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A dual-parameter method for seismic resilience assessment of buildings

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Abstract: To quantify the seismic resilience of buildings, a method for evaluating functional loss from the component level to the overall building is proposed, and the dual-parameter seismic resilience assessment method based on post-earthquake loss and recovery time is improved. A three-level function tree model is established, which can consider the dynamic changes in weight coefficients of different category of components relative to their functional losses. Bayesian networks are utilized to quantify the impact of weather conditions, construction technology levels, and worker skill levels on component repair time. A method for determining the real-time functional recovery curve of buildings based on the component repair process is proposed. Taking a three-story teaching building as an example, the seismic resilience indices under basic earthquakes and rare earthquakes are calculated. The results show that the seismic resilience grade of the teaching building is comprehensively judged as Grade Ⅲ, and its resilience grade is more significantly affected by postearthquake loss. The proposed method can be used to predict the seismic resilience of buildings prior to earthquakes, identify weak components within buildings, and provide guidance for taking measures to enhance the seismic resilience of buildings.

Key words: seismic resilience assessment; dual-parameter method; functional loss; recovery time; Bayesian networks

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Seismic resilience is a crucial performance metric under extreme events and has gained widespread attention in civil engineering, particularly in buildings[1-2], building portfolios[3-4], and infrastructure[5-6]. Bruneau et al.[7] introduced the concept of seismic resilience, defining it as the capacity of an engineering system to mitigate losses during disasters and achieve rapid recovery. Thereafter, Cimellaro et al.[8] employed the functional curve with time integration as a seismic resilience index, which has been widely used[9]. However, this approach treats the functional loss and the recovery time as equal weights, which overlooks the relative importance of these two aspects and fails to capture the government seismic resilience requirements for the target systems. To better align with the disaster prevention principle of prioritizing predisaster prevention over postdisaster assistance, Zhai et al.[10] proposed a dual-parameter seismic resilience assessment method. This method considers postearthquake loss and recovery time, with a particular emphasis on controlling postearthquake loss relative to recovery time. However, Zhai et al.[10] only applied this method to engineering systems and did not extend it to individual buildings. RISN-TG041—2022[11] adopts the dual-parameter method to assess the seismic resilience of individual buildings but does not consider functional loss, which is also quite important. Functional loss refers to damage to internal components or external infrastructure, resulting in the complete or partially lost functionality of buildings.

Qualifying postearthquake loss and recovery time is the basic content of seismic resilience assessment. Indicators such as economic loss ratio, the number of casualties, and asset value provide insights into building losses from a social or economic perspective[12]. From an engineering perspective, the postearthquake functional loss of a building is often evaluated using fault tree[13-15] or functionality-weighted average methods[16-18]. The fault tree method, widely used for system performance evaluation, describes the composition of a complex system and clarifies the causal relationships between the system and its components. However, evaluating functional loss with the fault tree method typically necessitates the definition of additional functional indicators, such as the ratio of successful paths to total possible paths in hospitals[14] and the percent of building area with compromised functionality[15]. The functionality-weighted average method, while not requiring another functional indicator, fails to explain the causal relationships between the functional loss of a system and its components.

The repair sequences of damaged building components follow a strong logical relationship, unlike power and

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water networks, which determine the repair sequences through network analysis and optimization algorithms[5]. During building component repairs, factors such as the external environment, equipment efficiency, and worker proficiency can either delay or expedite the repair duration. Previous studies[19-23] proposed feasible repair sequences for intra-story components and considered various repair sequences and component importance coefficients, but they did not explicitly account for the impact of these uncertain factors on the repair time.

To alleviate the issues discussed above, the dual-parameter seismic resilience assessment method is extended by introducing functional loss. A component-to-building functional loss evaluation method is proposed. This method integrates the advantages of the fault tree and functionality-weighted average methods. Specifically, fault tree modeling is used for systems with functional causality, while the functionality-weighted averaged method is applied to mutually independent systems. Bayesian networks are employed to analyze the effect of uncertain factors on component repair time, and a more generalized inter-story repair scheme is proposed.

1 Seismic Resilience Assessment Method

The dual-parameter method focuses on two key parameters: postearthquake loss and recovery time. It determines the seismic resilience grade of buildings by calculating the resilience indices based on both parameters. The process for seismic resilience assessment of buildings follows the steps outlined below:

(1) Gather comprehensive information on the building to be assessed, encompassing the area of each story, room functions, occupant distribution, as well as the types, quantities, materials, and geometric dimensions of structural and nonstructural components.

(2) Develop a structural model of the building and perform elastoplastic time-history analyses under predefined earthquake intensity levels. Extract the resulting engineering demand parameters (EDPs).

(3) Expand the EDPs and conduct seismic fragility analysis combined with Monte Carlo simulation to ascertain the damage states of each component across various simulation scenarios.

(4) Calculate postearthquake loss (i. e., functional loss, repair cost ratio, and casualty ratio) and recovery time for each simulation based on the damage states of components. Aggregate these results to determine the average postearthquake loss and average recovery time across multiple simulations.

(5) Derive the seismic resilience indices of the building based on postearthquake loss and recovery time and comprehensively assess its seismic resilience grade under different predefined earthquake intensity levels. The final resilience grade is the lowest grade calculated across different earthquake intensity levels.

The resilience index based on postearthquake loss is defined as the ratio of the actual postearthquake loss to its acceptable limit, which can be calculated as follows:

$$R_{\mathrm{F}} = \frac{F_{\mathrm{C}}}{F_{\mathrm{A}}} \tag{1}$$

where R_{F} is the resilience index based on postearthquake loss; F_{C} is the actual postearthquake loss; F_{A} is the acceptable postearthquake loss determined based on the resilience level of effective seismic fortification systems and the city's acceptable resilience level.

The resilience index based on recovery time is defined as the ratio of the actual recovery time to its acceptable limit. Considering the impact of rapid early-stage repairs on seismic resilience and varying time requirements to recover to specific functional levels for different functional buildings, a multi-functional level of resilience index based on recovery time is adopted:

$$R_{\mathrm{T}} = \sum_{z=1}^{Z} \beta_z \frac{T_{\mathrm{C},z}}{T_{\mathrm{A},z}} \tag{2}$$

where R_{T} is the resilience index based on recovery time; $T_{\mathrm{C},z}$ is the actual recovery time for the z-th functional level; $T_{\mathrm{A},z}$ is the acceptable recovery time for the z-th functional level determined based on the resilience level of effective seismic fortification systems and the city's acceptable resilience level; Z is the number of functional levels chosen for buildings; β_z is the weight for the z-th functional level.

Building seismic resilience is divided into three grades: Ⅰ (high resilience), Ⅱ (ordinary resilience), and Ⅲ (low resilience), as shown in Table 1. For the same resilience grade, the threshold of R_{F} is lower than that of R_{T}, indicating a greater emphasis on disaster prevention. The lower resilience grade based on postearthquake loss (i. e., functional loss, repair cost ratio, casualty ratio) and recovery time is taken as the seismic resilience grade for a building.

Table 1 Seismic resilience grade classification for buildings

Resilience index	Grade		
	Ⅰ (high resilience)	Ⅱ (ordinary resilience)	Ⅲ (low resilience)
R_{F}	≤0.8	0.8-1.1	>1.1
R_{T}	≤0.9	0.9-1.2	>1.2

2 Postearthquake Loss Evaluation

2.1 Functional loss

Building components are categorized into structural components, architectural components, service components, and internal facilities in terms of usage functions. Internal facilities vary with the building's function, with each type having specific facility requirements. Since different stories within a building may serve various functions, such as residence, office, commerce, or education, a quantitative analysis based on stories is more reasonable for evaluating postearthquake functional loss.

The three-level function tree model depicts the components that support the story function, as shown in Fig. 1. The components at the bottom of the tree are considered mutually independent, and the functional losses at the upper levels are calculated using the functionality-weighted average method. Notably, the functions of the electrical system and the heating, ventilation, and air conditioning (HVAC) system are causally linked to their components. Failure of any component may lead to system failure; thus, the fault tree method is used to evaluate their functional losses. Figs. 2 (a) and (b) show the fault tree models for the electrical system and the HVAC system. The lower event of the model affects the functional state of the upper event, and the "and" or "or" logic gate is selected based on event operation logic. All components in the three-level function tree model can be modified, replaced, added, or removed to meet specific research needs, ensuring flexibility in responding to different building characteristics.

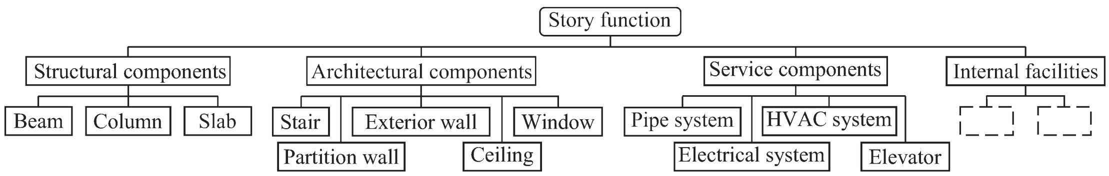

Fig. 1 Three-level function tree model

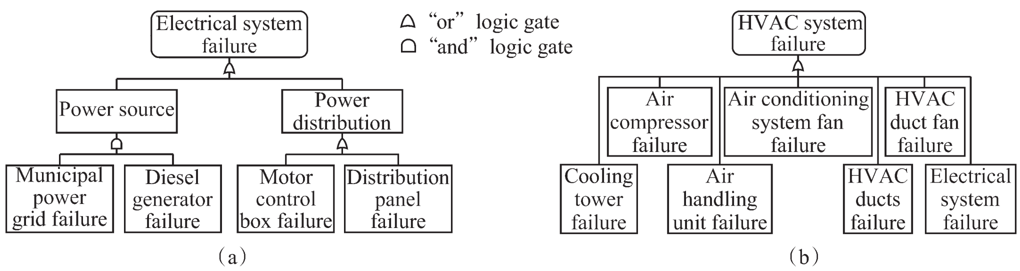

Fig. 2 Fault tree models for the electrical system and the HVAC system. (a) Electrical system; (b) HVAC system

Damage to building components directly results in functional loss. Component damage states are generally categorized from slight to severe as DS_0, DS_1, $\cdots$, DS_n, where DS_0 represents the basically intact state, and DS_n represents the most severely damaged state. To simulate the damage states of building components, seismic fragility analysis combined with Monte Carlo simulation is performed, which determines the probability that building components reach or exceed a certain damage state for a given EDP under one simulation.

Functional losses of many components cannot be precisely quantified due to insufficient testing and simulation data, leading to uncertainty between the damage state and functional loss. It is assumed that the functional loss of components follows a triangular distribution to account for the uncertainty in mapping from component damage state to functional loss. Each damage state of a component corresponds to a triangular distribution, where the mode represents the most likely functional loss for that particular damage state. Specifically, when a component is in the basic intact state (DS_0), the functional loss is 0; when in the most severely damaged state (DS_n), the functional loss is 1.

Functional losses of the electrical system and the HVAC system are evaluated using the fault tree method shown in Fig. 2 after determining the functional losses of their components. Functional losses of structural components, architectural components, service components, and internal facilities are calculated by

$$L_{k,\tau} = \sum_{v=1}^{V} L_{k,\tau,v}\,\omega_{k,\tau,v} \tag{3}$$

where $L_{k,\tau}$ is the functional loss of the τ-th category component in the k-th story, $\tau = 1, 2, 3, 4$, representing structural components, architectural components, service components, and internal facilities, respectively; $L_{k,\tau,v}$ is the functional loss of the v-th component of the τ-th category component in the k-th story; $\omega_{k,\tau,v}$ is the importance coefficient of functional loss of the v-th component of the τ-th category of components in the k-th story, satisfying $\sum_{v=1}^{V} \omega_{k,\tau,v} = 1$.

The functional loss of a story can be calculated by the weighted average of the functional losses of structural components, architectural components, service components, and internal facilities, as shown below:

$$L_k = \frac{\sum_{\tau=1}^{4} L_{k,\tau}\lambda_{k,\tau}}{\sum_{\tau=1}^{4} \lambda_{k,\tau}} \tag{4}$$

where L_k is the functional loss of the k-th story and $\lambda_{k,\tau}$ is the weight coefficient of the functional loss of the τ-th category component, representing the impact of the functional loss of the τ-th category component on the quantification of the functional loss of the story.

The four categories of components play an indispensable role in story function. While assigning a fixed weight coefficient to the functional loss of each component category can partially express the biased judgment of engineers and stakeholders, it may not adequately capture the dominant impact of the components with severe functional loss on the story functionality in a specific context. Therefore, the weight coefficients of components should be dynamically adjusted based on the extent of their functional losses. The weight coefficients of different category components can refer to the following data, which are derived from in-depth interviews and comprehensive surveys conducted among experts and scholars within the pertinent disciplines. It is important to note that the weight coefficients of components can be adjusted and refined to optimally align with the unique characteristics of a specific building if there are more suitable data available. For structural components, the weight coefficients fluctuate based on the functional loss intervals, spanning from [0, 0.2), [0.2, 0.4), [0.4, 0.6), [0.6, 0.8) to [0.8, 1.0], with corresponding values of 0.4, 0.5, 0.6, 0.8, and 1.0, respectively. For architectural components, the same intervals are utilized, but with differing values of 0.2, 0.3, 0.5, 0.6, and 0.8, respectively. As for service components, the weight coefficients vary within the functional loss intervals [0, 0.5) and [0.5, 1.0], with values of 0.3 and 0.5, respectively. The weight coefficients for internal facilities are determined based on the specific building.

The functional loss of a building is assembled from the functional loss of each story and quantified by introducing the story usage area to reflect the difference in its contribution to the functional loss of the building, as shown below:

$$Q_{\mathrm{loss}} = \frac{\sum_{k=1}^{s} L_k A_k}{\sum_{k=1}^{s} A_k} \tag{5}$$

where Q_{loss} is the functional loss of the building; s is the number of stories; A_k is the usage area of the k-th story.

Notably, the structural components of the building ensure its safety, while the stairs support the vertical traffic. To underscore the critical roles of these components, it is assumed that if the functional loss of any structural component, denoted as $L_{k,1}$, within a story is 1, the functional loss of that story and all subsequent stories above is considered 1. Similarly, if the functional losses of all staircases, denoted as $L_{k,2,1}$, within a specific story are 1, the functional loss of the story directly above it is also 1. This implies that these affected stories become unusable and lose their original functions. The aforementioned relationships can be mathematically formulated as follows:

$$\text{If } \exists k,\ L_{k,1} = 1,\ \text{then } L_f = 1 \text{ for all } f \in \{k,\ k+1, \cdots, s\} \tag{6}$$

$$\text{If } \exists k,\ L_{k,2,1} = 1,\ \text{then } L_f = 1 \text{ for all } f \in \{k+1,\ k+2, \cdots, s\} \tag{7}$$

2.2 Repair cost ratio

Repair cost involves the consumption of material resources, such as site cleaning, leasing of mechanical equipment, and the direct cost of supporting, repairing, and replacing each damaged component. The ratio of repair cost to building replacement cost is used to assess the magnitude of the repair cost, calculated based on [21]

$$\kappa = \frac{C_{\mathrm{R}}}{C_{\mathrm{T}}} \tag{8}$$

$$C_{\mathrm{R}} = \sum_{k=1}^{s} \lambda_{Ck} \left(\sum_{i=1}^{m} \left(\zeta_{Ci} \sum_{j=1}^{n} \eta_{1i,j} \eta_{2i,j} C_{i,j,k} \right) \right) \tag{9}$$

$$C_{\mathrm{T}} = \sum_{i=1}^{m} C_i \tag{10}$$

where κ is the repair cost ratio; C_{R} is the repair cost; C_{T} is the building replacement cost, which is the total cost required for constructing the target building according to current quotas; $\eta_{1i,j}$ is the loss coefficient for the i-th component when it is in the damage state of j; $\eta_{2i,j}$ is the repair coefficient for the i-th component when it is in the damage state of j; $C_{i,j,k}$ is the total cost of the i-th component when it is in the damage state of j within the k-th story, calculated using current quotas; ζ_{Ci} is the repair cost discount factor that considers the amount of repair work for the i-th component; m is the number of component types; λ_{Ck} is the coefficient that represents the influence of the story location on the repair cost; C_i is the construction cost of the i-th component calculated according to the current quotas.

2.3 Casualty ratio

In the event of damage to structural components or destruction of partition walls or exterior walls, there is a risk of injuries or fatalities to occupants inside the building. It is assumed that the more severe damage state of the structural components and partition walls or exterior walls within each story represents the damage state of the corresponding story. By combining the nominal casualty rates for the different damage states, the number of casualties can be determined. The ratio of the number of casualties to the total number of occupants is used as a quantitative indicator to evaluate the impact of an earthquake on personnel safety and is calculated as follows:

$$\gamma = \frac{M}{\sum_{k=1}^{s} \zeta_k A_k} \tag{11}$$

$$M = \sum_{k=1}^{s} \sum_{r=1}^{4} \zeta_k A_k \xi_k \alpha_r \tag{12}$$

where γ is the casualty ratio; M is the number of casualties; ζ_k is the occupant density of the k-th story; ξ_k is the in-building rate of the k-th story, representing the number of occupants indoors; α_r is the nominal casualty rate for different damage states[21].

3 Recovery Time Evaluation

3.1 Intra-story repair

3.1.1 Repair sequence

Fig. 3 illustrates the repair sequences at each story, which are determined by consolidating and comparing different repair frameworks[19,21]. Repair sequences specify the order of repairs to be conducted. For instance, the repairs of components other than the structure and stairs can only start once the structure and stairs have been repaired. The partition walls can be replaced only after the repairs of pipes and HVAC ducts. Some repairs can be executed concurrently. For example, the exterior repairs (repair sequence B) would not interfere with the interior repairs (repair sequence A). The repairs of internal facilities are typically scheduled toward the final stages. Given the differences in internal facilities among buildings with different functions, specific components are not explicitly listed, allowing for process design to be tailed down based on the unique characteristics of the building.

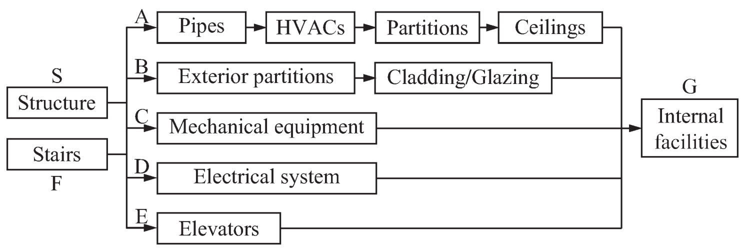

Fig. 3 Repair sequences at each story

3.1.2 Uncertainty in repair time

GB/T 38591—2020[21] provides the expected repair times for building components, expressed as the number of days for a single worker to complete the repair, but does not take into account the uncertainty in repair time. Based on Bayesian networks, Fig. 4 explains how weather conditions, construction technology levels, and worker skill levels impact component repair time. The probability values in Fig. 4 are determined by consulting with engineers and domain experts. Weather conditions are categorized as either impacting repair (Y) or not (N). Construction technology levels and worker skill levels are categorized into three levels: "L," "M," and "H." Level "M" aligns with the expected repair time for the component. For expedited repair completion, two cases are considered: "L" and "H," representing completion of 0-20% and 20%-40% earlier than the expected repair time, respectively. For delayed repair completion, three cases are outlined: "L," "M," and "H," representing delays of 0-20%, 20%-40%, and 40%-100% relative to the expected time, respectively. Table 2 defines various repair completion working conditions based on the interplay of weather conditions, construction technology levels, and worker skill levels.

The repair time after considering the uncertainty is calculated by

$$T_{CR} = \sum_{x=1}^{18} P_x T_x \tag{13}$$

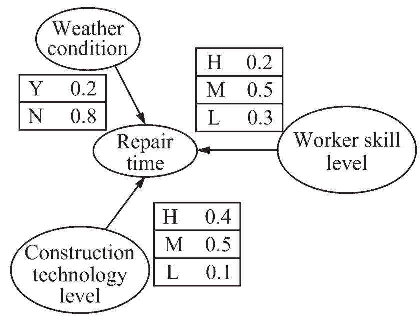

Fig. 4 Bayesian structure

where T_{CR} is the component repair time after considering the uncertainty; P_x is the probability of each working condition; T_x is the time under each working condition, which is assumed to follow a uniform distribution.

3.1.3 Labor allocation for each story

Labor allocation significantly impacts the repair schedule, both within and across multiple stories. A larger labor force typically can expedite component repairs across more stories but must be balanced against labor availability, working space, and site access. The recommended worker allocation for the repair sequences is as follows: 2 workers per 100 m^2 for sequence S, 1 worker per 100 m^2 for sequences A and B, 3 workers/unit for sequences C and D, and 2 workers/unit for sequences E and F. For structural repairs and components distributed throughout or around the entire story (i.e., interior and exterior repairs), the number of workers is determined based on the

Table 2 Various repair completion working conditions

State	Case	Weather	Construction technology level	Worker skill level
Expedite	L	N	H	M
		N	M	H
	H	N	H	H
Normal		N	M	M
Delay	L	N	H	L
		N	L	H
		Y	H	H
		Y	H	M
		Y	M	H
	M	N	L	M
		N	M	L
		Y	H	L
		Y	M	M
		Y	L	H
	H	N	L	L
		Y	M	L
		Y	L	M
		Y	L	L

story usage area. Other component types are allocated workers based on the quantity of damaged components. Considering the demand for workspace, a maximum limit of 0.026A_k has been set for the total number of workers that can be accommodated within a single story.

3.2 Inter-story repair

There is no consensus on the inter-story repair scheme, with a preference for conducting repairs based on the actual earthquake damage and available resources. A generalized inter-story repair scheme is proposed as follows:

(1) Divide all stories of the building into groups, with each group comprising several stories. Repairs among groups are carried out sequentially, while repairs of the stories within groups can be conducted simultaneously.

(2) Intra-story repairs follow the sequences outlined in Fig. 3. Upon completing the repairs of a specific type of component in a story, the repair of that component type in the next group of stories can begin on the premise of conforming to the inter-story repair sequences.

(3) If all stories are treated as a single group, the stories are repaired simultaneously; if each story is considered a separate group, the stories are repaired sequentially.

3.3 Functional recovery curve

The recovery time is assumed to be determined exclusively by the repair time of buildings, without considering any potential delay time. By integrating intra-story repair sequences and inter-story repair schemes with the three-level function tree model, a real-time functional recovery curve of the building can be established as the repair process unfolds. The procedure involves selecting a certain time after the earthquake and checking the repair progress of each component type in every story. Once the repair of a certain type of component is completed, all components of that type will return to their original functionality, resulting in a functional loss of 0. Conversely, if repairs are incomplete, the components will retain their postearthquake functional loss. Building functionality can be quantified based on the functional loss of the components at this stage, utilizing the method described in Section 2.1. This procedure can be repeated to track building functionality throughout the entire recovery process. The real-time functional recovery curve of the building can then be drawn with recovery time as the horizontal axis and building functionality as the vertical axis.

4 Case Study: A Teaching Building

4.1 Basic information

To validate the feasibility of the seismic resilience assessment method, a three-story reinforced concrete frame teaching building is selected as a case study. The structural layout plan is shown in Fig. 5 and considered components are listed in Table 3. This case assesses the seismic resilience grade of the teaching building under basic earthquakes and rare earthquakes. Considering that the main purpose is to validate the method, reasonable assumptions are made regarding the EDPs. For the basic earthquake, the inter-story drift ratios (IDRs) for each story are assumed to be 0.0029, 0.0046, and 0.0037, with peak floor accelerations (PFAs) of 0.15g, 0.24g, 0.29g, and 0.40g for each floor. Under the rare earthquake, the IDRs are assumed to be 0.0091, 0.0113, and 0.0075, with PFAs of 0.31g, 0.56g, 0.66g, and 0.80g for each floor.

4.2 Postearthquake loss

Based on questionnaire surveys, the importance coefficients of functional losses of components are presented in Table 4. The weight coefficients of internal facilities vary with the functional loss intervals from [0, 0.5), [0.5, 0.8) to [0.8, 1.0], taking values of 0.3, 0.5, and 0.8.

To quantitatively evaluate the functional losses of building components in a probabilistic manner, Monte Carlo simulation is employed. After conducting 1 000 simulations, the average functional loss of each component is shown in Fig. 6. Notably, for drift-sensitive components such as stairs and exterior walls, the most severe damage occurs at the second story, where the IDR is the largest. For acceleration-sensitive components such as

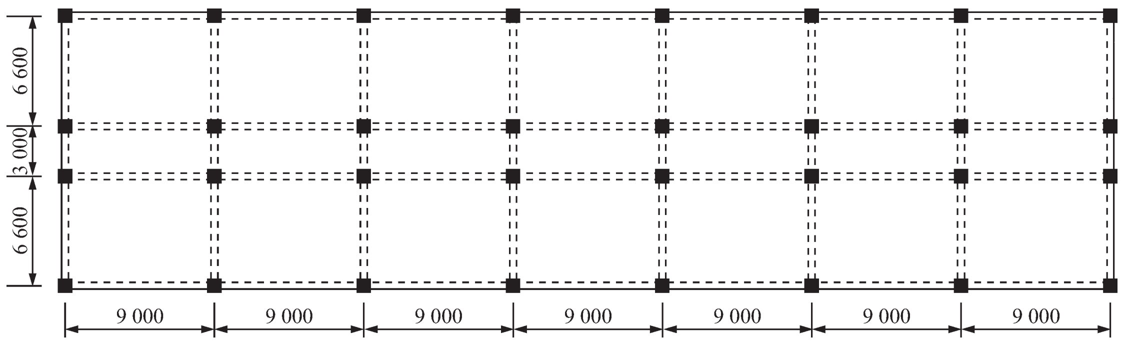

Fig. 5 Structural layout plan of the teaching building (unit: mm)

Table 3 Considered components in this teaching building

Component category	No.	Component	EDP	EDP(DS_1)[1]	EDP(DS_1)[2]	Ref.
Structural components	1	Beam	IDR	0.002	0.4	[24]
	2	Column	IDR	0.003	0.4	[24]
	3	Slab	IDR	0.02	0.4	[25]
Architectural components	4	Stair	IDR	0.005	0.6	[21]
	5	Partition wall	IDR	0.005	0.4	[21]
	6	Exterior wall	IDR	0.000 7	0.412	[26]
	7	Ceiling	PFA	0.56g	0.25g	[21]
Service components	8	Water pipe	PFA	1.5g	0.4g	[21]
	9	Drainage pipe	PFA	1.2g	0.5g	[21]
	10	Distribution panel	PFA	2.16g	0.45g	[21]
	11	Motor control box	PFA	0.73g	0.45g	[21]
	12	Air compressor	PFA	0.25g	0.45g	[21]
	13	HVAC ducts	PFA	1.5g	0.4g	[21]
	14	HVAC duct fan	PFA	1.9g	0.4g	[21]
	15	Air conditioning system fan	PFA	0.5g	0.4g	[21]
Internal facilities	16	Desk and chair	PFA	0.498g	0.5g	[25]
	17	Broadcasting speaker	PFA	2.5g	0.50g	[25]
	18	Blackboard	IDR	0.01	0.3	[25]

Note: EDP(DS_1)[1] is the median of the EDP threshold at DS_1; EDP(DS_1)[2] is the standard deviation of the EDP threshold at DS_1.

Table 4 The importance coefficients of functional losses of components

Component No.	1	2	3	4	5	6	7	8-9	10-11	12-15	16	17	18
Coefficient	0.33	0.34	0.33	0.3	0.2	0.3	0.2	0.3	0.2	0.5	0.2	0.4	0.4

Note: 8-9, 10-11, and 12-15 represent pipe system, electrical system and HVAC system, respectively. Other numbers correspond to the numbers in Table 3.

water pipes, drainage pipes, and ceilings, the functional loss gradually increases with the number of stories. Under basic earthquakes, the functional losses of structural components are within 0. 23. The functional loss of the slabs is found to be negligible. The maximum functional loss of the stairs is 0. 12, indicating that the vertical transportation function of the teaching building has not been significantly affected. The maximum functional losses of exterior walls are 0. 76, potentially resulting in a high number of cracks and voids. The air compressors experience a significant functional loss, reaching up to 0. 85. Other service components and the internal facilities of the teaching building suffer less functional loss. In the case of rare earthquakes, the functional losses of various components increase. The maximum functional losses of structural components reach 0. 71. The maximum functional loss of the stairs increases to 0. 36, which is three times that of basic earthquakes. Moreover, the maximum functional losses of exterior walls reach 0. 92, posing a potential threat to life safety. The maximum functional loss of motor control boxes increases to 0. 56, and the electrical system is likely to be in a failed state. Additionally, the functional losses of air compressors and air conditioning system fans within the HVAC system further increase, leading to nearly complete failure of the HVAC system. Lastly, the maximum functional losses increase to 0. 40 for desks and chairs and 0. 36 for blackboards, while the broadcast speakers maintain high functionality. Under both earthquake intensity levels, the exterior walls and air compressors exhibit notable functional losses, indicating weak components. To mitigate functional losses, targeted reinforcement of building components can be implemented based on the results depicted in Fig. 6.

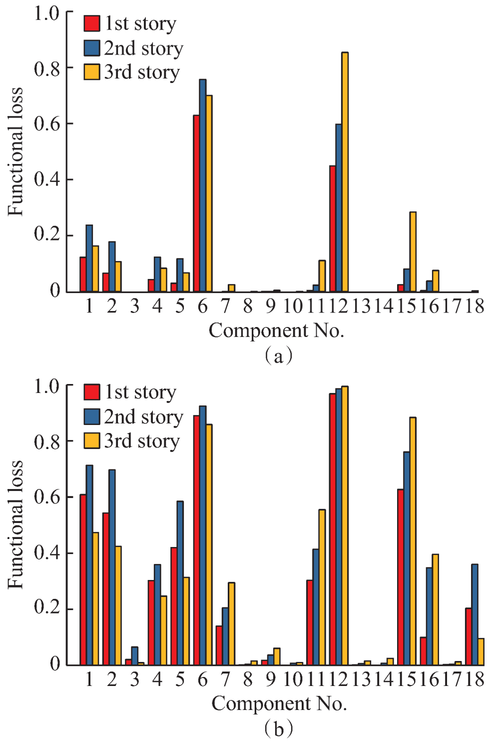

Fig. 6 Average functional loss of each component. (a) Basic earthquakes; (b) Rare earthquakes

The functional loss of the teaching building is shown in Fig. 7. Under basic earthquakes, there is a probability of 0. 5 that the functional loss of this building exceeds 0. 12. The main distribution interval of functional loss is from 0. 08 to 0. 14, with an average functional loss of 0. 125. Overall, the functional loss is within a controllable range and does not cause serious impacts. In the case of rare earthquakes, there is a probability of 0. 5 that the functional loss of this building exceeds 0. 42. The main distribution range of functional loss is from 0. 38 to 0. 46, with an average value of 0. 419, which represents a functional loss 3. 3 times greater than that experienced under basic earthquakes.

Based on the current quota in China, the estimated replacement cost of the teaching building is approximately 6. 5 million yuan. The average repair cost ratios of the teaching building under basic earthquakes and rare earthquakes are 0. 022 8 and 0. 032 5, respectively. It is assumed that the occupant density of the teaching building is 0. 4 occupants/m^2 and the in-building rate is 0. 98, i. e. , the earthquake occurs during class hours. The nominal casualty rate follows the recommended value in GB/T 38591—2020 [21]. The average casualty ratios of

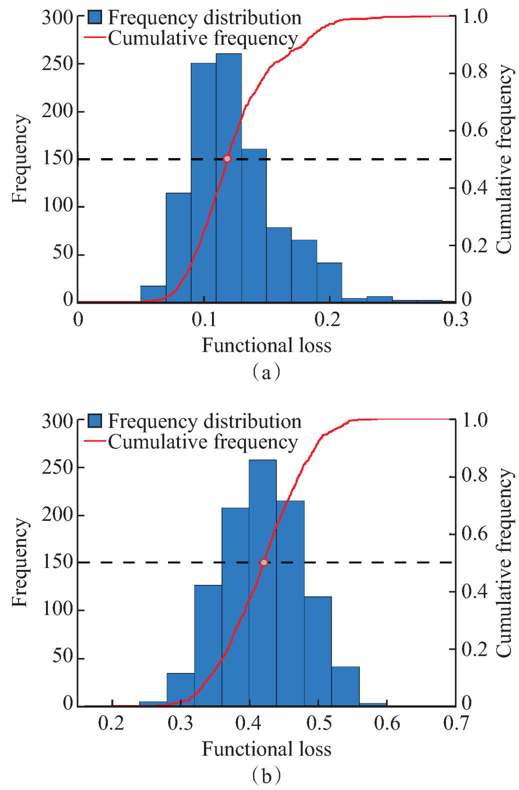

Fig. 7 Functional loss of the teaching building. (a) Basic earthquakes; (b) Rare earthquakes

the teaching building under basic earthquakes and rare earthquakes are 5.5×10^{-4} and 4.8×10^{-3}, respectively.

4. 3 Recovery time

Given that the available labor force may be constrained after the earthquake, three different inter-story repair schemes are considered. Scheme 1 assumes a sufficient labor force, enabling simultaneous repairs of all stories of the teaching building. Scheme 2 addresses scenarios with a moderately constrained labor force by dividing all stories into two groups: the first two stories, divided as a group, are repaired simultaneously, and once a specific component type in the first two stories completes the repair work, the repair of the third story begins. Scheme 3 caters to situations with a scarcity of labor force by dividing all stories into three groups, with repairs conducted sequentially.

To determine the functional recovery curve of the teaching building in each simulation, daily evaluations are made to check the completion of component repairs. The functionality of a component is only updated upon the completion of its repair. Fig. 8 and Fig. 9 show the functional recovery curves of the teaching building under different repair schemes, where the gray curve represents each simulation result, and the red curve represents the average result. Under basic earthquakes, the time taken to reach the 98% functional level of the teaching building is 26 d when all stories are repaired simultaneously. Repairing two stories in a group extends this time to 37 d, and sequentially repairing each story requires 58 d. The average recovery times for the three schemes are 26. 1, 34. 8, and 55. 4 d, respectively. In the case of rare earthquakes, where component damage is more severe, the recovery time increases substantially. Simultaneous repairs of all stories take 110 d to reach the 98% functional level. Repairing two stories in a group extends this time to 115 d, and sequential repair of each story requires 186 d. The average recovery times for the three schemes in this scenario are 66. 7, 83. 6, and 138. 3 d, respectively. When resources are sufficient and the building damage is manageable, simultaneous repairs are recommended to minimize the downtime of the teaching building and reduce the negative impact of educational interruptions. Additionally, implementing appropriate seismic isolation and reduction or building reinforcement measures is advised to minimize the damage to the components of the teaching building.

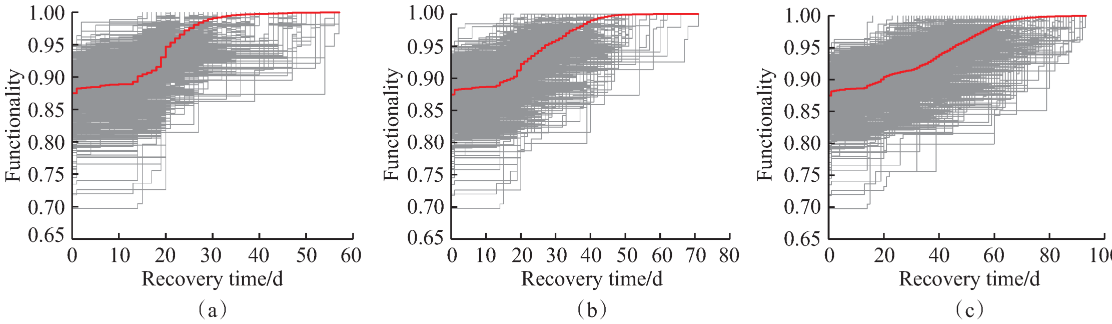

Fig. 8 Functional recovery curves of the teaching building under basic earthquakes. (a) Scheme 1; (b) Scheme 2; (c) Scheme 3

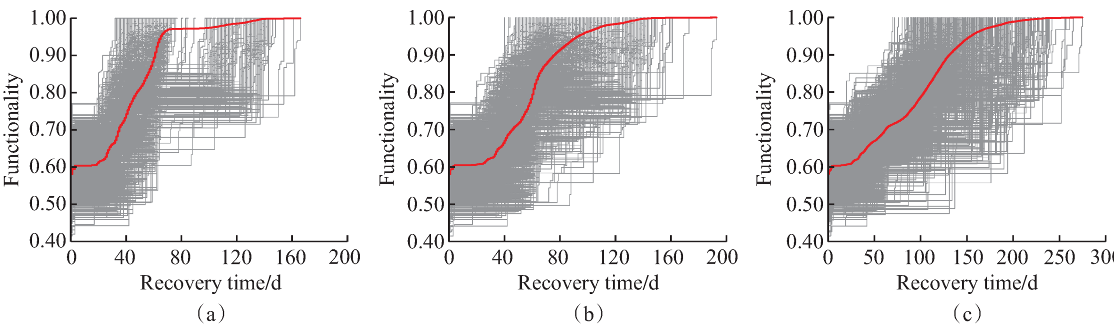

Fig. 9 Functional recovery curves of the teaching building under rare earthquakes. (a) Scheme 1; (b) Scheme 2; (c) Scheme 3

4. 4 Seismic resilience assessment

Table 5 presents the actual values and acceptable limits of postearthquake loss (i. e. , functional loss, repair cost ratio, casualty ratio) and recovery time of the teaching building. The resilience index based on postearthquake loss of the teaching building is determined as the maximum value among the indices calculated for the functional loss, repair cost ratio, and casualty ratio. When calculating the resilience index based on recovery time, only the time to achieve full recovery is considered. The seismic resilience grade based on recovery time is taken as the lowest grade across different repair schemes. Under basic earthquakes, the resilience index based on postearthquake loss is 55, corresponding to a seismic resilience grade of Grade Ⅲ (low resilience). The resilience index based on recovery time is 7. 9, resulting in a seismic resilience grade of Grade Ⅲ (low resilience). In the case of rare earthquakes, the resilience index based on postearthquake loss is 4. 8, indicating a seismic resilience grade of Grade Ⅲ (low resilience). The resilience index based on recovery time is 4. 6, and the seismic resilience grade is Grade Ⅲ (low resilience). Consequently, the seismic resilience grade of the teaching building is classified as Grade Ⅲ (low resilience). Although the seismic resilience grades, based on postearthquake loss and recovery time, are all classified as Grade Ⅲ, the impact of postearthquake loss is more significant. Therefore, enhancing seismic resilience can be more effectively achieved by focusing on reducing postearthquake loss through predisaster defense measures.

5 Conclusions

(1) A method is proposed for quantifying the functional loss of buildings through three rounds of assembly. The weight coefficients of the four categories of components, which vary with the functional loss, reflect the dominant impact of components with severe functional loss on the story functionality in a specific scenario. The story usage area illustrates the impact of functional losses of different stories on the overall functional loss of the building.

(2) Bayesian networks are employed to quantify the impact of weather conditions, construction technology levels, and worker skill levels on the component repair

Table 5 Actual values and acceptable limits of postearthquake loss and recovery time

Earthquake intensity level		Postearthquake loss			Recovery time/d		
		Functional loss	Repair cost ratio	Casualty ratio	Scheme 1	Scheme 2	Scheme 3
Basic earthquake	Actual values	0.125	0.022 8	5.5×10^{-4}	26.1	34.8	55.4
	Acceptable limits	0.15	0.035	1.0×10^{-5}	7	7	7
Rare earthquake	Actual values	0.419	0.032 5	4.8×10^{-3}	66.7	83.6	138.3
	Acceptable limits	0.30	0.06	1.0×10^{-3}	30	30	30

time. A more generalized inter-story repair scheme is proposed, providing flexibility for appropriate selection based on the available labor force.

(3) The dual-parameter seismic resilience assessment method based on postearthquake loss and recovery time places greater emphasis on predisaster defense. In this case study, when subjected to basic earthquakes, the resilience indices based on postearthquake loss and recovery time are 55 and 7. 9, respectively. Under rare earthquakes, the corresponding resilience indices are 4. 8 and 4. 6. The seismic resilience grade of the teaching building is Grade Ⅲ, indicating a low grade of resilience, and it is more affected by postearthquake loss.

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基于双参数的建筑抗震韧性评价方法

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摘要：为量化建筑的抗震韧性，提出了一种从组件层面到整体建筑的功能损失评价方法，并对基于震后损失和恢复时间的双参数抗震韧性评价方法进行了改进．建立了可以考虑各类组件权重系数随其功能损失动态变化的三级功能树模型．利用贝叶斯网络，量化了天气、施工技术水平和工人技术水平对组件修复时间的影响，基于组件修复过程提出了确定建筑功能恢复时变曲线的方法．以一栋3层教学楼为例，计算了设防地震和罕遇地震下教学楼的抗震韧性指标．结果表明，教学楼的抗震韧性等级综合判断为三级，且其韧性等级受震后损失的影响更为显著．所提出的方法可以用于预测震前建筑的抗震韧性，识别建筑中薄弱的组件，为采取措施提高建筑的抗震韧性提供指导．

关键词：抗震韧性评价；双参数方法；功能损失；恢复时间；贝叶斯网络

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