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Aseismic Optimization Design of Building Structures Based on Practical Reliability Algorithm

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Construction technology is closely related to social and economic development and directly affects personal safety. With the development of science and technology and the gradual improvement of architectural aesthetic and functional requirements, the height, safety and functionality of buildings have been significantly improved. In particular, the aseismic design of building structures plays a key role in improving architectural safety. In addition, the application of new materials and the improvement of construction management technology make aseismic design more applicable. Moreover, the structural reliability can objectively consider the influence and role of various random phenomena in the process of planning, construction and use of engineering structures, so as to optimize the balance between the safety and economy of building structures. At present, many high-rise buildings cannot effectively cope with the vibration and impact caused by earthquakes. The main reason is that the structural quality of high-rise buildings cannot respond well to large earthquakes. Therefore, this study analyzed the aseismic design of the building structure using the reliability practical algorithm, and optimized it so as to improve the aseismic ability of the building structure. The results showed that the aseismic capacity and structural load of the optimized building structure design were higher than the traditional ones; the aseismic capacity was about 9% higher, and the structural load was 6% higher.

Keywords: aseismic design of building structure, practical algorithm of reliability, aseismic structure optimization, optimal design

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1. INTRODUCTION

With the progress of urbanization, the use of loads or structural strength for building construction can no longer meet the structural damage and financial losses caused by earthquakes. Also, the protection of structural components of buildings and internal structures is not taken into account, resulting in poor seismic capability and reliability of buildings, and affecting the deflection angle of structures. Due to the huge financial losses caused by an earthquake, when carrying out structural design based on the existing bearing design, aseismic performance optimization should consider the performance requirements of the structure and its safety and economic feasibility so as to achieve the aseismic reliability of the building structure.

An aseismic building structure can effectively deal with the disaster caused by earthquake. Behnamfar proposed a new aseismic design method for structures, aiming to control the earthquake damage at a specified level. This method was applicable to special moment frame buildings with vertical and horizontal rules [1]. Special Moment Frame is a type of reinforced concrete or steel frame system with high ductility and toughness. It strengthens the structure and reinforcement of the beam-column connection nodes to ensure that the structure will not fail even if plastic deformation occurs in a strong earthquake, effectively dissipating the seismic energy. The "special frame buildings with vertical

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and horizontal rules" mentioned in the article refer to those buildings with regular layouts in plane and elevation and adopt special seismic frame systems. Such buildings are more suitable for the seismic damage control method proposed by Behnamfar. In order to improve the aseismic performance of modern buildings and the safety of buildings during earthquakes, Rong examined the aseismic performance design of building structures from multiple perspectives. He analyzed the structural components by changing the deflection angle, structural torsion and number of floors of the building structure [2]. Ye proposed an innovative mega substructure system to overcome this vulnerability and further improve its horizontal aseismic performance, and carried out single-objective and double-objective optimization to obtain the best parameters and capture the potential of representative models [3]. Xiang studied the effectiveness of the linear response spectrum analysis method for nonlinear cable net systems. The energy-based parameters were used to determine the structural rigidity, on which the equivalent single degree of freedom system of cable network structures with various irregularities can be established [4]. In order to improve the calculation efficiency of nonlinear dynamic time history analysis of super high-rise building structures under strong earthquakes, He Z proposed some accelerated algorithms. These algorithms were mainly used to analyze the efficiency of nonlinear dynamic time history of high-rise buildings [5]. Bai designed a structure consisting of vertical suspension and lateral elastic support by combining the elastic constraint that can absorb seismic energy with the suspended structure, and appropriately simplified its stress conditions [6]. In order to study the influence of heat treatment on steel and its application potential in aseismic design, Yu conducted seven tensile tests on steel samples at different peak temperatures and cooling rates to study its influence on material strength and ductility [7]. The advantages of aseismic features for building structures are explained above, but they are rarely combined with the reliability algorithm.

The aseismic optimization of building structure can significantly increase the reliability of the structure. Li simulated the aseismic structure optimization of buildings based on finite element numerical simulation and improved genetic algorithm. By simulating the anti-seismic structure of the building, the changes in the bearing capacity and stress of the building were analyzed, which provided a reference for the improvement of the anti-seismic design of the building [8]. Yan proposed a multi-objective optimization method of failure mode based on genetic algorithm for reinforced concrete frame shear wall structures. The maximum drift ratio and global structural damage index were used to construct the objective function of genetic correlation, and there was a niche factor through the crossover and mutation of gene sequences [9]. He proposed an aseismic design framework based on multi-objective optimization in order to achieve simultaneous optimization of multiple design objectives, and then selected the final optimal design scheme through the decision-making method of objective weight [10]. Sun carried out topology optimization for a multi-objective anti-collision structure under impact load to obtain the optimal structure configuration meeting multi-objective conditions [11]. Jiang conducted load analysis of the sluice structure with new lifting device, and compared and analyzed the displacement and stress of the sluice structure with new and ordinary lifting technology [12]. Hao conducted aseismic analysis of high-rise residential structures from the perspective of aseismic design of high-rise buildings, discussed the basis for aseismic analysis of high-rise residential structures, and found feasible countermeasures to improve the rationality of aseismic design and structural design of buildings [13]. All of the aforementioned studies described the advantages of aseismic structure optimization, but did not elaborate on the practicality.

The building structure needs to have an aseismic design so as to meet the strength, bearing capacity, stability and energy requirements of the building during an earthquake. The purpose is to improve the earthquake resistance, structural stability and bearing capacity of the building structure. In fact, the dynamic response of structures to earthquakes involves absorbing energy from earthquakes. Therefore, according to the requirements and characteristics of a building's function, this paper proposes aseismic design methods, objectives, characteristics and implementation of aseismic performance design methods.

2. ASEISMIC DESIGN ELEMENTS OF BUILDING STRUCTURE

(1) Principle of aseismic design of building structure

In the aseismic design of building structures, the three principles shown in Figure 1 are followed.

1) Structural symmetry

During the planning process, it is necessary to ensure the symmetry and integrity of the blueprint and three-dimensional structure to ensure the high aseismic of the structure. In aseismic structure, the mass and stiffness of the structure must be changed uniformly to avoid the vibration of the stiffness center and the mass center rotating sharply on the plane. In order to effectively prevent the formation of thin layers in vertical and lateral force structures, it is necessary to ensure that the vertical and lateral damping structures increase gradually from top to bottom [14]. So as to ensure the rationality of building layout, it is necessary to reduce the impact of the difference between internal components and vertical components on the building. This is done mainly to reduce the structural torsion of the building structure by changing the difference between the internal components.

2) Declination angle

Building materials, systems, structural renewal standards, lateral loads and other factors are the main causes of the displacement limit value. Aseismic design must be carried out according to the actual construction environment. In order to better control the torsional and lateral stiffness of the structure, it is necessary to accurately calculate the displacement angle between floors.

3) Structural torsion

During construction, the cylinders in the building must have medium strength and flat dimensions. If 50% of the seismic torque at the bottom of the structure is greater than the first impact, houses and shear walls should be used as supports,

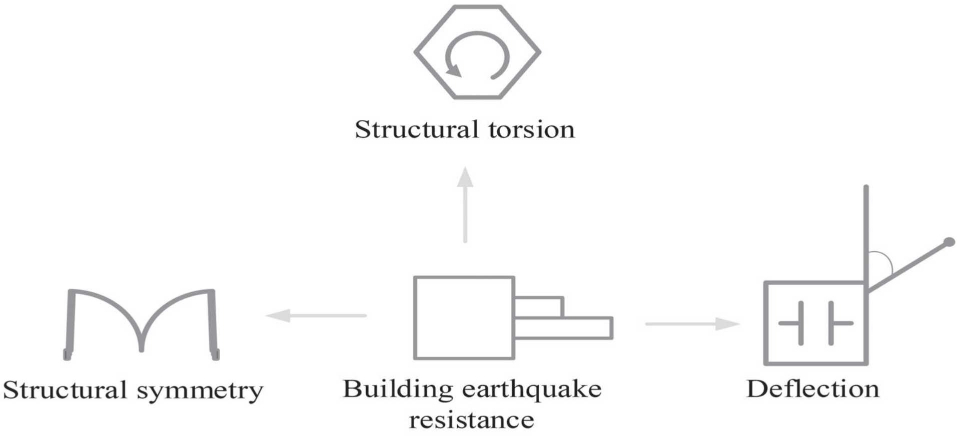

Figure 1 Principle of seismic design of building structure.

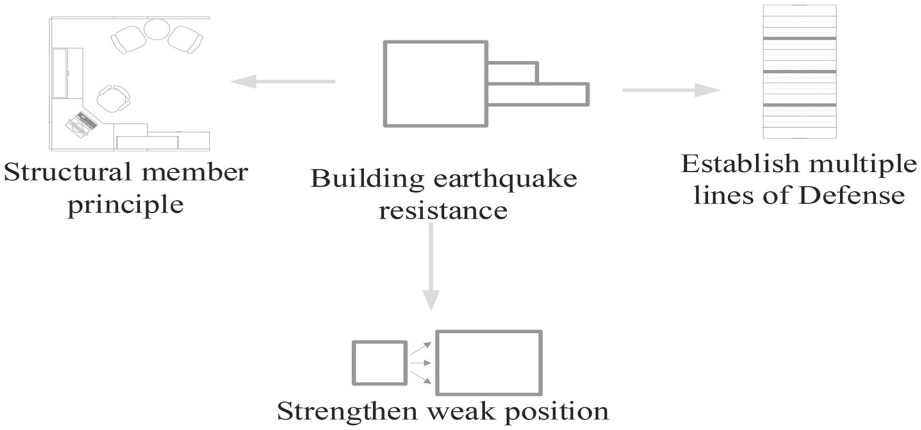

Figure 2 Seismic design principles of building structures.

and multi-channel protection should be set in the building to improve the aseismic capacity of the building [15]. Due to the impact of earthquake, the whole building may collapse due to structural problems. Therefore, the architectural design should consider the structural changes and take into account the rotation angle of the structure.

(2) Design principles of aseismic building structure

The design of aseismic building structures follows three design principles, as shown in Figure 2. First of all, according to the principle of structural components, the structure of weak links in the building is designed with high aseismic structure. The structural design must meet the requirements of structural components in terms of load, strength, stiffness, stability, tension and energy consumption. The main energy carrier must have high viscosity and strength. Basic elements with vertical loads cannot be considered as basic energy-consuming elements. The second is to build multiple earthquake defense lines. When planning aseismic structures, it is necessary to reduce internal and external redundancy as much as possible through appropriate allocation and distribution of functional areas, so as to ensure that the main energy consuming components have high viscosity, high strength and high stiffness, and improve the seismic energy absorption and scattering capacity. The purpose is to avoid building collapse or long stay time under earthquake conditions. The third is to strengthen the aseismic performance of weak locations. While ensuring the overall consistency of the building structure, it is necessary to strengthen the seismic resistance of weak parts, increase local loads, consciously control weak parts, improve their deformation and bearing capacity, ensure that weak parts do not shift, and take appropriate measures to strengthen weak links during the construction process.

(3) Factors influencing aseismic ability of building structures

There are seven factors influencing the aseismic force of a building structure, as shown in Figure 3. The first is the overall structure. The structural shape, structural symmetry, strength and solidity are consistent. The overall layout level of the structure has a significant impact on the aseismic performance of buildings. The second is the choice of structure. Geological characteristics shall be selected according to the design type to ensure static uncertainty, maximize the use of earthquake input energy, and improve the aseismic reliability of buildings [16]. The third is structural integrity. In order to improve the vertical strength of the building, attention should be paid to the combination of different components to ensure the integrity of the building. On this basis, the tensile requirements of possible large deformation during earthquake are determined. It passes through the internal deflection angle of the structure and the vertical strength of the structural members. The fourth is the selection of materials. The quality of building materials plays a very important role in the quality of structures. The quality assurance of building materials is the basis to

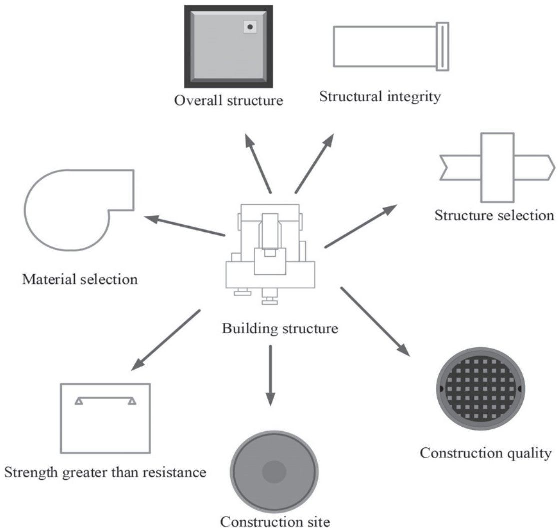

Figure 3 Factors affecting seismic resistance of building structure.

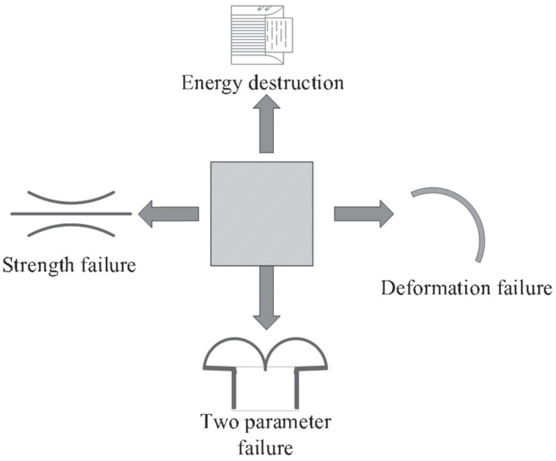

Figure 4 Damage principle of building seismic structure.

ensure the quality of subsequent construction projects and aseismic performance. The fifth is that the strength is superior to the tensile strength. The aseismic performance of building structures must be compatible with strength, tension and rigidity to achieve appropriate proportions, which is an internal requirement of building structures. The sixth is the construction site. Before building begins, the construction site must be carefully inspected, and a favorable construction site must be selected to avoid site potential damage from earthquakes. The seventh is construction quality. The use of wrong materials and damage to the geometric characteristics of buildings would affect the actual aseismic performance of their structure.

3. OPTIMIZATION OF ASEISMIC DESIGN OF BUILDING STRUCTURES BASED ON RELIABILITY

(1) Damage principle of aseismic structure

Traditional structures often fail mainly in terms of strength or stiffness under earthquake action, while earthquake-resistant structures need to combine multiple failure criteria to comprehensively evaluate their performance. The failure criteria of earthquake-resistant structures are shown in Figure 4. The strength failure criterion takes into account the fact that the structural strength exceeds the allowable bearing capacity of the structure, resulting in structural damage. The tensile failure standard deals with the situation where the structural deformation exceeds the allowable deformation of the structure and causes structural deformation loss [17]. The energy failure criterion considers the structural failure when the accumulated residual energy exceeds the failure limit. The elastoplastic deformation and address fatigue effect of the structure under strong earthquake are studied by double failure criteria. The aseismic structure is optimized to make it reliable, and the optimal structure size under certain reliability conditions is given.

(2) Implementing the objective of building aseismic performance design

The aseismic performance index of buildings is an index indicating the expected performance of buildings under the influence of earthquakes. The use layer of a building consists of three parts: structure, non-structure and infrastructure. According to the specific structural strength, terrain conditions, height, irregular location and perimeter of the building

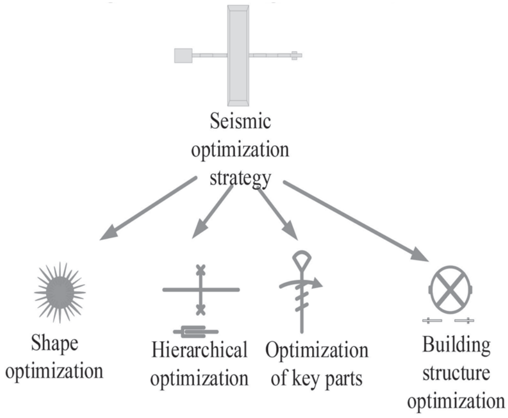

Figure 5 Strategies for seismic optimization of building structures.

and the financial status of the building owner, the type of structural characteristics can be selected under the influence of a magnitude 3 earthquake to achieve the building's intended function. According to the energy principle of structural seismic stability assessment, the higher the bearing capacity of structures and components, the lower the deformation toughness. The low bearing capacity of structures and components requires higher deformation toughness [18]. In order to ensure the safety of building structures, the selection of appropriate and practical methods can increase the structural load, improve the extension capacity and aseismic performance reliability. This involves changing the torsion angle of the building structure and the stability of the floor construction. Therefore, aseismic performance design must have an appropriate performance level, and a wider range of factors should be considered when selecting performance indicators.

(3) Aseismic optimization strategy of building structure

There are four aseismic optimization strategies for building structures, as shown in Figure 5.

1) Modeling aseismic optimization strategy

Building scale, architectural planning and architectural planning are closely related, and architectural design is the key factor. In the design process, the performance of the building must be taken into, and the appearance of the building should be emphasized to avoid any asymmetry or irregularity. Improper layout of buildings would lead to uneven distribution of building loads in the face of earthquakes [19]. Therefore, prior to construction, square, rectangular and other orderly forms must be selected as far as possible to avoid the negative impact of external forces on the building's structure. While ensuring the quality of aseismic design, proper design should also reflect the technology and aesthetics of architecture, and realizes the combination of architectural structure, aesthetics and strength.

2) Anti earthquake optimization strategy

Building planning and design must be based on the principles of consistency and symmetry to meet the functional requirements of the building space. If the wall and steel structure are asymmetric, an earthquake would have a severe impact on the structure, damaging the local walls or the whole building. The basic element of design is the combination of blueprint and overall design. When designing rooms, people need to determine the area of each room and the location of doors and windows. When selecting the plane layout according to the single building surface and doors and windows, the actual location of the project construction should be considered. For example, in order to achieve the best utilization of space, buildings generally adopt a combination of layer elements [20]. Modular devices are widely used in high-rise residential and commercial buildings, and play an important role in improving both the torsional and overall strength of building structures. When designing the vertical motion center outside the plane, measures must be taken to reduce the heat dissipation of each door and window to avoid the "steering effect".

3) Performance optimization of key components aseismic

In the optimization design of aseismic buildings, stairs and floors are the core components that affect the performance of aseismic buildings. Because stairs are vertical, they cannot be placed on both sides and corners of the building. The traditional aseismic design of the foundation involves laying alternate layers of clay and sand to support the structure, or laying the foundation directly on the clay or sand cushion, and using special materials to create aseismic structures to reduce earthquake damage to the building. Currently, asphalt is the most commonly-used insulation layer in foundations [21].

4) Aseismic reinforcement of building structure

In building structures, aseismic reinforcement measures include direct reinforcement methods such as wide section, embedded tendons, wrapped steel wires, anchor bolts, etc. Before construction, the employer plans according to aseismic design requirements. During construction, aseismic facilities are provided for key parts of the building, and after construction, aseismic facilities are also provided.

4. APPLICATION OF RELIABILITY PRACTICAL ALGORITHM IN BUILDING ASEISMIC OPTIMIZATION DESIGN

In order to understand the aseismic performance of building structure optimization design, this paper analyzes the aseismic optimization effect of buildings through the reliability practical algorithm. When the limit state equation is linear, the reliability index is equal to the shortest distance from the origin to the limit state surface (or line) in the standard normal coordinate system. First, it can assume the initial lateral force distribution of the building, and then the additional load of the floor force is calculated in the load step to obtain the load distribution of the current floor:

$$\Delta A_i^{k+1} = B^j \left(\frac{A_i^k}{B_b^k} - \frac{A_i^{k-1}}{B_b^{k-1}} \right) + \Delta B_b^{k+1} \left(\frac{A_i^k}{B_b^k} \right) \tag{1}$$

where i is the number of floors, k is the increment, and then according to the lateral force, the modal force can be obtained as:

$$A_i = \sqrt{\sum \left(\frac{\sum_{k=1}^{M} n_k \alpha_{kj}}{\sum_{k=1}^{M} n_k \alpha_{kj}^2} \right)^2 \cdot \alpha_{kj} Q \delta_j n_k} \tag{2}$$

Then according to formula (2), the equivalent vibration mode of the building can be obtained as follows:

$$\overline{\alpha_i} = \sqrt{\sum \left(\alpha_{ij} \beta_j \right)^2} \tag{3}$$

$$A_i = \frac{n_k \overline{\alpha_i}}{\sum_{k=1}^{M} n_k \overline{\alpha_i}} \tag{4}$$

As the aseismic effect of the building changes with the strength of the earthquake, its lateral force distribution needs to be calculated repeatedly. The floor force of each floor is obtained with:

$$A_{ij} = \beta_j \alpha_{ij} C_i Q(j) \tag{5}$$

Then compare the ratio of the scale factors according to the proportion of each floor, and the scale factor is:

$$B' = Q_n B_j = \frac{\Delta B}{B} B_j \tag{6}$$

$$A' = Q_n A_{ij} = \frac{\Delta B}{B} A_{ij} \tag{7}$$

The scale factor is used to judge whether the strength between floors conforms to the seismic standard. Then, the reliability analysis of the floor system of the building structure can be carried out. The system failure mode i of the floor can be expressed as:

$$\overline{\eta_i} = \left\{ \bigcap_{j=1}^{n_i} \overline{\varepsilon_j} \right\} \tag{8}$$

$\overline{\varepsilon_j} = \{ Z_j < 0 \}$ is the number of failure stories of j, the failure probability of the building is:

$$P = P_f \left\{ \bigcup_{i=1}^{m} \overline{\eta_i} \right\} \tag{9}$$

m is the total number of failure modes. Then, according to the aseismic effect of building floors, some floors can be ignored. Formula (9) can be converted to

$$P \approx P_f \left\{ \bigcup_{i=1}^{m_n} \overline{\eta_i} \right\} \tag{10}$$

where m_n is the main failure mode of the building floor. Then, using the weakest failure mode, the failure probability of the building floor can be obtained with:

$$P = P_f(\overline{\eta}_{n1}) + P_f(\overline{\eta}_{n2}) + P_f(\overline{\eta}_{nm}) \tag{11}$$

Then, using reliability analysis, the failure criteria of building floors can be calculated with:

$$\left. \begin{aligned} a_m &= \max |a(t)| \\ a_m &\le b \end{aligned} \right\} \tag{12}$$

Then the effective displacement mode mass of the floor can be obtained from the failure criteria of the building:

$$M_n' = \left(\sum_{i=1}^{n} a_m \right)^2 \tag{13}$$

Finally, according to the failure probability and failure criteria, the aseismic design seismic response of the building is:

$$Z_m = \sqrt{\sum_{i=1}^{n} Z_n} \tag{14}$$

5. EXPERIMENTAL ANALYSIS OF ASEISMIC DESIGN OF BUILDING STRUCTURE

In order to understand the aseismic design practicability of building structures, this paper applies the reliability practical algorithm to determine the reliability of aseismic structures. Firstly, the residents' satisfaction with the aseismic design of the building structure in three communities, A, B and C, was analyzed and studied. There were 100 people in each community. The level of satisfaction was rated as: satisfied, average or dissatisfied. The survey results are shown in Table 1.

Table 1 shows that the residents of the three communities are satisfied with the aseismic design of the building structure because it is solid, has many fire escapes, and regular maintenance and repair would be carried out. In addition, the structural performance of the building is adequate, and the deflection angle and structural torsion conform to the aseismic standard of the building. Those residents who are not satisfied may feel that the site of high-rise buildings is not solid, and aseismic ability may be weak. The main reason is that the site of the building would affect the stability of the whole structure and indirectly affect the seismic capacity of the building.

(1) Reliability index analysis of floor deformation in optimal design of building structures

In order to understand the aseismic capability of the optimized building structure design, this paper analyzes the reliability index of building floor deformation, as shown in Figure 6.

It can be seen from the figure that the reliability index of the building is also changing with the increase of time in the face of different earthquake levels. The reliability index of the building declines slowly under small earthquake levels, with an average of 4.13. The decline rate of building reliability index under a moderate earthquake level is between the two, and the average value is 4.04. The decline rate of the building reliability index under a large earthquake is the fastest, with an average of 3.98. The reliability index of large earthquake is 0.15 lower than that of small earthquake, indicating that the

Table 1 Residents' satisfaction with the aseismic design of the building structure.

	Satisfied	Commonly	Dissatisfied
Community A	80	15	5
Community B	86	12	2
Community C	81	13	6

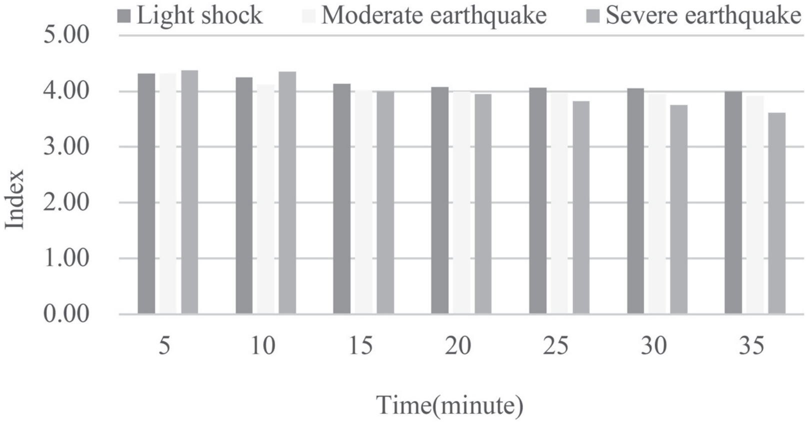

Figure 6 Reliability index analysis of floor deformation in optimized design of building structure.

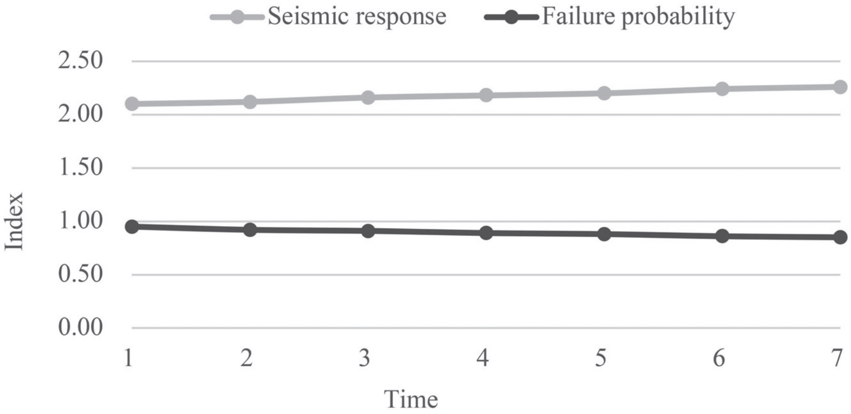

Figure 7 Analysis of building seismic response under practical reliability algorithm.

reliability index of the building is relatively good in the face of small and medium earthquakes, and the aseismic effect is not very obvious in the face of a large earthquake [22].

(2) Analysis of building seismic response based on practical reliability algorithm

In order to understand the aseismic capability of building optimization design, this paper also analyzes and studies the seismic response and failure probability of buildings by applying a practical reliability algorithm, as shown in Figure 7.

Over time, the response of the optimized building design to the earthquake is increasing, but the failure probability is decreasing. The seismic response on the seventh day is 0.16 higher than that on the first day, and the overall average is about 2.18. The failure probability of the first day is 0.10 higher than that of the seventh day, and the average value is about 0.89. The increasingly high seismic response indicates that the building can capture more detailed seismic waves, allowing building designers to make quick decisions to reduce the number of casualties and the amount of financial losses. The reduction of failure probability shows that the floor structure becomes increasingly stable when the building structure responds to the earthquake, and the effectiveness of each floor plan is relatively high. The main reason is that the floor stability type can affect the probability of failure of the structure, and this can change the effectiveness of the floor.

(3) Aseismic capability analysis of building structure optimization

In order to understand the aseismic capability of building structure optimization, this study conducted a comparative analysis of the aseismic capability and structural load of traditional building structures, as shown in Figure 8.

It can be seen from the above figure that the aseismic capacity and structural load of the optimized building structure design are higher than the traditional ones; the aseismic capacity is about 9% higher and the structural load is 6% higher. This shows that the optimized building structure focuses on the stability of the structure, and improves the deflection angle between structures and structural torsion, thus increasing the aseismic ability of the building. In addition, the optimized building structure also includes many durable materials as well as multiple fire escapes, thereby improving the aseismic function of the building structure.

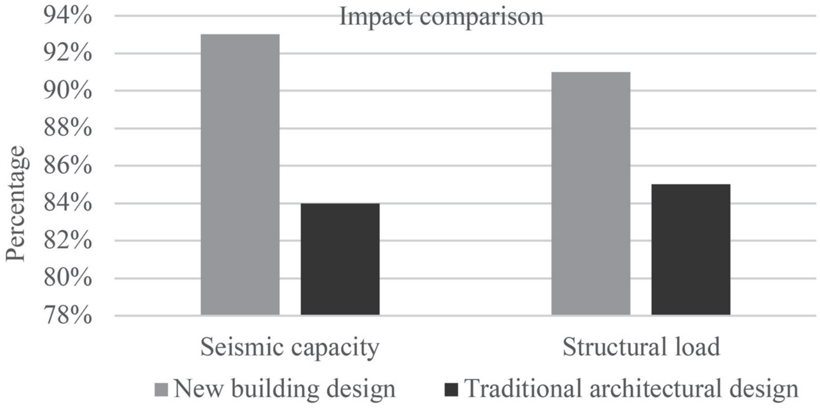

Figure 8 Seismic capacity analysis of building structure optimization.

6. CONCLUSION

The development of the construction industry is closely related to the development of densely-populated and labor-intensive cities, which is conducive to the growth of high-end housing demand. The construction of buildings often requires architects and planners to consider the seismic capacity of building structures, thus increasing the demand for housing. The planning of an aseismic building is an important indicator to determine whether the building structure meets the requirements, and whether various aseismic design methods have been correctly applied. It is crucial to select and optimize the structure adequately. The optimization design based on structural reliability and aseismic performance not only safeguards the structure against natural disasters; it also ensures the high quality of the project, improves the aseismic performance of building structures, and ultimately ensures the safety of people's lives and property.

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