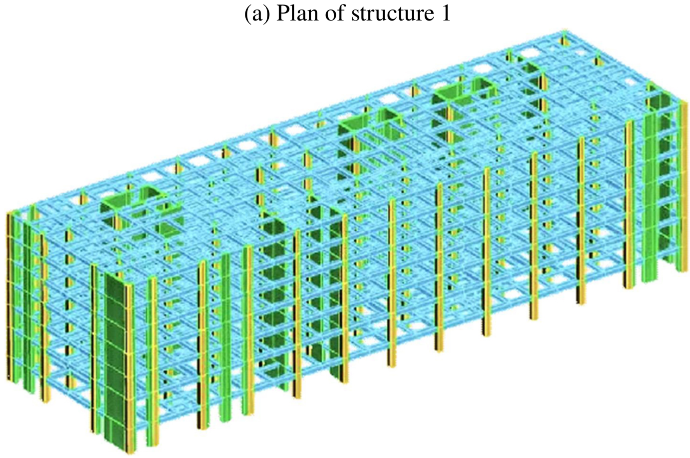
2.1. Overview of reinforced concrete structural engineering

To visually analyze the seismic performance of reinforced concrete structures, YJK software is applied to accurately build a 3D finite element model of the reinforced concrete structure based on detailed construction drawings. The site category is divided into the third category, which involves evaluating soil characteristics and geological conditions that may affect structural response. Structure 1 is a 7-floor building with a natural cycle of 0.609 s and a total height of 27.7 m. Its floor height design is uneven, with the first floor being 4.1 meters, the second floor being 4.85 m, and each floor from the third to seventh floors being 3.75 m. The structure has a length and width of 88.9 m and 25.8 m, respectively, exhibiting a relatively flat shape with an aspect ratio of 1.07, which helps to provide better stability. The total construction area of Structure 1 is 15925 m^2, suitable for medium scale commercial or residential use. The detailed plan and 3D view of Structure 1 are shown in Fig. 1.

Figure 1 provides an intuitive reference for engineers and designers to better understand and analyze the geometric characteristics and spatial layout of the structure. Through these models, a series of structural analyses can be conducted to ensure that the structure can safely resist the expected seismic effects.



(a) Plan of structure 1



(b) Three-dimensional diagram of structure 1

Fig. 1. Detailed floor plan and 3D view of structure 1: (a) Plan of structure 1, (b) Three-dimensional diagram of structure 1

2.2. Selection of functional recovery indicators in structural resilience design

A comprehensive evaluation is conducted on the relevant literature on direct economic losses of structures. It is extracted as the loss ratio, which refers to the ratio between repair cost and reconstruction cost. Furthermore, based on the repairable characteristics of elastic structures after earthquakes, a suitable elastic function recovery index for the design phase is proposed. Considering that the loss ratio only reflects the functional loss of the structure during earthquakes and does not fully cover its post earthquake recovery ability, it is necessary to make appropriate adjustments to form functional recovery indicators. In order to simplify the seismic design process, the relationship between the structural loss ratio and the engineering requirement parameters should be clarified. The damage to buildings and their components can be quantified by engineering parameters such as inter floor displacement angle and floor acceleration [11, 12]. The displacement angle limits between floors of brick filled walls and frame structures are shown in Table 1.

Table 1. Limits of displacement angle between floors

Brick filled walls				Frame structure		
Failure state		Inter floor displacement angle		Structural damage state		Limit of inter floor displacement angle
		Median value	Standard deviation			
DS0	Basically sound	–	–	DS0	Basically sound	0.0040
DS1	Minor damage	0.0005	0.1100	DS1	Minor damage	0.0050
DS2	Moderate failure	0.0013	0.2900	DS2	Moderate failure	0.0090
DS3	Serious damage	0.0040	0.5500	DS3	Serious damage	0.012
DS4	Destroy	0.0127	0.2900	DS4	Destroy	0.0160

In seismic performance evaluation, the repair cost of each component can be determined by analyzing the structural performance. The cost of structural pair can be simplified as a single variable function that only includes the displacement angle between floors, thereby establishing a direct relationship between functional recovery indicators and the displacement angle between floors. The study determines the repair cost of components based on the method in the "Evaluation Standards for Seismic Resilience of Buildings;;. This method uses vulnerability curves to express the probability of different loss states that components may suffer under different engineering requirement parameters [13–15]. Combining the loss coefficient, repair coefficient, and reduction coefficient of components under different damage states, the repair cost of components can be calculated. When carrying out structural design, the required unit repair cost function of components can be selected. Combining parameters such as the number of components and reduction factors, the repair cost and functional recovery indicators corresponding to displacement angles between different floors can be determined, so as to integrate information on structural components [16, 17]. The indicators of repair cost and functional restoration are directly related to the displacement angle of each floor. The larger the displacement angle between floors, the more severe the structure deformation, which may exacerbate structural damage and increase repair cost. In seismic design, controlling the displacement angle between floors can effectively manage the repair cost and ensure that the structure can quickly recover its function after an earthquake. After synthesizing the information of structural components, the inter floor displacement angles that match the predetermined functional recovery goals can be selected to assist in subsequent design work. The relevant process is shown in Fig. 2.

In Fig. 2, after determining the basic structure information, the unit repair cost function of acceleration sensitive non structural components is selected from the functional recovery index library. The floor response amplification coefficient is used to determine the acceleration of each floor, and then the unit repair cost of acceleration sensitive components on each floor is calculated. Finally, the unit repair cost of various components is multiplied by the corresponding number of floors and reduction factors, and summed up to integrate structural component information.

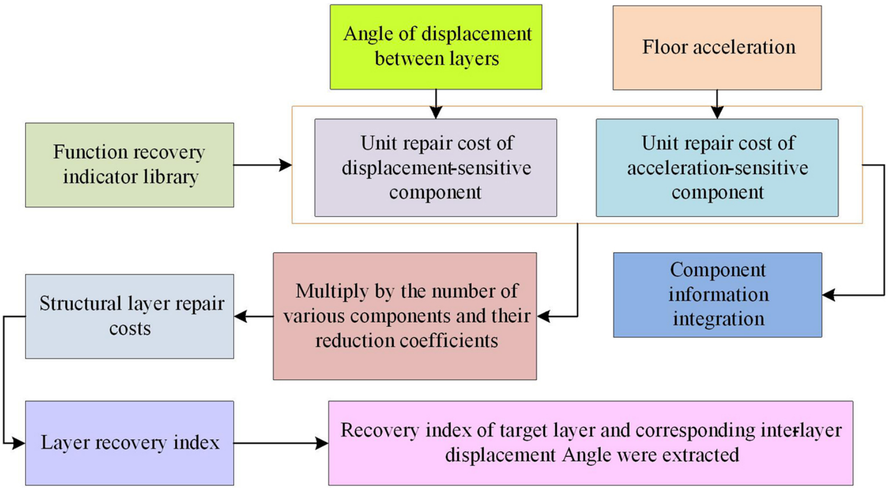


Fig. 2. Flow for calculating function recovery counters

2.3. Resilience-based seismic design method for reinforced concrete structures

Based on the functional recovery indicators constructed through research, the expected elastic level of the structure is directly set as the standard for its seismic protection. Next, it is necessary to calculate the relative displacement angle between each floor by analyzing the lateral displacement curve, as displayed in Fig. 3.

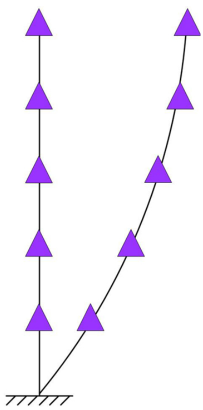


Fig. 3. Structural lateral movement curve

In Fig. 3, based on the specific properties of the structure, a bending or shear type lateral displacement curve is preset to achieve the predetermined displacement angle of the weak layer, while ensuring that the displacement angle of other floors does not exceed the value of the weak layer. After determining the target inter floor displacement angle of each floor slab and drawing the corresponding lateral displacement curve, the entire structure can be simplified into a single degree of freedom system model. In this model, key parameters such as equivalent displacement, equivalent mass, and equivalent damping ratio can be computed [18, 19]. The equivalent damping ratio of reinforced concrete structures is shown in equation (2.1).

$$\xi_{\text{eff}} = 0.05 + 0.2\left(1 - \frac{1}{\sqrt{\mu}}\right) \tag{2.1}$$

In equation (2.1), ξ_{eff} represents the equivalent damping ratio of reinforced concrete structures. μ represents the ductility coefficient. The ductility coefficient is shown in equation (2.2).

$$\mu = \frac{\Delta u}{\Delta y} \tag{2.2}$$

In equation (2.2), Δu represents the maximum displacement. Δy represents the yield displacement. In order to ensure that buildings can be repaired under the influence of earthquakes, it is important to control their residual displacement at a lower level. After determining the vibration period, post yield stiffness, and site conditions, the residual displacement angle of a single degree of freedom system can be calculated. The fitting method is shown in equation (2.3).

$$\begin{cases} \theta_r = \theta_{r0} e^{-b/0.11} \\ \theta_{r0} = \begin{cases} \beta_1 T & 0 \le T < 2 \\ 2\beta_1 + \beta_2 (T - 2b) & 2 \le T < 6 \end{cases} \end{cases} \tag{2.3}$$

In equation 2.3, θ_r represents the residual displacement angle. β_1 and β_2 represent the parameter values obtained after data fitting. b represents the post yield stiffness ratio of the structure. When conducting resilient seismic design, the displacement response spectrum is first constructed. It can be transformed into a displacement response spectrum through a conversion method. The specific calculation process is shown in equation (2.4).

$$S_d = \left(\frac{T}{2\pi}\right)^2 S_a \tag{2.4}$$

In equation (2.4), S_d represents the displacement response spectrum. S_a represents the acceleration response spectrum. Secondly, the expected displacement of a single degree of freedom system is determined. After determining the target inter floor displacement angle for each floor of the building, the target displacement for each floor can be calculated. The equivalent expected displacement of the entire structure is shown in equation (2.5).

$$u_{\text{eff}} = \frac{\sum_{i=1}^{n} m_i u_i^2}{\sum_{i=1}^{n} m_i u_i} \tag{2.5}$$

In equation (2.5), u_{eff} represents the equivalent expected displacement. Next, the equivalent mass of the single degree of freedom system is determined. The equivalent mass usually involves the system dynamic characteristics, such as natural frequency, damping ratio, and mass distribution. The equivalent mass of the main vibration modes is determined through modal analysis. The equivalent mass is shown in equation (2.6).

$$m_{\text{eff}} = \frac{\sum_{i=1}^{n} m_i u_i}{u_{\text{eff}}} = \frac{\left(\sum_{i=1}^{n} m_i u_i\right)^2}{\sum_{i=1}^{n} m_i u_i^2} \tag{2.6}$$

In equation (2.6), m_{eff} represents the equivalent mass of a single degree of freedom system. When designing the bearing capacity of a structure, it is necessary to analyze the combination of internal forces under seismic and non seismic actions separately. By evaluating the most unfavorable situations in these two situations, the internal force design value of the key section of the structure can be determined. Subsequently, based on these design values, cross-sectional design work is carried out to determine the required reinforcement configuration for each component. The specific process of resilience-based seismic design method for reinforced concrete structures is shown in Fig. 4.

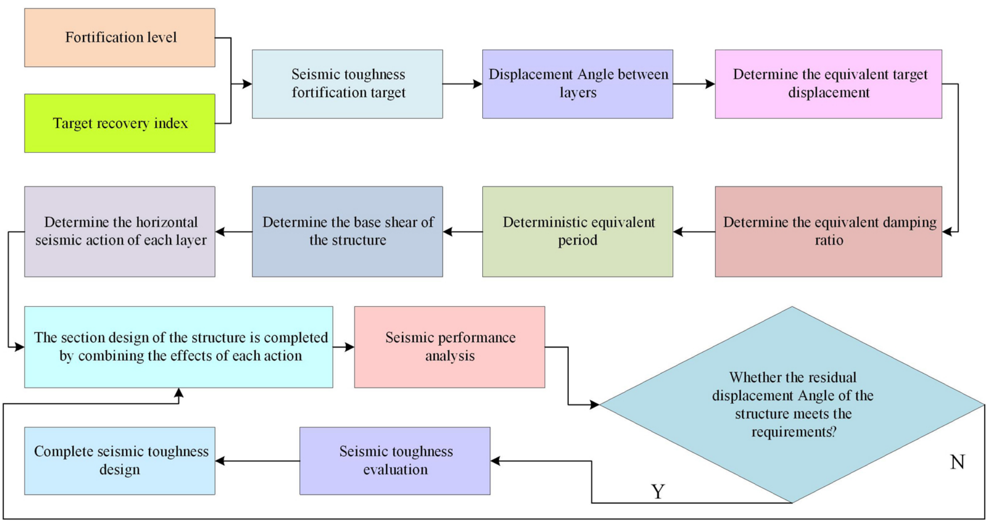


Fig. 4. Method flow of seismic design of reinforced concrete structures

In Fig. 4, if the measured acceleration exceeds the theoretical threshold, corresponding seismic reinforcement measures need to be taken based on the acceleration sensitivity of non structural components. For example, for equipment components installed on elevated floors, a cushion layer can be added or fixed to the wall through angle steel. For hanging non structural components such as chandeliers, additional vertical suspension support can be added. Meanwhile, based on the analysis results, the residual displacement angle of the structure can be calculated and evaluated whether it is within the allowable range. If the residual displacement angle of the layer is too large, the seismic measures mentioned earlier can be taken to ensure that the residual displacement angle is controlled within the specified limit value. If the floor acceleration and residual displacement angle are both within the specified limits, the next step of resilience evaluation can be continued. When evaluating the resilience of a structure, it is necessary to calculate the repair cost, repair time, and possible personnel casualties of the structure under specific seismic actions. Then, based on the repair cost, the functional recovery indicators of the structure can be calculated. If the evaluation results meet the expected resilience recovery, the design phase can be concluded. If it is not achieved, it is necessary to strengthen the floors that do not meet the resilience recovery and iterate the design until the requirements are met.

3. Results

The study first compares the seismic performance of reinforced concrete structures on the basis of the resilience objective and standard reinforced concrete structure seismic methods. Finally, the repair cost, repair time, and functional recovery indicators are evaluated to verify the effectiveness of the resilience-based seismic design method.

3.1. Seismic performance evaluation and analysis

On the basis of the resilience design method and standard method proposed in the study, corresponding structural models are created using SAP2000 software. The performance of the components is simulated using a degenerate trilinear model, and five seismic waves are selected for elastic-plastic dynamic response analysis. Based on the response spectrum in the Design Standards for Seismic Isolation of Buildings, five seismic records are selected from the PEER NGA-West2 seismic wave database, labeled as A, B, C, D, and E. These seismic records are adjusted to the magnitude 8 rare earthquake for nonlinear dynamic analysis of the structure. The inter floor displacement between the standard seismic design method and the resilience-based seismic design method is shown in Fig. 5.

In Fig. 5(a), the average inter floor displacement of the standard reinforced concrete structure seismic method was 168 mm. In Fig. 5(b), the inter floor displacement of the resilience-based seismic design method was 192 mm. The standard method was about 13% lower than the method used in this study. For the first floor of the upper structure, both methods showed that the inter floor displacement was greater than the other floors. This reflects that the proposed method is more reasonable in design, effectively utilizing the function of isolation layers, achieving smaller inter floor displacement of the upper structure, and demonstrating better performance. The inter floor displacement response between the standard seismic method and the designed method is shown in Fig. 6.

In Fig. 6(a), under frequent earthquakes, the average inter floor displacement of the standard seismic method was 10 mm, and the average inter floor displacement angle of the designed method was 30 mm. In Fig. 6(b), under seismic fortification, the average inter floor displacement

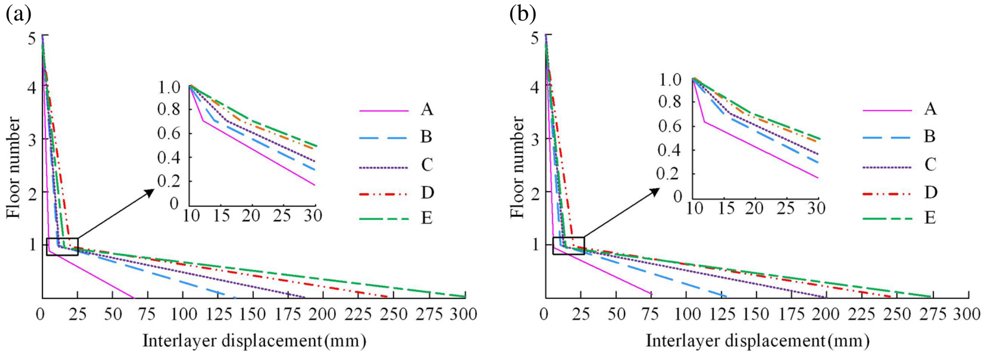


Fig. 5. Inter-floor displacement comparison: (a) Standard seismic method for reinforced concrete structures, (b) Seismic method of reinforced concrete structure based on toughness

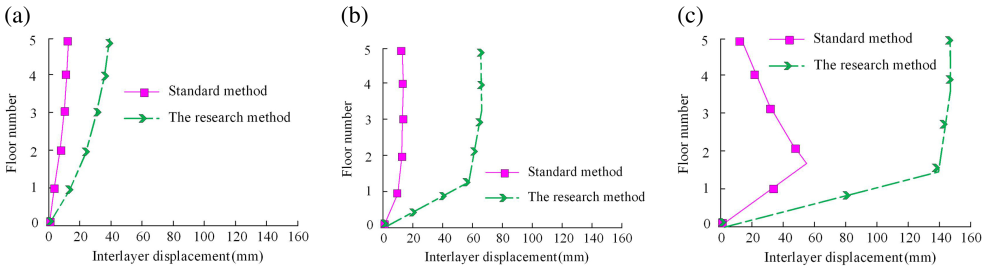


Fig. 6. Comparison of displacement response between layers: (a) Frequent earthquake, (b) Fortify against earthquake, (c) Rare earthquake

of the designed method was 70 mm, while the standard seismic resistant method was 18 mm. In Fig. 6(c), under rare earthquakes, the average inter floor displacement of the standard seismic method for reinforced concrete structures was 45 mm, and the designed method was 140 mm. The resilience-based seismic design method has good energy dissipation and deformation capabilities, which can absorb and disperse seismic energy during earthquakes, reducing damage to the structure. The floor acceleration between the standard seismic method for reinforced concrete structures and the seismic method for reinforced concrete structures based on resilience objectives is shown in Fig. 7.

In Fig. 7(a), the floor acceleration of the standard reinforced concrete structure seismic method increased with the increase of floors, reaching 0.50 g. In Fig. 7(b), the average floor acceleration of the designed method for reinforced concrete structures was 0.47 g, which was 6% lower. The average floor acceleration on the first floor was 0.42 g, and the maximum acceleration was 0.46 g, which exceeded the design limit of 0.4 g. In response to this situation, anchoring measures can be implemented on the acceleration sensitive non structural components of the first floor to ensure that they meet the design requirements. For other floors, the maximum floor acceleration did not exceed the design limit, which met the standard for floor acceleration in resilient design.

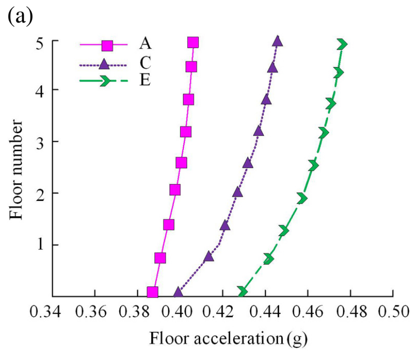


Fig. 7. Floor acceleration comparison: (a) Standard seismic method for reinforced concrete structures, (b) Seismic method of reinforced concrete structure based on toughness

3.2. Evaluation and analysis of seismic resilience

The study uses the evaluation tool PACT developed by FEMA to evaluate structural resilience. Due to the vulnerability data in PACT software being based on data from specific regions in the United States in 2012, it is not appropriate to directly apply these data for seismic resilience assessment. Therefore, the study updates key information such as the vulnerability function, repair cost, repair time, and reduction coefficient of components to the vulnerability database of PACT. A new component performance combination is constructed. These data mainly refer to the "Evaluation Standards for Seismic Resilience of Buildings", which is more in line with the actual Chinese architecture. After updating the vulnerability database, the basic information and response parameters of the structure are input into PACT software for analysis. Through this process, the repair cost, repair time, and potential casualties of the structure can be evaluated. Furthermore, by calculating the repair cost, the functional recovery indicators of the structure can be obtained, thereby verifying whether the proposed design has achieved the predetermined resilient seismic fortification goals. The repair cost of the standard seismic method and the designed method is shown in Fig. 8.

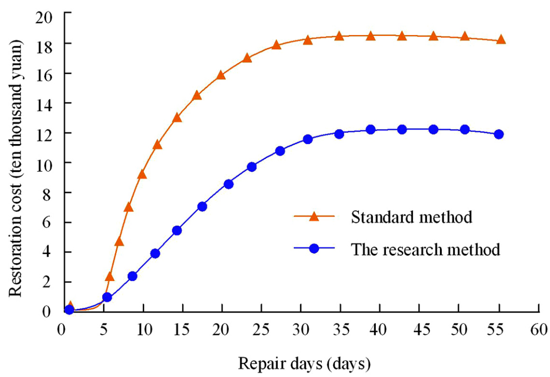


Fig. 8. Comparison of restoration costs

In Fig. 8, the repair cost of the standard reinforced concrete structure seismic resistance method was mainly reflected in the masonry infill wall, and the repair cost of the entire repair cycle reached 182500 yuan. The damage to the infill wall of the resilience-based seismic design method was more significant, and the total repair cost for the entire repair cycle was 121700 yuan. The seismic resistance method for reinforced concrete structures based on resilience has lower repair cost and economic practicality. The repair time of the standard seismic method and the seismic method based on resilience objectives is displayed in Fig. 9.

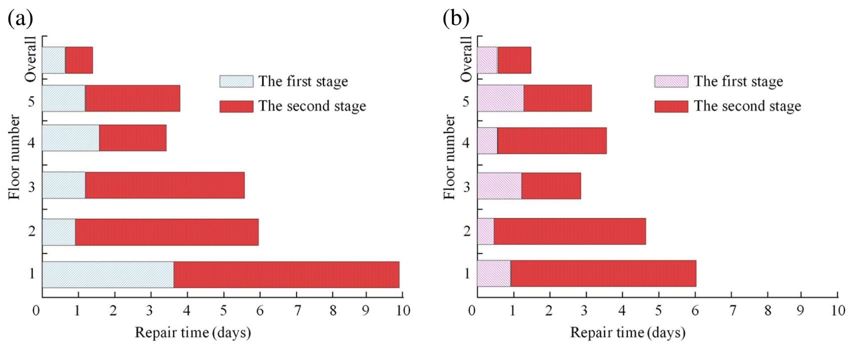


Fig. 9. Comparison of repair time: (a) Standard seismic method for reinforced concrete structures, (b) Seismic method of reinforced concrete structure based on toughness

In Fig. 9(a), the repair time for the standard seismic resistance method was 33 days. In Fig. 9(b), the repair time for the seismic resistance method based on resilience objectives was 24 days. This indicates that the seismic resistance method for reinforced concrete structures based on resilience is more time-saving, demonstrating the practicality of this method. The functional recovery index results of the standard seismic method for reinforced concrete structures and the seismic method based on resilience objectives are displayed in Table 2.

Table 2. Comparison results of function restoration indicators

Standard seismic method for reinforced concrete structures			**Seismic method of reinforced concrete structures based on resilience**		
Floor number	Loss ratio of each layer	Functional recovery index	Floor number	Loss ratio of each layer	Functional recovery index
1	0.052	0.953	1	0.044	0.936
2	0.093	0.848	2	0.056	0.858
3	0.071	0.873	3	0.063	0.891
4	0.065	0.886	4	0.048	0.923
5	0.038	0.943	5	0.025	0.927
Overall	0.025	0.965	Overall	0.009	0985

In Table 2, the average loss ratio of the designed method in each layer was 0.013, which was lower than the standard method's 0.026. At the same time, the adopted method also showed a higher level in functional recovery indicators than the standard method. The method proposed in the study is superior to traditional normative methods in terms of structural resilience.

4. Discussion and conclusions

A resilience-based seismic design method for reinforced concrete structures was proposed and compared with standard methods. The research results indicated that in the comparison of inter floor displacements, the average inter floor displacement of the standard method was 168 mm, while the resilience-based seismic design method was 192 mm. The latter had a larger displacement and the structure had greater deformation ability under seismic action without collapse. In terms of floor acceleration, the maximum floor acceleration of the standard method was 0.50 g, while the average floor acceleration of the resilient-based method was 0.47 g, which was 6% lower. This helped to reduce non structural damage caused by earthquakes. From an economic perspective, the repair cost of the standard method was 182500 yuan, and the repair time was 33 days. However, the repair cost of the resilience-based method was only 121700 yuan, and the repair time was shortened to 24 days, significantly reducing the economic burden and recovery time. The functional recovery index also showed that the average loss ratio of the structure based on resilience at each layer was 0.009, and the functional recovery index reached 0.985, which was significantly better than the standard method's loss ratio of 0.025 and functional recovery index of 0.965. These data indicate that the design method based on resilience can not only provide higher structural safety during earthquakes, but also demonstrate faster repair capabilities and lower economic cost during post disaster recovery, thus verifying the effectiveness in improving building seismic resilience. However, the limitation of the study lies in the limited number of seismic waves used in simulation analysis, which may not fully reflect the complexity of actual seismic actions. Future research needs to further expand the sample size, and improve the universality and reliability of the method.

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