Journal of Building Engineering 82 (2024) 108422

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Rapid recovery strategy for seismic performance of seismic-damaged structures considering imperfect repair and seismic resilience

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ARTICLE INFO

Keywords:
Damage index
Seismic-damaged structure
Seismic performance
Imperfect repair
Seismic resilience
Fragility

ABSTRACT

In the emergency repair process of seismic-damaged structures, it is necessary to determine the optimal repair strategy according to damage assessment results, available repair resources and repair time. In this study, the applicable conditions of various member-level and structure-level damage indexes or models are compared. Then, considering the actual conditions of limited available repair resources and repair time in the emergency repair process, the determination method of the optimal imperfect repair strategy is established. On this basis, the determination method of the optimal repair sequence is proposed by taking seismic resilience as the evaluation index. Finally, a seismic fragility analysis method that considers uniform collapse risk and residual service life of structures is introduced, which can be used to analyze the seismic performance of seismic-damaged structures and to compare the repair effectiveness of different repair strategies. Taken a 5-story reinforced concrete structure as an example for analysis. The analysis results show the optimal imperfect repair strategy and the optimal repair sequence determined by the proposed methods can effectively improve the seismic performance of seismic-damaged structures. The fragility analysis results further confirm that the repair based on the optimal imperfect repair strategy can effectively reduce the collapse risk of seismic-damaged structures.

1. Introduction

A strong earthquake can cause serious damage to engineering structures. The damage or collapse of engineering structures and secondary disasters caused by structural damage or collapse are the main causes of casualties and economic losses [1,2]. After a main shock, it is of great theoretical significance and engineering value to repair seismic-damaged structures according to feasible damage assessment methods and the ideas of seismic performance rapid improvement, so as to reduce the damage degree and collapse risk of seismic-damaged structures under aftershocks, and to reduce casualties and economic losses.

The whole process of performance restoration of seismic-damaged structures includes three important parts: damage assessment, structure repair and retrofit, and seismic performance analysis. In the research on damage assessment, the damage of members can be assessed by damage indexes or models such as maximum drift ratio [3,4], residual drift ratio [5], crack characteristics [6–8], and Park-Ang model [9], and the overall damage of an integral structure system can be comprehensively assessed by deformation-related [10,11] or energy-related [12,13] damage indexes or models. Liu et al. [14] proposed a rapid damage assessment method for reinforced concrete members based on the fractal dimension of cracks, considering the correlation between the fractal characteristics of

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https://doi.org/10.1016/j.jobe.2023.108422
Received 5 July 2023; Received in revised form 4 December 2023; Accepted 30 December 2023

cracks and the damage state. The reliability of this method was demonstrated through experiments. Tazarv et al. [15] established the relationship between the damage state and deformation of beam and column members, and the computer vision technology was used to quickly detect cracks and failure modes of members, thereby achieving rapid identification of damage state. Makhloof et al. [16] reviewed existing damage assessment methods and emphasized the overall damage assessment methods based on deformation, frequency or modal parameter.

However, the static and dynamic response information required by some damage indexes or models is difficult to measure effectively under actual conditions or real scenes, which makes it difficult to apply these damage indexes or models directly to the actual earthquake damage assessment [13]. Taking Park-Ang model as an example, when Park-Ang model is used to assess the damage of members, the deformation and shear force of members must be known. However, the actual shear force information of the members in an earthquake is difficult to obtain due to the limit of the actual measurement technology. Therefore, Park-Ang model is generally only applicable to assessing the damage of the member under the quasi-static test and simulation. In recent years, a great deal of attention has been paid to the damage identification based on frequency-related methods. However, those frequency-related methods can only assess the overall damage of structures and cannot be used to assess the damage of members. More importantly, these methods are severely influenced by factors such as environmental noise, temperature, humidity, and multi-modal.

Currently, research on seismic-damaged structures mainly focuses on repair materials and repair techniques, while research on repair strategies mainly focuses on the life-cycle repair strategy of structures under operating conditions. Due to factors such as insufficient emphasis on seismic-damaged structures, there is limited study on repair strategies for seismic-damaged structures. In addition, when formulating the repair strategy for seismic-damaged structures, it is necessary to consider multiple aspects such as the number and damage degree of members, and repair methods, which makes it difficult to determine the optimal repair strategy for actual seismic-damaged structures.

A complete earthquake sequence includes main shock and aftershock. After a strong main shock, seismic-damaged structures still may be subject to damaging aftershocks [17], and the damage degree of seismic-damaged structures may be further aggravated. Therefore, seismic-damaged structures face a high collapse risk under aftershocks and are prone to cause more serious casualties and economic losses. So, it is necessary to quickly repair seismic-damaged structures after the main earthquake to ensure that seismic-damaged structures have good seismic performance and the ability to resist aftershocks.

However, due to many constraints such as transportation conditions and the allocation of repair resources, it is difficult to achieve the goal of repairing all damaged members in seismic-damaged structures during the emergency repair process. The concept of imperfect maintenance originated from equipment maintenance in the aviation and mechanical fields [18,19]. Imperfect maintenance refers to that limited by available repair resources and repair time, only partial key damaged members are selected for maintenance during the maintenance process of damaged systems. Therefore, formulating an optimal maintenance strategy based on the concept of imperfect maintenance can maximize the performance of damaged systems while controlling maintenance costs. In relevant research, Wang et al. [20] established an imperfect maintenance strategy model to ensure the availability of wind turbines and minimize maintenance costs; Pandey et al. [21] developed a mathematical model between the level of imperfect maintenance and the number of resources required for maintenance, and demonstrated that making the optimal imperfect maintenance strategy is beneficial for superb allocation of maintenance resources.

Under the condition of limited repair resources and repair time, emergency repair of seismic-damaged structures can be regarded as imperfect maintenance (i.e., imperfect repair). Moreover, different types of damaged members in the seismic-damaged structure have different effects on the overall seismic performance of the seismic-damaged structure after repair. Therefore, it is advisable to repair the key damaged members in the seismic-damaged structure based on the optimal imperfect repair strategy, so as to rapidly improve the seismic performance of the seismic-damaged structure and effectively reduce the collapse risk of the seismic-damaged structure.

In addition, the determination of the optimal repair sequence of key damaged members based on the optimal imperfect repair strategy can ensure the most rapid improvement of the structural performance during the repair process. At the overall level, the improving process of the structural seismic performance reveals structural seismic resilience. In the related studies, Bruneau et al. [22] and Tirca et al. [23] investigated the effects of repair function and repair methods on the seismic resilience of the structure, respectively; Zhai et al. [24] and Liu et al. [25] investigated the seismic resilience of medical systems and water distribution networks, respectively. Therefore, the ability of a structure to resist and recover its original function from a disaster can be evaluated according to seismic resilience. In 2012, FEMA proposed a new generation of building seismic performance evaluation method FEMA P-58 [26]. In 2020, China has prepared a relevant evaluation standard (GB/T 38591) for the seismic resilience of buildings [27]. Different repair sequences of key damaged members in the seismic damaged structure lead to different seismic resilience. Therefore, it is necessary to propose a method to determine the optimal repair sequence of the seismic damaged structure considering the seismic resilience.

Fine structural seismic performance analysis can comprehensively reveal the performance state of structures under different intensity earthquakes. At present, the seismic performance analysis method of structures has been developed from the traditional dynamic time history analysis to the probabilistic statistical performance analysis that can involve ground motion differences and structural differences [28–32]. In the related studies, the fragility analysis method can quantify the probability of a structure reaching or exceeding a certain damage state under a given intensity of earthquake action [33]. However, some fragility analysis studies have revealed that the seismic design based on uniform hazard spectrum does not guarantee the uniform collapse risk of structures in different regions [31]. This means that the collapse risk of different building structures under the same earthquake is difficult to be uniformly controlled. Therefore, the seismic design method based on the uniform risk principle is proposed [34]. Silva et al. analyzed the various parameters involved in the development of risk-targeted design maps [35]. Zaman et al. conducted a probabilistic seismic hazard analysis, and provided the risk-targeted map for Tehran [36]. Wang and Lu constructed a uniform risk spectrum for a specific site, and established a fragility analysis framework considering the uniform collapse risk [37,38]. It is worth noting that in a specific site, the construction time of existing structures (i.e., structures in service) are not the same. Meanwhile, the residual service life of existing structures varies due to durability factors such as concrete carbonization and steel corrosion. This makes existing structures face different risks. Hence, it is necessary to consider the influence of the residual service life of structures in the process of establishing a uniform risk spectrum.

In view of the above problems, this study focuses on the repair decision-making of seismic-damaged structures. Firstly, the applicability of different damage indexes or models is compared. Subsequently, a method for determining the optimal imperfect repair strategy based on structural seismic performance loss, exhaustive method, and Euclidean distance calculation method under limited repair resources and repair time is proposed, and a method for determining the optimal repair sequence considering seismic resilience is established. Finally, the seismic fragility analysis method considering the uniform collapse risk and structural residual service life is introduced, which can provide support for assessing repair strategies of seismic-damaged structures and analyzing the seismic performance of repaired structures. The specific flow of this study is shown in Fig. 1.

2. Damage indexes or models

The existing damage indexes or models can quantify the damage degree and performance level of a structure from the member-level and structure-level. The member-level damage indexes or models can characterize the damage degree of members in the seismic-damaged structure in detail, and the structure-level damage indexes or models can macroscopically reveal the overall performance of the seismic-damaged structure. The repair of seismic-damaged structures is usually done at the member-level, that is, through the repair of damaged members to complete the repair of seismic-damaged structures. Therefore, it is suggested that the damage degree of members can be quantified according to the member-level damage indexes or models, and then the repair strategy of seismic-damaged structures based on members can be formulated. In this way, the overall seismic performance of seismic-damaged structures can be improved by repairing the damaged members, so as to achieve the “member-structure" repair process of seismic-damaged structures. Moreover, the overall seismic performance of seismic-damaged structures before and after repair can be evaluated according to the structure-level damage indexes or models, and further reflect the influence of repair strategies on the overall seismic performance.

Therefore, this study summarizes some typical damage indexes or models, and compares the applicability of different damage indexes or models.

2.1. Member-level

The deformation of members under earthquake action can reveal the basic mechanical properties and damage state of members. Therefore, it is assumed that the damage degree of members can be directly assessed according to the deformation in traditional research. In related studies, Powell et al. [39] established deformation-related damage indexes for members. However, the damage indexes based on deformation cannot fully reflect the influence of the duration and frequency spectrum characteristics of ground motion on the damage state of members. Some researchers have suggested the use of energy-based damage indexes or models to assess the damage of members. Among, the two-parameters model proposed by Park and Ang et al. [9], which comprehensively involves deformation and hysteretic energy dissipation, is the most representative, and can be expressed as

$$D = \frac{\delta}{\delta_u} + \beta_c \frac{E_H}{F_y \delta_u} \tag{1}$$

where D is the damage value, δ is the deformation of the member, δ_u is the ultimate deformation of the member, E_H is the cumulative hysteretic energy dissipation, F_y is the yield load of the member, β_c is the weight coefficient.

However, Park-Ang model has many shortcomings, such as a not strict threshold. Therefore, Jiang et al. [40] and Rajabi et al. [41] modified Park-Ang model from different perspectives. In particular, Kunnath et al. [42] proposed a modified Park-Ang model in the form of moment-curvature. In addition, Darwin et al. [43] and Kratzig et al. [44] proposed different damage models from the energy perspective to assess the damage of members, and verified the effectiveness of the proposed damage models through experimental data.

From the transformation perspective of energy-damage, He et al. [12] assumed that the damage of a member can be characterized by the difference between the deformation energy of the member in the ideal elastic state (i.e., intact state) and the actual elastoplastic state (i.e., damaged state). Based on this, the damage model based on elastic-plastic energy dissipation ratio (EPEDR) was proposed. The EPEDR model can be expressed as

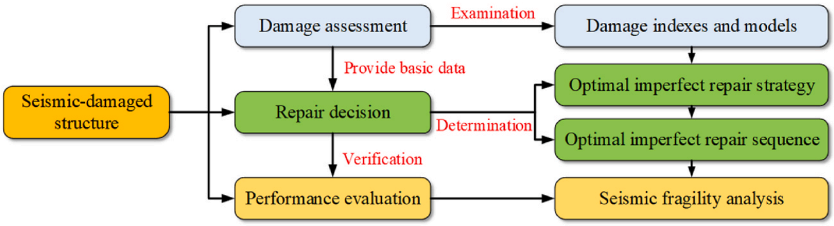


Fig. 1. The specific flow of this study.

$$D = \frac{E_E - E_F}{E_E} = 1 - \frac{\sum_{i=1}^{t} |F_{Fi} \Delta u_{Fi}|}{\sum_{i=1}^{t} |F_{Ei} \Delta u_{Ei}|} \tag{2}$$

where E_E and E_F are the cumulative deformation energy of the member in the ideal elastic state and the actual elastic-plastic state, respectively; F_{Ei} and F_{Fi} are the shear forces of the member in the ideal elastic state and the elastic-plastic state at loading step i, respectively; Δu_{Ei} and Δu_{Fi} are the deformation increments of the member in the ideal elastic state and the elastic-plastic state at loading step i, respectively.

The damage degree of a member can also be reflected by comparing the changes of its own characteristic parameters before and after damage. For this reason, some researchers have proposed damage models based on stiffness degradation [45]. In addition, the residual deformation and cracks of a member are the most visual indexes of its damage degree. Therefore, the damage of a member can be assessed according to the residual deformation and the length, width and number of cracks. In FEMA 310 [46], JGJ/T 415 [47] and JBDPA guideline [8], it is recommended to assess the damage degree of members according to the width of cracks.

2.2. Structure-level

In the overall damage assessment, adopting the maximum inter-story drift ratio to assess the overall damage degree of a seismic-damaged structure is the most common method. In related studies, the limits of the maximum inter-story drift ratio and damage value corresponding to different damage states were given [48]. In addition, some researchers have used the maximum inter-story drift ratio as the overall performance index of structures in the fragility analysis and performance analysis of structures [49].

Some researchers assume that energy-related damage indexes or models can more accurately evaluate structural damage. Xiao et al. presented a novel damage model considering the combination of deformation and hysteretic energy [50]. He et al. used the EPEDR model for the overall damage evaluation of structures and verified the applicability of the model through an example analysis [12].

However, generalized energy is usually expressed as the product of deformation and shear force. In actual seismic damage assessment, the shear force of structures or members is difficult to obtain. Therefore, the application of energy-related damage indexes or models in actual seismic damage assessment is limited. To solve this problem, He et al. proposed a generalized elastic-plastic energy dissipation ratio (GEPEDR) model based on EPEDR model, combined with the extended Kalman filter algorithm [13]. GEPEDR model assesses the overall damage of a structure according to the measured response information of the structure only.

In addition, the overall damage degree of seismic-damaged structures can also be characterized by the changes in structural characteristic parameters such as stiffness, period, and frequency [51]. Therefore, a large number of researchers have combined health monitoring techniques and theories to monitor the changes of the structure's own characteristic parameters in real-time. These techniques and theories can provide effective help for the overall damage assessment and performance monitoring.

Moreover, the multivariate weighting method and system evaluation method can be used to comprehensively assess the overall damage degree of seismic-damaged structures based on the damage assessment results of members [52]. The specific process of the

Table 1
Comparison of different damage indexes or models.

Level	Damage indexes or models	Category	Applicable condition		Consider loading path or duration	Strict threshold	Actual measurement
			Static	Dynamic			
Member-level	Drift ratio	Deformation	●	●	○	○	●
	Residual drift ratio		●	●	○	○	●
	Powell model		●	●	○	●	●
	Park-Ang model	Energy	●	○	●	○	○
	Modified Park-Ang model		●	●	●	○	○
	Darwin model		●	○	●	●	○
	Kratzig model		●	○	●	●	○
	EPEDR model		●	●	●	●	○
	Stiffness	Characteristic parameter	●	●	●	●	○
	Crack		●	●	●	○	●
Structure-level	Maximum inter-story drift ratio	Deformation	●	●	○	○	●
	Residual inter-story drift ratio		●	●	○	○	●
	Huang model	Energy	●	○	●	○	○
	EPEDR model		●	●	●	●	○
	GEPEDR model		●	●	●	●	●
	Weighting method	Comprehensive	●	●	○	●	●
	Stiffness	Characteristic parameter	●	●	●	●	○
	Period/Frequency		○	●	●	●	●

Note: ● means having the corresponding ability; ○ means not having the corresponding ability.

method is as follows: firstly, the damage degree of each member in the seismic-damaged structure is determined according to the appropriate member-level damage indexes or models; secondly, considering the weight coefficients of each member, the damage degree of each story is determined according to the damage assessment results of members; finally, considering the importance of each story, the overall damage degree of the seismic-damaged structure is determined according to the damage assessment results of stories. In this method, how determining the importance coefficients of members and stories is a key link that affects the damage assessment results. Park et al. [9] and Du et al. [53] proposed importance coefficient determination methods from different perspectives, respectively.

2.3. *Application scope*

To further compare the assessment capabilities of different damage indexes or models, the above-mentioned damage indexes or models at the member-level and structure-level are compared from various perspectives, such as the category, the applicable conditions, and the feasibility of the actual measurements. The comparison results are shown in Table 1.

At the member-level, the deformation-related damage indexes or models can basically be obtained through actual measurement. However, these damage indexes or models cannot reveal the influence of loading path and duration on damage state. Although the energy-related damage indexes or models can reveal the dynamic influence of loading path and duration on damage, they are difficult to apply in actual engineering due to the load information needs to be known in advance. Some damage indexes or models related to their own characteristic parameters can be obtained through actual measurement, but they are easily affected by environmental factors.

At the structure-level, damage indexes or models of deformation-related, energy-related, and related to its own characteristic parameters also present similar advantages and disadvantages.

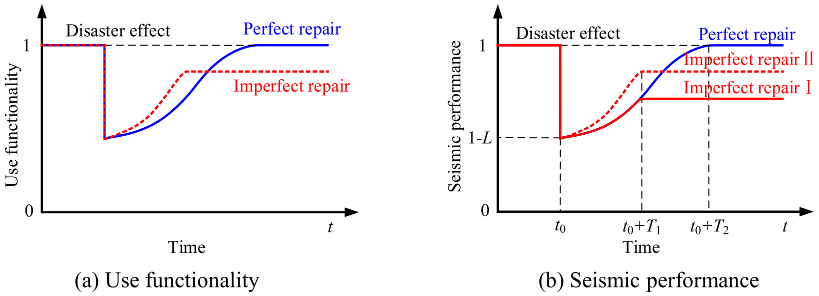
From the comparison results, it is clear that most of the energy-related damage indexes or models are difficult to apply in the actual earthquake damage assessment. Therefore, damage indexes or models of deformation-related or related to their own characteristic parameters can be used to assess the damage of members or structures in the actual earthquake damage assessment. On the basis of the damage assessment results of members, the multivariate weighting method can also be used to assess the overall damage of structures. In the absence of a structural health monitoring system or device, it is generally only possible to assess the damage degree of members and structures based on damage indexes or models related to residual deformation or cracks.

In view of this, two measurable deformation-related damage indexes (maximum drift ratio and residual drift ratio) are used to assess the damage degree of the members in this study. According to the damage assessment results, available repair resources and repair time, repair strategies for seismic-damaged structures can be formulated. On this basis, EPEDR model can be used as the overall performance index for structural seismic fragility analysis, so as to analyze the seismic performance of the repaired structures and verify the effectiveness of the repair strategy.

3. Determination method of imperfect repair strategy

The members (including structural and non-structural members) of building structures will be damaged to different degrees under the strong earthquake, which lead to a rapid reduction of the seismic performance and the operation function of building structures. After an earthquake, to quickly improve the seismic performance of seismic-damaged structures and restore the use function, different repair measures could be adopted. Among many influencing factors, the repair strategy, repair method and repair sequence used in the repair process are the main factors affecting the seismic performance and seismic resilience of seismic-damaged structures.

As shown in Fig. 2(a), the use functionality of seismic-damaged structures can be ideally restored to an intact level (i.e., perfect repair) under the condition that the available repair resources and repair time are sufficient. Under the condition of limited available repair resources and repair time, the use functionality of seismic-damaged structures cannot be restored to an intact level (i.e., imperfect repair). To avoid more serious damage to important seismic-damaged structures under aftershocks, the seismic-damaged structures should be repaired immediately after the main shock. In the emergency repair process, the main consideration should be to improve the seismic performance of seismic-damaged structures (i.e., reduce the seismic performance loss of seismic-damaged structures) rather than to restore the use functionality of seismic-damaged structures. Therefore, similar to the recovery process of the use functionality, the recovery process of the seismic performance of seismic-damaged structures during the emergency repair is shown in Fig. 2(b). Among, L is the overall seismic performance loss of the structure; t_0 is the damage moment of the structure; T_1 and



(a) Use functionality (b) Seismic performance

Fig. 2. Influence of repair strategy on seismic resilience.

T_2 are the repair times required under different repair strategies, respectively.

In Fig. 2(b), imperfect repair I and imperfect repair II represent two different imperfect repair strategies, and the corresponding curves indicate the whole recovery process (i.e., resilience) of the seismic performance of seismic-damaged structures. It can be seen from Fig. 2(b) that under the same repair time, imperfect repair II can result in better seismic performance of seismic-damaged structures after repair. Therefore, different imperfect repair strategies can lead to various seismic performances after repair. To maximize the seismic performance of seismic-damaged structures after repair, it is necessary to adopt effective methods to determine the optimal repair strategy and repair sequence of seismic-damaged structures in the imperfect repair process.

3.1. *Calculation method of seismic performance loss*

In this study, the seismic performance losses of member, story and structure are calculated in the progressive form of “member-story-structure". It is assumed that the seismic performance loss $L_{i,j}$ of the member is approximately linearly related to the damage degree of the member, so the seismic performance loss $L_{i,j}$ of the member can be estimated directly from the damage value $D_{i,j}$ of the member (i.e., $L_{i,j} = D_{i,j}$). When calculating the seismic performance loss of the story, the importance of different types of members in the story is firstly considered to give them different weight coefficients, and then the seismic performance loss of the story is calculated by Eq. (3) based on the seismic performance loss and the weight coefficients of the members.

$$L_i = \sum_{j=1}^{n} \frac{\lambda_{i,j} L_{i,j}}{\sum_{j=1}^{n} \lambda_{i,j}} \tag{3}$$

where L_i is the seismic performance loss of story i, $L_{i,j}$ is the seismic performance loss (i.e., damage value $D_{i,j}$) of the j-th member of story i, $\lambda_{i,j}$ is the weight coefficient of the j-th member of story i, and n is the total number of members of story i.

The damage value $D_{i,j}$ of members can be determined according to various member-level damage indexes or models introduced above. The weight coefficients of members can be determined according to existing research results or engineering experience. In related studies, Gharaibeh et al. [54] proposed a reliability-based method to identify and rank important members in complex structures; Du et al. [55] analyzed the structural robustness through the mechanical characteristics of the structure during the continuous collapse, so as to determine the importance ranking of corner column, exterior column and interior column.

Considering the importance of each story, the overall seismic performance loss of the structure can be calculated by Eq. (4) based on the seismic performance losses of stories.

$$L = \sum_{i=1}^{m} \frac{\lambda_i L_i}{\sum_{i=1}^{m} \lambda_i} \tag{4}$$

where L is the overall seismic performance loss of the structure, which is a normalized value, λ_i is the weight coefficient of story i, and m is the total number of stories in the structure.

The weight coefficients of stories can be taken according to the existing research results or engineering experience. For example, Du et al. [53] believed that the damage of lower stories has a more serious influence on the overall damage of the structure, and used the number of stories as the weight coefficient. This means that for an m-story structure, the weight coefficient of the bottom story is m, and the weight coefficient of the top story is 1. However, due to the difference of spectral characteristics of different earthquakes and the irregularity of structures, the distribution rule of weak stories of different structures is not consistent. Usually, the more severely damaged stories have a greater influence on the overall seismic performance of the structure. Therefore, this study suggests to determining the weight coefficient of each story according to the seismic performance loss of stories, i.e., $\lambda_i = L_i$.

3.2. *Optimal imperfect repair strategy*

As shown in Fig. 2(b), the overall seismic performance of a structure in the intact condition is 1. Under the condition of encountering an earthquake, the structure is damaged (i.e., seismic-damaged structure) and the overall seismic performance is reduced to 1-L. In the process of repairing the damaged members in the seismic-damaged structure according to the formulated repair strategy, the overall seismic performance of the seismic-damaged structure is gradually improved.

Repair resources used in the repair process can be characterized by the repair cost, which mainly includes material cost, labor cost and machinery cost. Among, the material cost for repairing a damaged member is closely related to the damage degree of the member and the adopted repair method, and the labor cost and machinery cost are closely related to the repair time.

Generally, the damage state of members can be divided into five types of degrees, which include basic intact, minor damage, moderate damage, severe damage and collapse. In different damage states, various repair methods could be adopted to repair the damaged members. This causes the repair cost and repair time of damaged members in different damage states is discrepant. In addition, under the same damage state, the repair cost and repair time of members with different damage degrees are also different. In relevant research, Gulec et al. [56,57] investigated the seismic performance and fragility of reinforced concrete walls and eccentrically braced frames repaired through different repair methods under different damage states. The appropriate repair methods for different types of structures under different damage states are given in ASCE 41-13 [3] and JGJ/T 415 [47]. FEMA P-58 [26] and GB/T 38591 [27] empirically provided the time and cost required for repairing different types of members in different damage states.

As shown in Fig. 3, it is assumed that the member is in the state of basic intact or collapse, there is unnecessary to repair the member. When the member is in the other three damage states, it is necessary to take different repair methods to repair the member, and assumed that the seismic performance of the member can be fully restored after repair (i.e., $D_{i,j} = 0$). In the three damage states of minor damage, moderate damage, and severe damage, it is assumed that the material cost and repair time required to repair a member are linearly related to the damage degree of the member. For example, when the damage value $D_{i,j}$ of the member is between D_2 and D_3 (i.e., moderate damage), the required material cost $C_{i,j}$ and the repair time $T_{i,j}$ can be expressed as follows

$$C_{i,j} = C_{m1} + (C_{m2} - C_{m1})\frac{D_{i,j} - D_2}{D_3 - D_2} \tag{5}$$

$$T_{i,j} = \frac{1}{r}\left[T_{r1} + (T_{r2} - T_{r1})\frac{D_{i,j} - D_2}{D_3 - D_2}\right] \tag{6}$$

where D_2, D_3 are the damage limit values in the moderate damage state; C_{m1}, C_{m2} are the material cost limit values required to repair the member in the moderate damage state; T_{r1}, T_{r2} are the repair time limit values required for a single person to repair the member under the moderate damage state; R is the number of workers in the repair process.

Under the condition of limited available repair cost and repair time, only some key damaged members in the seismic-damaged structure can be repaired. According to the number and location of members selected for repair, various repair strategies can be determined. In different repair strategies, the repair time and repair cost required to repair the seismic-damaged structure is different, and the overall seismic performance of the seismic-damaged structure after repair is also different. In a specific repair strategy, the required repair time T_z and repair cost F_z can be calculated by Eq. (7) and Eq. (8), respectively, and the overall seismic performance loss of the seismic-damaged structure after repair can be calculated by Eq. (3) and Eq. (4). In addition, the difficulty of transporting materials during the repair process increases with the number of stories. Therefore, the factors such as the number of stories can affect the difficulty of the repair, so it will raise the repair time and repair cost. Thus, the story influence coefficient η_i is introduced in Eq. (7) and Eq. (8), and its specific value can be determined according to the suggestions in GB/T 38591 [27].

$$T_z = \sum_{i=1}^{m}\left(\sum_{j=1}^{n}\gamma_{i,j}T_{i,j}\eta_i\right) \tag{7}$$

$$C_z = \sum_{i=1}^{m}\left(\sum_{j=1}^{n}\gamma_{i,j}C_{i,j}\eta_i\right) + T_zC_rr + T_zC_a \tag{8}$$

where $\gamma_{i,j}$ is the repair determination coefficient, $\gamma_{i,j} = 0$ means no repair for the j-th member of story i, $\gamma_{i,j} = 1$ means repair for the j-th member of story i; C_r is the payroll of workers per unit time; C_a is the machinery cost per unit time.

The optimal imperfect repair strategy for seismic-damaged structures should ensure that the seismic performance loss of each story can be reduced to within the target range and the overall seismic performance is the best (i.e., the overall seismic performance loss is the minimum), while meeting the constraints of available repair time and repair cost. The formulation of the optimal imperfect repair strategy can be regarded as an optimization problem under multiple constraints, and the relevant optimization objectives and constraints can be expressed as follows

$$\left.\begin{array}{l}\min L\\ T_z = \sum_{i=1}^{m}\left(\sum_{j=1}^{n}\gamma_{i,j}T_{i,j}\eta_i\right) < T_k\\ C_z = \sum_{i=1}^{m}\left(\sum_{j=1}^{n}\gamma_{i,j}C_{i,j}\eta_i\right) + T_zC_rr + T_zC_a < C_k\\ L_i \le L_m\end{array}\right\} \tag{9}$$

where T_k is the available repair time, C_k is the available repair cost, and L_m is the limit of acceptable seismic performance loss of each story of the seismic-damaged structure. The acceptable damage degree of seismic-damaged structures after imperfect repair should be controlled within the range of minor damage. Therefore, referring to the range of damage values corresponding to different damage

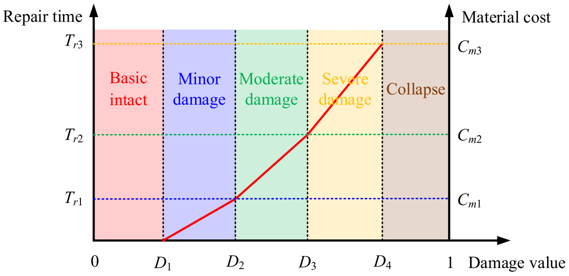


Fig. 3. Relationship between repair time, material cost and damage state of member.

states given in Ref. [48], the value of L_m should not exceed 0.3.

Different from the optimization problem of continuous functions, the optimization problem for the formulation of optimal repair strategies is essentially discrete. This optimization problem can be solved by intelligent algorithms or the exhaustive method. However, intelligent algorithms are complex and easy to fall into the local optimal solution, so it is difficult to obtain the global optimal solution accurately. The steps to determine the optimal imperfect repair strategy for seismic-damaged structures according to the exhaustive method are as follows: firstly, enumerate the imperfect repair strategies that can be used to repair seismic-damaged structure; secondly, calculate the repair cost, repair time and overall seismic performance loss of seismic-damaged structures after repair under each repair strategy; finally, find the global optimal imperfect repair strategy according to the constraints. However, the exhaustion method is inefficient and difficult to determine the global optimal imperfect repair strategy quickly and effectively. Taking a 5-story structure with only 10 members in each story as an example, when all feasible repair strategies are listed by the exhaustive method, there are 1024 repair strategies in each story, and the number of overall repair strategies enumerated can exceed 1×10^{15}.

To reduce the computational expense of the exhaustive method, it is suggested to simplify the optimization problem under multiple constraint conditions according to the following methods. Firstly, the members in each story of the structure are categorized, so that different repair strategies that contain the same type of members can be regarded as the same repair strategy. In the categorization process, according to the distribution of beam and column members in the floor plan, the members at the symmetrical position are considered as the same type of members. Secondly, screening the repair strategies for each story using the limit of acceptable seismic

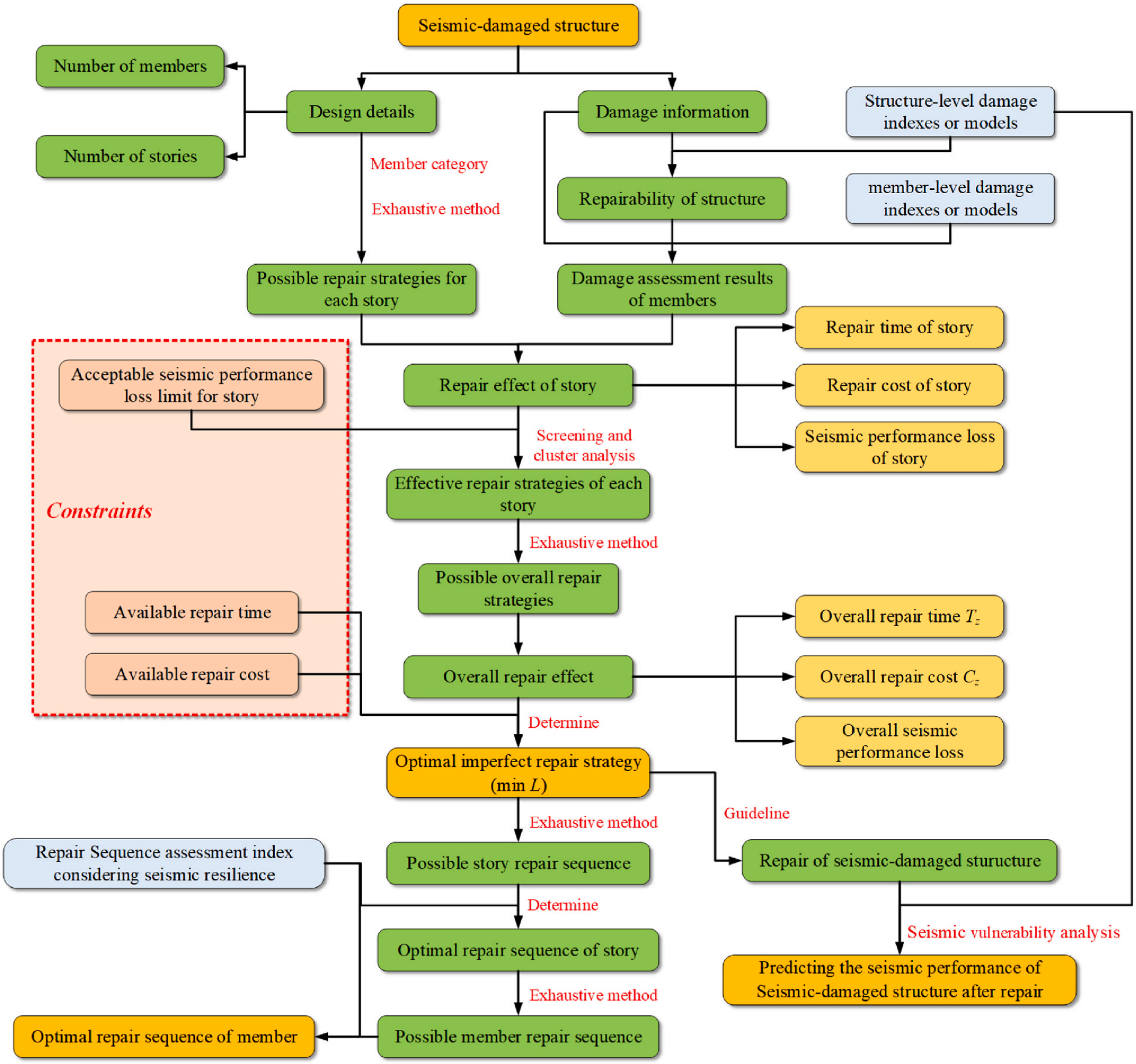


Fig. 4. Deduction process of optimal imperfect maintenance strategy for seismic-damaged structures.

performance loss of each story as a constraint. Thirdly, the Euclidean distance calculation method [58] is used to cluster the repair strategies of each story, and the repair strategy at the most central position in each type is taken as the representative of repair strategies. Subsequently, the repair strategies after clustering in each story are combined and all possible overall repair strategies are further obtained using the exhaustive method. Finally, the overall repair strategies are screened according to the available repair cost and repair time, and the strategy that minimizes the overall seismic performance loss is selected from the overall repair strategies that satisfy the constraints. This repair strategy is the optimal imperfect repair strategy for seismic-damaged structures.

The determination process of the optimal imperfect repair strategy for seismic-damaged structures based on the exhaustive method is shown in Fig. 4.

3.3. Optimal repair sequence considering seismic resilience

As shown in Fig. 5, if the optimal imperfect repair strategy is determined, the repair time and the seismic performance of seismic-damaged structures after repair are also determined. However, the use of different repair sequences can obviously affect the seismic performance of seismic-damaged structures at any instant during the repair process. The three gradient lines in Fig. 5 reveal the effect of different repair sequences on the seismic performance of seismic-damaged structures. Among them, a more superior repair sequence can ensure that seismic-damaged structures have better seismic performance in the repair process. Therefore, on the basis of the optimal imperfect repair strategy, it is of great significance to determine the optimal repair sequence to ensure that seismic-damaged structures have excellent seismic performance at any instant during the repair process.

In the resilience evaluation of structures, researchers have suggested using the change of the structural use function with time before and after the occurrence of a disaster to characterize resilience. In this study, it is considered that a good repair sequence should be able to ensure good seismic resilience of seismic-damaged structures during the repair process. Therefore, the effect of different repair sequences can be compared through seismic resilience. As shown in Fig. 5, the seismic resilience can be expressed as the enclosure area between the seismic performance improvement gradient curve and the seismic performance after repair. The optimal repair sequence corresponds to the minimum enclosure area.

In a specific repair sequence X_1, the enclosure area S_1 can be expressed as

$$S_1 = (L_b - L_a)T_{s1} + (L_b - L_a - L_{s1})T_{s2} + \cdots\cdots + \left(L_b - L_a - L_{s1} - \cdots\cdots - L_{s(r-1)}\right)T_{sr} \tag{10}$$

where L_b and L_a are the seismic performance loss of seismic-damaged structures before and after repair, respectively; T_{sr} is the time used to repair the r-th member, which can be calculated according to Eq. (6); L_{sr} is the contribution of repairing the r-th member to the overall seismic performance of the seismic-damaged structure. Combining Eq. (3) and Eq. (4), L_{sr} can be calculated according to Eq. (11).

$$L_{sr} = \frac{\lambda_i}{\sum\limits_{i=1}^{m}\lambda_i}\frac{\lambda_{i,j}D_{i,j}}{\sum\limits_{j=1}^{n}\lambda_{i,j}} \tag{11}$$

where L_{sr} is the contribution of repairing the r-th member (originally the j-th member in the story i with damage value $D_{i,j}$) to the overall seismic performance of the seismic-damaged structure. In addition, the contribution of the story repair to the overall seismic performance can be obtained by summing the contributions to the overall seismic performance from the repair of all members in the story that needs to be repaired.

In a specific repair strategy, there are many repair sequence schemes. Taking a repair strategy including 10 members to be repaired as an example, the repair sequence schemes obtained by the exhaustive method exceeds 3.6×10^6, which greatly increases the difficulty of determining the optimal repair sequence through Eq. (10). Usually, seismic-damaged structures are repaired in a story-by-story mode during the repair process. Therefore, once the overall repair strategy of the seismic-damaged structure is determined, the repair time and the contribution to the overall seismic performance of each story can be determined. To simplify the difficulty of

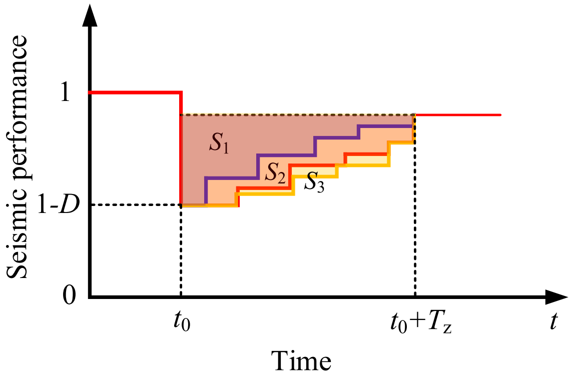


Fig. 5. Effect of repair sequence of members on the overall seismic performance.

determining the optimal repair sequence, the following method is suggested in this study. Firstly, the possible repair sequences of stories are obtained by the exhaustive method. Secondly, the optimal story repair sequence is determined according to seismic resilience by combining the repair time of each story and the contribution of story repair to the overall seismic performance. On this basis, the possible repair sequences of members in each story are obtained by the exhaustive method. Finally, combining the contribution of member repair to the overall seismic performance and the member repair time, the optimal repair sequence of members in each story is determined according to seismic resilience.

4. Fragility analysis of seismic-damaged structures considering uniform collapse risk

In structural seismic performance analysis, the finite element method and seismic fragility analysis method have been widely used. Therefore, in order to effectively predict the seismic performance of seismic-damaged structures after being repaired by the optimal imperfect repair strategy, it is necessary to use the nonlinear finite element simulation method and the seismic fragility analysis method. The existing research results show that under the same seismic design requirements, the collapse risk of building structures in different regions is very different. This means that the current seismic design method based on the principle of uniform hazard cannot guarantee that different building structures have the same collapse risk under the same earthquake. So, the uniform risk seismic design and collapse resistance design considering both the seismic risk of the site and the seismic fragility of the structure have received a lot of attention.

In the seismic design and collapse resistance design considering uniform risk, in order to analyze whether the collapse probability of a structure meets the predetermined collapse risk target, the determination of risk-targeted ground motion parameters is the core part. Risk-targeted ground motion parameters can be determined by the risk integral method or approximate analytical method [37]. Based on reliability theory, the risk integral can be expressed as

$$v_0 = \int_0^{\infty} F_R(x)|\mathrm{d}H_A(x)| \tag{12}$$

where v_0 is the target collapse risk of 1 a, v_0 and the target collapse risk v_{ft} of t a can be converted by v_{ft} = 1-(1-v_0)^t; x is the ground motion intensity; $F_R(x)$ is the seismic fragility function of the structure, which can reveal the conditional probability of the structure to damage; $H_A(x)$ is the seismic risk function that obeys the type II extreme value distribution. Assuming the seismic fragility of the structure obeys the normal distribution, $F_R(x)$ can be expressed as

$$F_R(x) = \Phi\left[\frac{x/m_R}{\beta}\right] \tag{13}$$

where β is the logarithmic standard deviation of structural seismic fragility; m_R is the median value of structural seismic fragility.

Generally, $H_A(x)$ can be expressed as a first-order approximation of a power exponential function [59], and $H_A(x)$ can be expressed as

$$H_A(x) \approx \left(\frac{x}{u}\right)^{-k} = u^k x^{-k} = k_0 x^{-k} \tag{14}$$

where u is the scale parameter; k is the shape parameter, and $k_0 = u^k$. The values of k and k_0 can be determined according to the recommendations of Bradley et al. [60].

Therefore, the analytical expression of seismic risk can be given by

$$v_0 = H(m_R) \cdot \exp\left(\frac{1}{2}k^2\beta^2\right) \tag{15}$$

Combining Eq. (14) and Eq. (15), Eq. (16) can be obtained.

$$m_R = k_0^{\frac{1}{k}}\left[1-\left(1-v_{ft}\right)^{\frac{1}{t}}\right]^{-\frac{1}{k}} \cdot \left[\exp\left(\frac{1}{2}k^2\beta^2\right)\right]^{\frac{1}{k}} \tag{16}$$

On this basis, according to Eq. (13) and the known conditional collapse probabilities p_{dD} and p_{dM} for the design-based earthquake and the rare earthquake, the risk-targeted ground motion parameters D_R and M_R for the design-based earthquake and the rare earthquake can be expressed as

$$D_R = m_R \cdot \exp\left[\beta \cdot \Phi^{-1}(p_{dD})\right] \tag{17}$$

$$M_R = m_R \cdot \exp\left[\beta \cdot \Phi^{-1}(p_{dM})\right] \tag{18}$$

By calculating the risk-targeted ground motion parameters D_R and M_R of different periods, the risk-targeted uniform risk spectra of the design-based earthquake and the rare earthquake can be obtained.

In addition, in the process of calculating the uniform risk spectrum, the ground motion parameters D and M corresponding to the design-based earthquake and the rare earthquake can be determined according to the basic seismic design intensity and site conditions. Usually, the basic seismic design intensity is taken as the intensity with an exceedance probability of 10 % in 50 years. However, for existing structures (i.e., structures in service), their residual service life is often less than the 50-year service life specified in national standards such as China standard GB50011-2010 [61]. Therefore, it is not in line with the actual situation to determine the seismic action that existing structures may suffer in the residual service life according to the basic seismic design intensity of the site. In this study, the following methods are recommended to determine the ground motion parameters D and M of existing structures considering the residual service life.

Firstly, the exceedance probabilities for different seismic design levels (minor earthquake, design-based earthquake and rare earthquake) in the residual service life are converted into equal exceedance probability $P_{50}(I)$ in 50 years according to the equal exceedance probability method shown in Eq. (19). Subsequently, the equivalent seismic design intensity I of the existing structure in the residual service life t is obtained by substituting $P_{50}(I)$ into Eq. (20). Finally, the peak acceleration $A_{\max}$ of seismic waves corresponding to the equivalent seismic design intensity I in the residual service life can be obtained by substituting I of the existing structure under the conditions of minor, design-based and rare earthquakes into Eq. (21).

$$P_{50}(I) = 1 - (1 - P_m)^{\frac{50}{t}} \tag{19}$$

$$I = 12 - (12 - I_0)\left\{ - 10^{0.9773} \ln[1 - P_{50}(I)]\right\}^{\frac{1}{h}} \tag{20}$$

$$A_{\max} = 10^{I \cdot \lg 2 - 2.1155} \tag{21}$$

where t is the residual service life of the existing structure; P_m is the exceedance probabilities of different seismic design intensities within 50 years, and m can be taken as 1, 2, 3, $P_1 = 0.632$, $P_2 = 0.1$, $P_3 = 0.02$ corresponding to minor, design-based and rare earthquakes respectively; I_0 is the basic seismic design intensity corresponding to an exceedance probability of 10 % in 50 years; h is the hazard characteristic parameter in the probability distribution function of type III of intensity extreme value, which can be taken according to the recommendations in the relevant national standards. For example, in the China standard of CECS 160–2004 [62], h can be taken as 6, 10 and 20 in Zone I, Zone II and Zone III with different seismic hazards, respectively. Among, Zone I belongs to high seismic intensity area, Zone II belongs to middle seismic intensity area and Zone III belongs to low seismic intensity area.

According to Eq. (19) to Eq. (21), the ground motion parameters D and M corresponding to the design-based earthquake and the rare earthquake of the existing structure under the condition of considering the residual service life can be determined. On this basis, the uniform risk spectrum for the existing structure under the condition of considering the residual service life can be further determined. The specific determination process is shown in Fig. 6. Under the condition that the residual service life of the existing structure is not considered, the ground motion parameters D and M of the existing structure can be determined directly according to the recommendations in national standards such as GB50011-2010 [61].

Meanwhile, the seismic performance of RC structures in service gradually decreases with the increase of service time. This

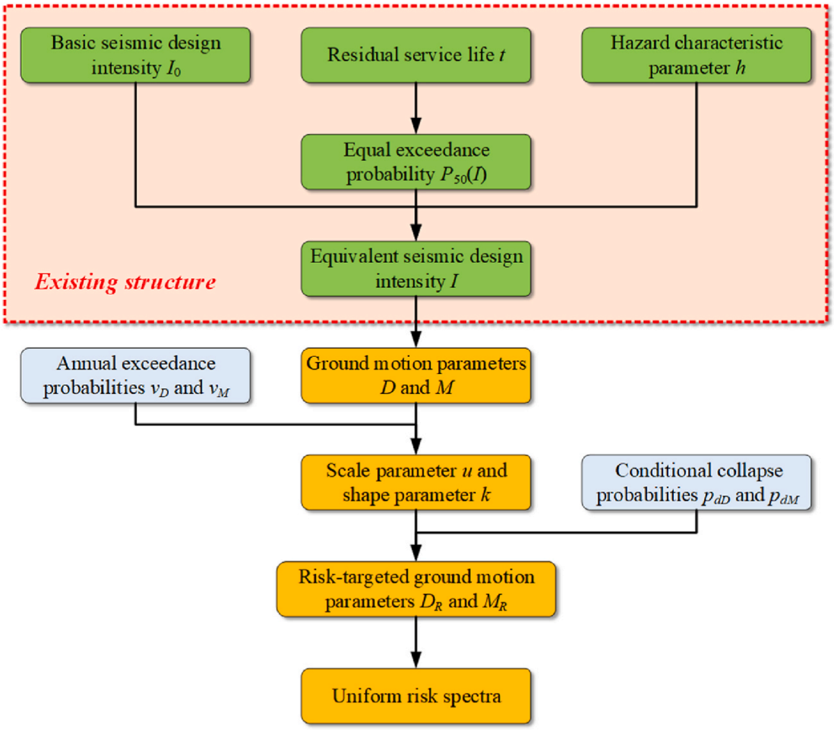


Fig. 6. The determination process of uniform risk spectrum.

reduction in seismic performance is mainly manifested in the form of carbonation of concrete and corrosion of steel bars. In related studies, the refined time-varying models have been developed to predict the concrete strength and the corrosion depth of the steel bar. The related calculation models are shown in Eq. (22) and Eq. (23). Therefore, in the finite element analysis, the influence of the service time on the seismic performance of the existing RC structures can be displayed by adjusting the strength of the concrete and the sectional area of the steel bar. The relevant series formula is as follows

$$\mu_f(t) = 1.4529e^{-0.0246(\ln t - 1.7154)^2} f_{cu} \tag{22}$$

$$\delta(t) = 46k_{cr}k_{ce}e^{0.04H}(RH - 0.45)^{\frac{2}{3}}c^{-1.36}{f_{cu}}^{-1.83}(t - t_i) \tag{23}$$

where μ_f(t) is the time-varying strength of concrete; t is the time of the structure has been in service (unit: year); f_{cu} is the compressive strength of concrete; $\delta(t)$ is the corrosion depth of the steel bar; k_{cr} is the correction factor of the corrosion location of the steel bar; k_{ce} is the environmental correction factor; c is the protective layer thickness; t_i is the time when the steel bar begins to corrosion (unit: year); H is the annual average temperature of the environment; RH is the annual average humidity of the environment.

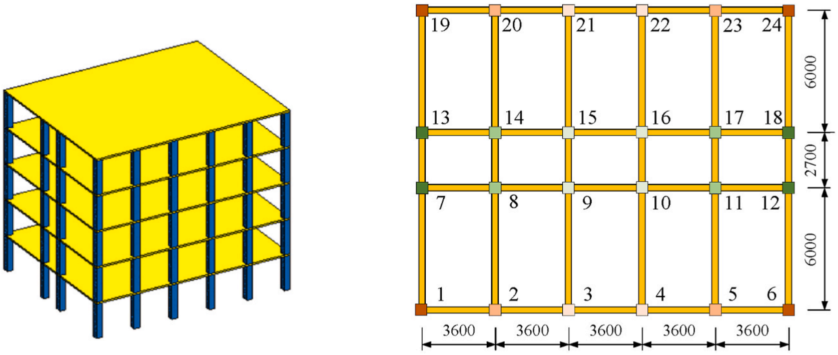
In the seismic design of building structures, studies on seismic fragility analysis to verify the seismic collapse risk of intact structures by selecting ground motion records based on uniform risk spectra have been reported [63]. However, the seismic fragility analysis of seismic-damaged structures and repaired seismic-damaged structures considering uniform collapse risk is relatively scarce, and the determination of risk-targeted ground motion parameters considering the residual service life of structures and related seismic fragility analysis are more rare. To analyze the repair effect of seismic-damaged structures and their collapse risk, suitable seismic records can be selected for seismic fragility analysis based on the residual service life, site conditions and the corresponding uniform risk spectrum.

For a period of time after the earthquake disaster (i.e., within the time range of possible aftershock effects), seismic-damaged structures and seismic-damaged structures after imperfect repair are different from intact structures in terms of seismic performance and seismic requirements. Furthermore, a large number of measured main-aftershock data show that the magnitude and PGA of aftershocks are usually smaller than the magnitude and PGA of the main shock in a complete main-aftershock sequence. In relevant studies, it is concluded that the PGA of aftershocks is usually 0.5297~0.5888 times that of the main shocks [64]. Therefore, it is unreasonable and difficult to require that the conditional collapse probability of seismic-damaged structures and seismic-damaged structures after imperfect repair is the same as that of intact structures. Considering the actual seismic performance of seismic-damaged structures and seismic-damaged structures after imperfect repair, it is necessary to adjust the seismic performance requirements according to the relationship between the main and aftershocks.

In view of this, this study suggests that the repair of seismic-damaged structures can be divided into two stages: imperfect repair and full repair. The first repair stage (i.e., imperfect repair) aims to rapidly improve the seismic performance of seismic-damaged structures in a short repair time, so as to avoid damage aggravation of seismic-damaged structures under aftershocks. Because the seismic performance of seismic-damaged structures is not restored to an intact state and the magnitude of the aftershock is usually smaller than that of the main shock, a greater conditional collapse probability can be used. The second stage is the full repair of seismic-damaged structures. This stage aims to sufficiently repair the seismic-damaged structures in a long time after the aftershock, so that the seismic performance and use function of the seismic-damaged structure can be restored to an intact state. Only when seismic-damaged structures have been fully repaired, the conditional collapse probability of intact structures can be used strictly. Therefore, the requirements for conditional collapse probability of seismic-damaged structures and imperfectly repaired seismic-damaged structures should be appropriately lower. In this study, it is suggested that the conditional collapse probability p_{dDa} and p_{dMa} for the design-based earthquake and the rare earthquake of seismic-damaged structures and imperfectly repaired seismic-damaged structures can be taken as

$$p_{dDa} = \gamma_a p_{dD} \tag{24}$$

$$p_{dMa} = \gamma_a p_{dM} \tag{25}$$



(a) Three-dimensional view (b) Structural plan

Fig. 7. Three-dimensional and structural plan of the 5-story RC structure.

where γ_a is the conditional collapse probability adjustment coefficient of seismic-damaged structures and imperfectly repaired seismic-damaged structures. According to the statistical relationship between the main and aftershocks, this study suggested to take γ_a as 2.5.

If the conditional collapse probability of seismic-damaged structures and imperfectly repaired seismic-damaged structures meet the requirements of p_{dDa} and p_{dMa}, it can be considered that seismic-damaged structures have sufficient seismic capacity to withstand aftershocks and prevent collapse.

5. Example analysis

To verify the effectiveness of the optimal imperfect repair strategy and the optimal repair sequence determination method proposed in this study, a 5-story RC frame structure in service is taken as an example for analysis. Furthermore, the seismic fragility of the 5-story seismic-damaged structure after imperfect repair is calculated based on uniform risk spectrum.

The three-dimensional view and structural plan of the 5-story RC frame structure are shown in Fig. 7. For the purpose of calculation and analysis, the number of frames of the structure is 5. The height of the bottom story of the structure is 3300 mm, and the height of the other stories of the structure is 3000 mm. The sectional dimension of the beam members is 250 mm × 500 mm, and the sectional dimension of the column members is 500 mm × 500 mm. The mechanical longitudinal reinforcement ratio of the beam members is 1.63 %, and the mechanical longitudinal reinforcement ratio of the column members is 1.22 %. The compressive strength of concrete is 26.8 MPa, and the tensile strength of steel bar is 360 MPa. The site of the structure is class II category, the design ground motion is grouped as Group II, and the basic seismic design intensity is 7-degree. It is assumed that the residual service life of the structure is 40 years.

The finite element model of the 5-story RC frame structure is established in OpenSEES. Among, the beam and column members simulated with fiber elements, the Concrete02 model is selected as the constitutive model of the confined (core) concrete, the Concrete01 model is selected as the constitutive model of the unconfined (cover) concrete, and the Steel01 model is selected as the constitutive model of the steel bar.

According to the suggestion of Wang et al. [37], the target collapse risk v_{ft} of the structure in 50 years is taken as 1.0 %, the conditional collapse probability p_{dD} of the design-based earthquake is taken as 0.2 %, the conditional collapse probability p_{dM} of the rare earthquake is taken as 10 %, and the logarithmic standard deviation β of the seismic fragility of the structure is set as 0.6. Combined with the site condition and the residual service life of the structure, the uniform risk spectrum of the rare earthquake as shown in Fig. 8 is calculated according to the determination process shown in Fig. 6. According to the uniform risk spectrum of the rare earthquake, 16 groups of seismic waves are selected from the PEER database for incremental dynamic analysis (IDA). In the selection process, the average spectrum was set within the target spectrum range of 0.8~1.2 times, and the errors of the period point spectra values were controlled within ±15 %. The specific information of the selected seismic waves is shown in Table 2, and the comparison between the seismic wave response spectrum and the uniform risk spectrum of the rare earthquake is shown in Fig. 8. In addition, the conditional collapse probabilities p_{dDa} and p_{dMa} of seismic-damaged structure and imperfectly repaired seismic-damaged structure under the design-based earthquake and the rare earthquakes were calculated from Eq. (24) and Eq. (25) as 0.5 % and 25 %, respectively.

In this study, multi-dimensional earthquake waves are used to simulate the damage of the 5-story RC structure under an earthquake. Compared with beam members and non-structural members, the damage of column members has a more serious influence on the overall seismic performance of the structure. Therefore, under the premise of limited available repair time and repair cost, in order to maximize the seismic performance of the structure and improve the efficiency of formulating the optimal imperfect repair strategy, only the repair of column members is considered in this study. Firstly, the El-Centro wave (Number: RSN6) with PGA of 0.3 g was input into the finite element model of the 5-story RC structure for dynamic time history analysis, so that the intact structure can become a

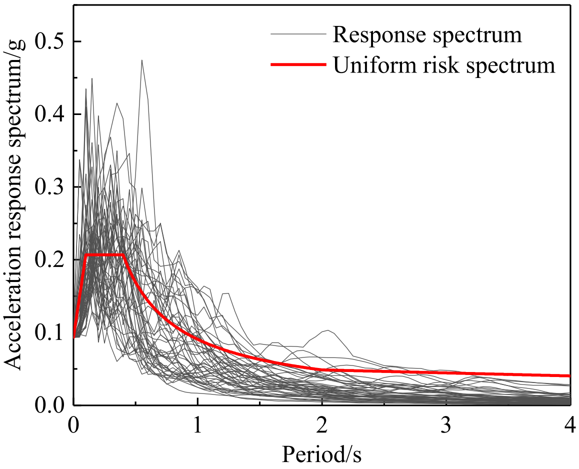


Fig. 8. Comparison of ground motion response spectra.

Table 2
Information of seismic waves.

Number	Seismic wave	Observation station	Magnitude	Year	Number	Seismic wave	Observation station	Magnitude	Year
RSN1	Helena_ Montana-01	Carroll College	6.0	1935	RSN5	Northwest Calif-01	Ferndale City Hall	5.5	1938
RSN6	Imperial Valley-02	El Centro Array #9	6.95	1940	RSN7	Northwest Calif-02	Ferndale City Hall	6.4	1941
RSN11	Northwest Calif-03	Ferndale City Hall	5.8	1951	RSN15	Kern County	Taft Lincoln School	7.36	1952
RSN30	Parkfield	Cholame - Shandon Array #5	6.19	1966	RSN33	Parkfield	Temblor pre-1969	6.19	1966
RSN34	Northern Calif-05	Ferndale City Hall	5.6	1967	RSN50	Lytle Creek	Wrightwood - 6074 Park Dr	5.33	1970
RSN57	San Fernando	Castaic - Old Ridge Route	6.61	1971	RSN79	San Fernando	Pasadena - CIT Athenaeum	6.61	1971
RSN81	San Fernando	Pearblossom Pump	6.61	1971	RSN88	San Fernando	Santa Felita Dam (Outlet)	6.61	1971
RSN95	Managua_ Nicaragua-01	Managua_ ESSO	6.24	1972	RSN97	Point Mugu	Port Hueneme	5.65	1973

seismic-damaged structure. Subsequently, the maximum drift ratio and residual drift ratio of each column member in the seismic-damaged structure are extracted, and the damage of column members is quantified according to Table 3. In actual engineering, two deformation-related damage indexes, maximum drift ratio and residual drift ratio, can be measured by displacement sensors, acceleration sensors, GPS (Global Positioning System) technology, and computer vision based methods.

In Table 3, the limits corresponding to different damage states are determined according to statistical analysis and the recommendation in Ref. [61]. Considering that the column members can be damaged in both principal axis directions, the damage average value of the column members in both directions is used in this study to comprehensively quantify the damage of the column members. The damage quantification results of column members are shown in Fig. 9.

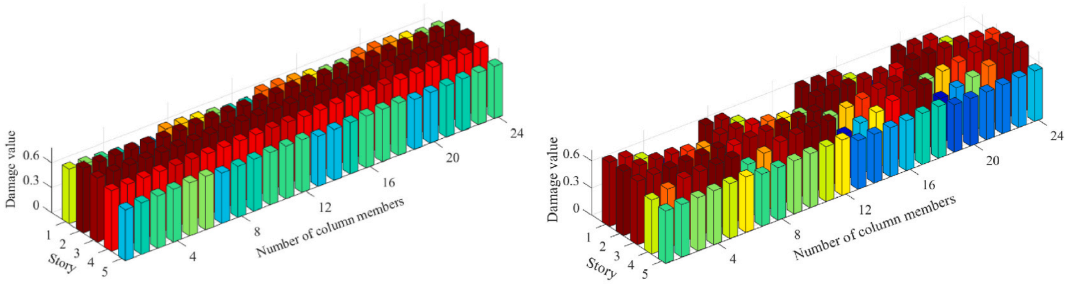
According to the symmetry of the plan layout of column members, the column members of each story are divided into 6 types (including 1 type of corner column, 3 types of exterior columns and 2 types of interior columns). Referring to the suggestion of Du et al. [55] to assign weight coefficients to corner, exterior and interior columns, the ratio of weight coefficients of corner, exterior and interior columns is taken as 3:2:1 in this study. It is assumed that when the column member is in the state of minor damage, moderate damage and severe damage, the repair methods of the epoxy resin grouting method, the micro expansion cement grouting method and the replacement concrete method can be used respectively, and the corresponding repair costs are 100 $/m^2, 300 $/m^2 and 500 $/m^2 respectively. Considering the influence of section width b and plastic hinge length l_p of column members, the repair costs under different damage state limits are $C_{m1} = 100 \times b \times 1.5l_p \times 2 = 60$ \$, $C_{m2} = 300 \times b \times 1.5l_p \times 2 = 180$ \$ and $C_{m3} = 500 \times b \times 1.5l_p \times 2 = 300$ \$ respectively, and the corresponding repair time of one worker are $T_{r1} = 0.62$ d, $T_{r2} = 0.94$ d and $T_{r3} = 2.78$ d respectively. Assumed that the payroll of workers is 20 $/d, the mechanical cost is 1500 $/d, and the number of workers in the repair process is 20. It is required that the performance loss L_i of each story of the seismic-damaged structure after repair is less than 0.2, the available repair cost C_k is 32000 $, and repair time T_k is 3.5 d.

According to the damage quantitative results of members based on the maximum drift ratio and residual drift ratio, the seismic performance loss of each story of the seismic-damaged structure can be calculated by Eq. (3), and the results are shown in Fig. 10. The overall seismic performance loss L of the seismic-damaged structure can be calculated according to Eq. (4). Among, the overall seismic performance loss L based on the maximum drift ratio is 0.7193, and the overall seismic performance loss L based on the residual drift ratio is 0.6332.

On this basis, the optimal imperfect repair strategy for the seismic damage structure is determined according to the method proposed in this study. Firstly, listed all possible repair strategies for each story, and selected the story repair strategies that meet the requirements of story seismic performance loss. Secondly, the repair strategies of each story were clustered according to the Euclidean distance calculation method, and the typical clustering analysis results are shown in Fig. 11. Finally, the optimal imperfect repair strategy for the seismic-damaged structure satisfying the constraints of available repair time and repair cost is obtained by the exhaustive method. The optimal imperfect repair strategies based on maximum drift ratio and residual drift ratio are shown in Fig. 12. When the seismic-damaged structure is repaired under the guidance of the optimal imperfect repair strategy based on the maximum drift ratio, the overall seismic performance loss L of the seismic-damaged structure after repair is 0.1636, the used repair time T_z is 3.3920 d, and the used repair cost C_z is 31909 $. When the seismic-damaged structure is repaired under the guidance of the optimal imperfect repair strategy based on the residual drift ratio, the overall seismic performance loss L of the seismic-damaged structure after

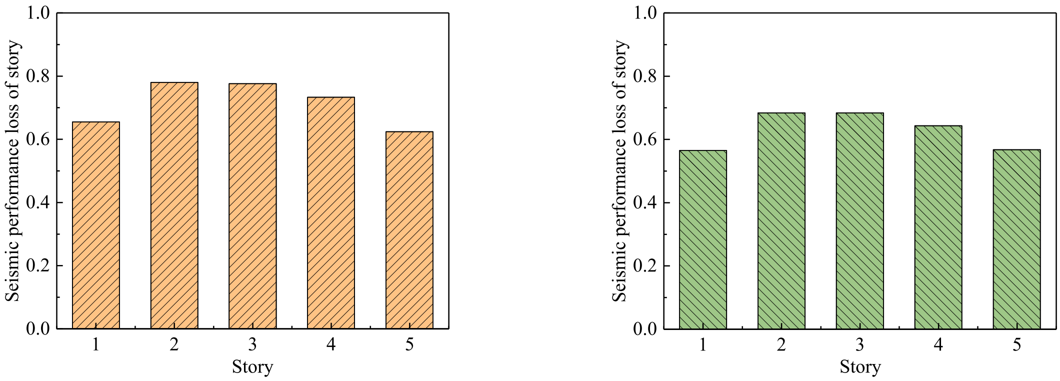
Table 3
The limits corresponding to different damage states.

Damage state	Basic intact	Minor damage	Moderate damage	Severe damage	collapse
Damage value	0~0.1	0.1~0.3	0.3~0.7	0.7~1.0	1.0
Maximum drift ratio	<1/550	1/550~1/275	1/275~2/275	2/275~1/50	>1/50
Residual drift ratio	$<8\times10^{-6}$	8×10^{-6}~2×10^{-5}	2×10^{-5}~1×10^{-4}	1×10^{-4}~8×10^{-4}	$>8\times10^{-4}$



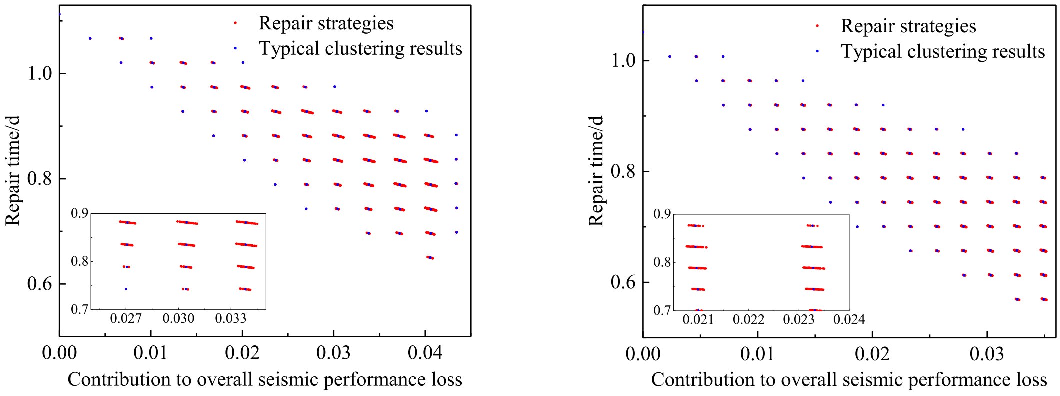
(a) Maximum drift ratio (b) Residual drift ratio

Fig. 9. Damage quantification results of column members.



(a) Based on the maximum drift ratio (b) Based on the residual drift ratio

Fig. 10. Seismic performance loss of each story.

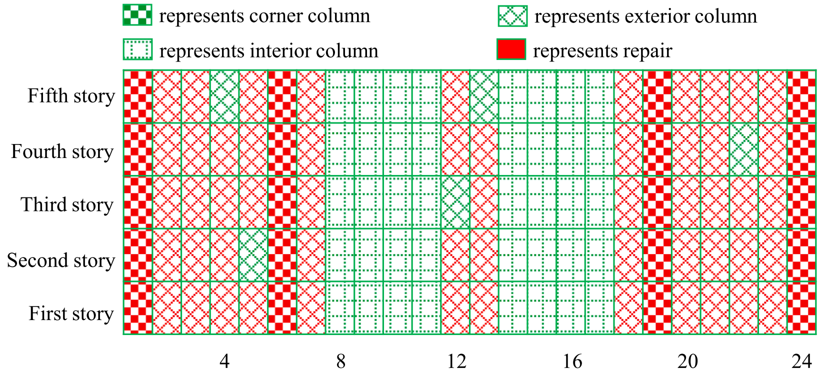


(a) Second story (b) Fifth story

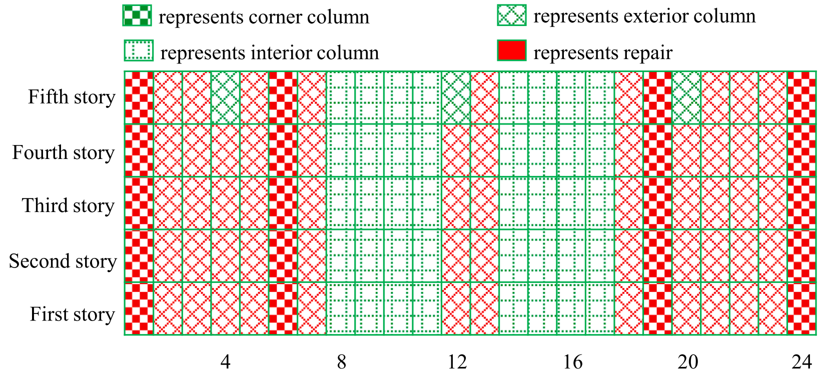
Fig. 11. Clustering analysis results of story repair strategies based on residual drift ratio.

repair is 0.1306, the used repair time T_z is 3.4674 d, and the used repair cost C_z is 31541 $.

It is assumed that the performance of damaged members can be restored to the intact state after repair. To verify the repair effect of the optimal imperfect repair strategy, the repair of damaged column members in the seismic-damaged structure is simulated in OpenSEES by the command of birth-death element. According to the command of birth-death element, the repair of damaged members can be achieved by deleting damaged member elements and creating new relevant member elements on the basis of original nodes in OpenSEES. To further emphasize the repair effect, the sectional dimensions of the new column members were designed to be 550 mm × 550 mm. Subsequently, the El-Centro wave with PGA of 0.3 g was put into the repaired seismic-damaged structure for dynamic time history analysis. The top displacement response of the repaired seismic-damaged structure is shown in Fig. 13. In addition, the top displacement responses for the two conditions are additionally supplemented in Fig. 13. The two conditions are the seismic-damaged structure with no repair and the seismic-damaged structure is repaired according to the general imperfect repair strategy based on



(a) Maximum drift ratio



(b) Residual drift ratio

Fig. 12. Optimal imperfect maintenance strategy for seismic-damaged structure.

residual drift ratio. The general imperfect repair strategy is the repair strategy obtained according to the exhaustive method that meets the constraint conditions, except the optimal imperfect repair strategy. In this study, only one of the many general imperfect repair strategies is selected as a typical representative to be analyzed.

In Fig. 13, the top displacement response of the seismic-damaged structure has a similar behavior under different conditions of no repair and imperfect repair. This is mainly because only some members are selected for repair in the imperfect repair strategy and the damping ratio of the structure is a specific value, resulting in insignificant changes in the stiffness of the seismic-damaged structure. However, it can be observed from Fig. 13 that the repair can effectively reduce the response of the seismic-damaged structure when it encounters an earthquake. Among, by comparing the top displacement responses of the seismic-damaged structure repaired according to two optimal imperfect repair strategies (i.e., optimal imperfect repair strategy I and optimal imperfect repair strategy II) based on the maximum drift ratio and the residual drift ratio, it is clear that the top displacement responses are basically the same. It indicates that the optimal imperfect repair strategy I and the optimal imperfect repair strategy II have the same repair effect. The maximum top displacement of the seismic-damaged structure without repair is 155.85 mm, while the maximum top displacement of the seismic-damaged structure repaired by the general imperfect repair strategy, optimal imperfect repair strategy I, and optimal imperfect repair strategy II is 145.34 mm, 140.09 mm, and 139.97 mm, respectively. Therefore, guiding the repair of the seismic-damaged

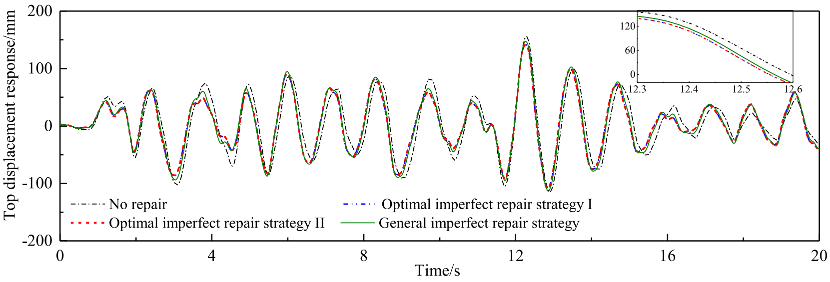


Fig. 13. Comparison of top displacement response.

structure according to the optimal imperfect repair strategy can reduce the maximum top displacement response of the seismic-damaged structure by 10.23 %. This proves the accuracy and effectiveness of the optimal imperfect repair strategy proposed in this study.

In earthquake disasters, if sensors are not arranged in the structure in advance, it is difficult to obtain response information such as the maximum drift ratio of the structure, and only limited information such as the residual drift ratio can be obtained. Therefore, it is more appropriate to evaluate the damage and formulate the repair strategy according to the residual drift ratio for the actual seismic-damaged structure.

From the overall seismic performance loss of the imperfectly repaired seismic-damaged structure and the top displacement response when encountering an earthquake, it is clear that the repair according to the optimal imperfect repair strategy based on the residual drift ratio has a better repair effect. Therefore, on the basis of the optimal imperfect repair strategy based on the residual drift ratio (i.e., optimal imperfect repair strategy II), the optimal repair sequence of the seismic-damaged structure is further determined according to the method proposed in this study.

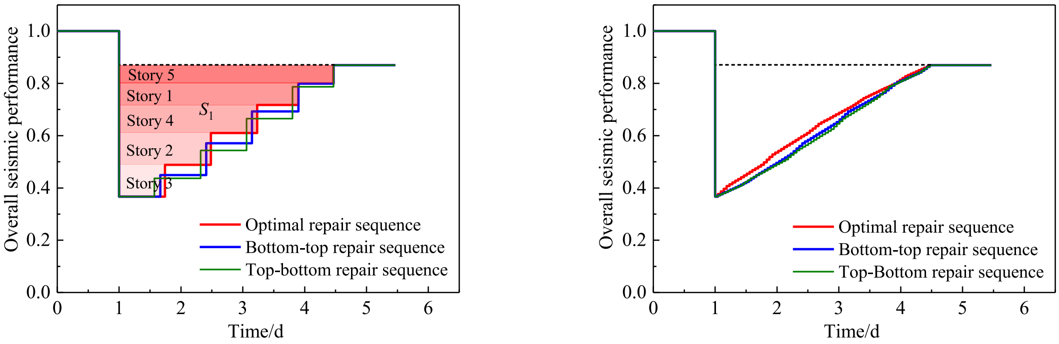
Combined with the optimal repair sequence determination method proposed in this study, the optimal repair sequence of stories was first determined according to the optimal imperfect repair strategy based on the residual drift ratio. The result is shown in Fig. 14 (a), and the optimal repair sequence of stories is: story 3, story 2, story 4, story 1, and story 5. Compared with bottom-top repair and top-bottom repair, the envelope area S_1 of the performance improvement gradient curve for the optimal repair sequence of stories is the smallest. On this basis, the best repair sequence of column members is further determined, and the results are shown in Fig. 15. Under the optimal repair sequence of column members, the improvement process of the overall seismic performance is shown in Fig. 14(b). From the calculation results of the envelope area, when the column members are repaired according to the optimal repair sequence, $S_1 = 0.8097$; When the column members are repaired according to the bottom-top sequence, $S_1 = 0.8883$; When the column members are repaired according to the top-bottom sequence, $S_1 = 0.9072$. Compared with the top-down repair sequence, the optimal repair sequence can increase the seismic resilience of the structure by 10.75 %. This proves the reasonableness and effectiveness of the optimal repair sequence determination method proposed in this study. In addition, comparing the overall seismic performance at different moments in the repair process, it can be seen that the seismic performance of the seismic-damaged structure can be improved fastest in the repair process guided by the optimal repair sequence.

According to Figs. 9 and 12, it is appropriate to combine the damage degree and weight coefficient of the members to determine the members to be repaired in each story when formulating the optimal imperfect repair strategy. From the results in Figs. 12 and 15, it can be seen that when determining the repair sequence of stories, the story with the most serious damage should be selected first for repair. In determining the repair sequence of damaged members of each story, it is advisable to repair damaged members in the sequence of corner column, exterior column and interior column.

To further analyze the effect of optimal imperfect repair strategy on the seismic performance of the seismic-damaged structure, the seismic fragility of the seismic-damaged structure was analyzed in combination with the seismic waves selected according to the uniform risk spectrum of rare earthquakes. In the analysis process of seismic fragility, four working conditions (i.e., four structural models) are considered: (1) the intact structure; (2) the seismic-damaged structure with no repair; (3) The seismic-damaged structure is repaired according to the general imperfect repair strategy based on residual drift ratio; (4) The seismic-damaged structure is repaired according to the optimal imperfect repair strategy based on residual drift ratio.

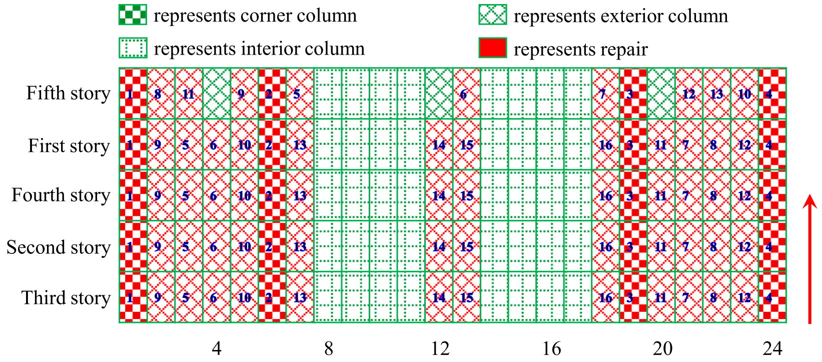
Input the selected 16 groups of seismic waves into the four structural models for IDA analysis. During IDA analysis, the amplitude modulation range of PGA is 0.1 g–1.0 g, and the PGA increment is 0.1 g. When each dynamic time history analysis is completed, the overall damage value of the structure is calculated according to EPEDR model, and this damage value is taken as the overall seismic performance index of the structure. In the four structural models, the change of the overall damage value of the structure with PGA is shown in Fig. 16. Then, the exceedance probabilities of different damage states for four structural models under different PGAs are calculated, and the corresponding seismic fragility curves are obtained. The seismic fragility curves of the four structural models under different damage states are shown in Fig. 17.

Compare the damage values of the seismic-damaged structure under the three conditions of no repair, repair by general imperfect



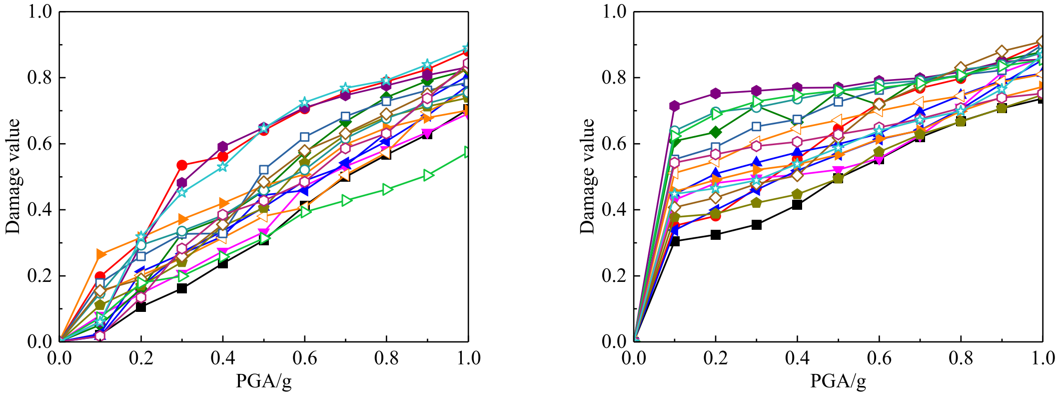
(a) Stories (b) Members

Fig. 14. Repair sequence of the seismic-damaged structure.



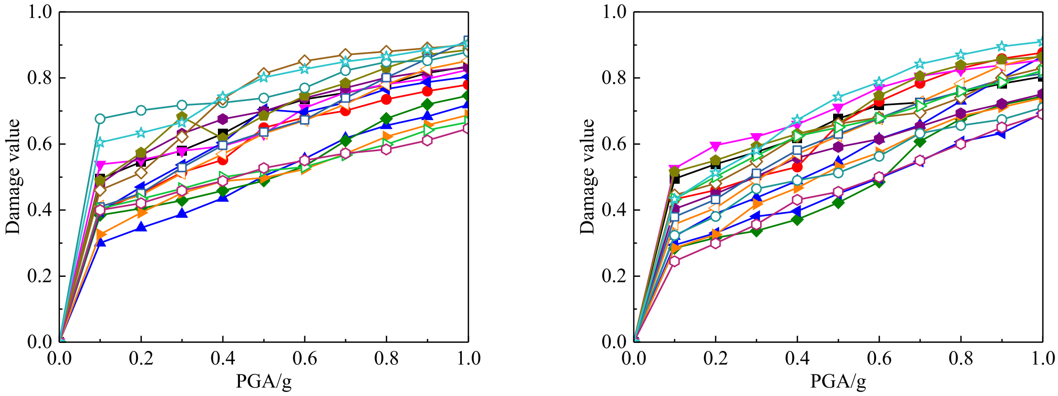
Note: The number in the square represents the repair sequence of members

Fig. 15. Optimal repair sequence of members.



(a) Intact structure

(b) No repair



(c) General imperfect repair strategy

(d) Optimal imperfect repair strategy

Fig. 16. Damage value changes with PGA.

repair strategy and repair by optimal imperfect repair strategy, it can be seen that the repair of the seismic-damaged structure can effectively improve the seismic performance, and thus reduce the damage degree of the seismic-damaged structure when it is exposed to an earthquake. Under the two conditions of repair by general imperfect repair strategy and repair by optimal imperfect repair strategy, the repair according to the optimal imperfect repair strategy can restore the structural seismic performance more effectively and make the seismic-damaged structure with better ability to resist aftershocks. This conclusion can be proved by the structural seismic fragility curve shown in Fig. 17.

Compare the exceedance probability of collapse under four conditions (i.e., four structural models), and the results are shown in Fig. 17(d). From Fig. 17(d), it can be seen that the repair can effectively reduce the collapse risk of the seismic-damaged structure. However, with the increase of PGA, the exceedance probability of collapse of the seismic-damaged structure under three conditions (no

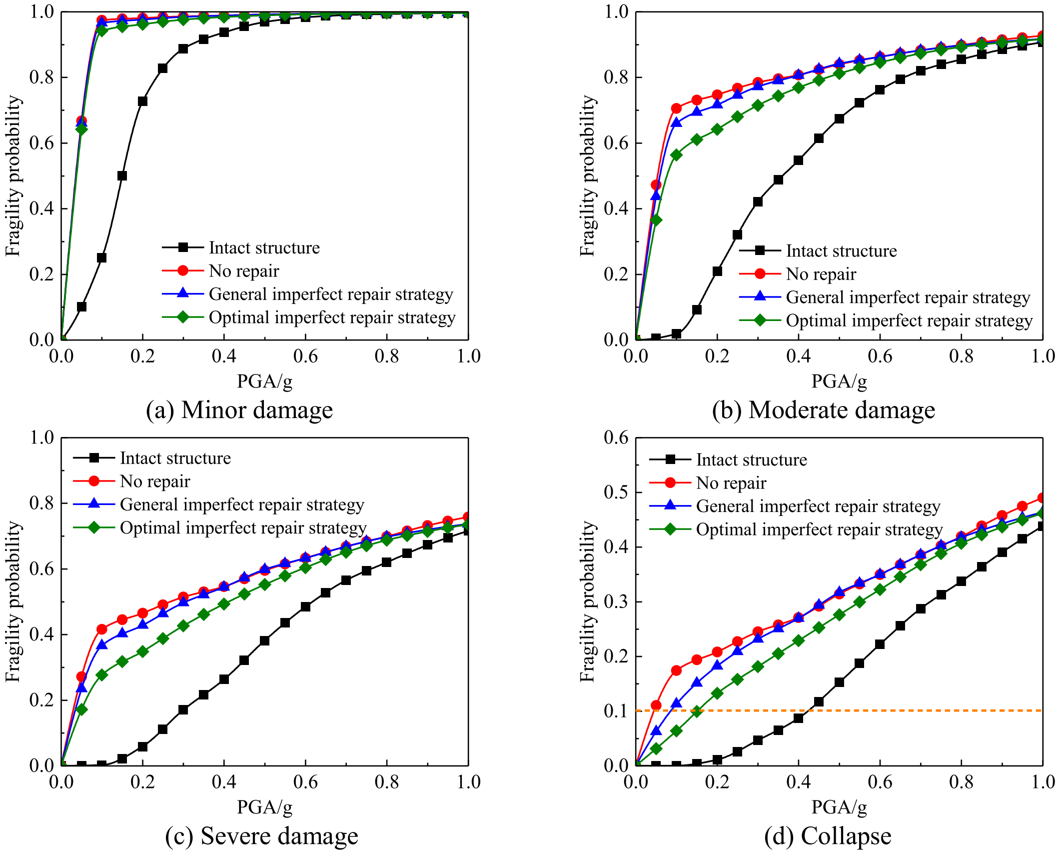


Fig. 17. The comparison of seismic fragility curves.

repair, repair by general imperfect repair strategy and repair by optimal imperfect repair strategy) is gradually approaching, and is generally greater than the exceedance probability of collapse of the intact structure. This phenomenon is due to the fact that the seismic-damaged structure does not restore the full seismic performance after imperfect repair, and some or even most members are still in a damaged state. Under an earthquake with a low PGA, the seismic performance improvement effect of the seismic-damaged structure after the imperfect repair is obvious. Under an earthquake with a high PGA, the collapse risk of the seismic-damaged structure with imperfect repair can gradually approach to those without repair. Generally, the PGA of aftershocks is low, so the imperfect repair of the seismic-damaged structure can effectively improve the ability of the seismic-damaged structure to withstand aftershocks.

According to the uniform risk spectrum and the characteristic period of the 5-story structure, it is known that the spectral acceleration of the structure under the rare earthquake is 0.14 g. It can be seen from Fig. 17(d) that under the conditions of available repair time and repair cost limited in this study, the repair of the seismic-damaged structure according to the optimal imperfect repair strategy can ensure that the conditional collapse probability under the rare earthquake is less than p_{dM}. However, it is difficult to guarantee that the conditional collapse probability of the seismic-damaged structure under the rare earthquake can meet the requirement of p_{dM} under two conditions of no repair and repair according to the general imperfect repair strategy. When using the conditional collapse probability p_{dMa} recommended by Eq. (25) for verification, it is further ensured that the collapse risk of the seismic-damaged structure after the optimal imperfect repair is meet the requirement. In addition, according to the relationship of PGA between the main and aftershocks [64], the PGA of the aftershock is about 0.16~0.18 g under the condition that the PGA of the main shock is 0.3 g. Under this condition, the conditional collapse probability of the seismic-damaged structure after repair by the optimal imperfect strategy still meets the requirements of p_{dM} and p_{dMa}.

Through the above analysis, the feasibility and effectiveness of the optimal imperfect repair strategy determination method and the optimal repair sequence determination method proposed in this study are proved. Under the condition that the available repair cost and repair time are limited, it is appropriate to determine the optimal repair strategy and optimal repair sequence for the seismic-damaged structures based on the proposed method, so as to effectively improve the seismic performance of the seismic-damaged structures in a short time and make the seismic-damaged structures have a good ability to resist aftershocks.

6. Conclusions

The repair strategy formulated through the damage assessment results of seismic-damaged structures can effectively improve the seismic performance. In this study, the application scope and application condition of different damage indexes or models are compared, the methods for determining the optimal imperfect repair strategy and the optimal repair sequence for seismic-damaged structures under the condition of limited available repair resources is proposed, and a seismic fragility analysis method considering the uniform risk and the residual service life of structures is introduced. Taking a 5-story RC frame structure with a residual service life of 40 years as an example for analysis, the main conclusions obtained from this study are as follows:

(1) Some classical damage indexes or models are difficult to assess the damage of members or structures under the actual service environment. In the circumstance without pre-installed sensors, the damage of members or structures could only be assessed according to residual displacement (residual drift ratio) or crack characteristics.
(2) Guiding the repair of the seismic-damaged structure by the optimal imperfect repair strategy can significantly reduce the maximum top displacement response. It proved that the optimal imperfect repair strategy determined according to the method proposed in this study can most effectively improve the seismic performance of seismic-damaged structures under the condition of limited available repair time and repair cost.
(3) On the basis of the optimal imperfect repair strategy, the optimal repair sequence determination method considering seismic resilience can ensure the seismic performance of seismic-damaged structures improved most rapidly during the emergency repair process. Compared with other repair sequences, the determined optimal repair sequence can make seismic-damaged structures have excellent seismic resilience.
(4) The results of structural seismic fragility analysis considering the uniform collapse risk and the residual service life proved that the collapse risk of seismic-damaged structures can be effectively reduced through repairing seismic-damaged structures according to the optimal imperfect repair strategy.

CRediT authorship contribution statement

Shitao Cheng: Writing – review & editing, Writing – original draft, Methodology. **Haoxiang He:** Writing – review & editing, Resources, Formal analysis. **Haoding Sun:** Writing – review & editing, Software. **Yang Cheng:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was partially supported by National Natural Science Foundation of China [Grant No. 52378469] and National Key R&D Program of China [Grant No. 2017YFC1500604, 2017YFC1500603].

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