Research paper

Comparison study on seismic isolation design of RC frame structure based on two different codes

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Abstract: With the development of building seismic isolation technology and the official release of the Isolation Code in September 2021, seismic isolation design in China will now rely on two foundational codes: the Seismic Code and the Isolation Code. This paper take a ceramic jar storage of the RC frame structure as the research object, and carry out the seismic isolation design based on the separated calculation design method of the Seismic Code and the unitary calculation design method of the Isolation Code respectively, and clarify the control index of the Isolation Code is the story drift angle. The maximum displacement is reduced by 37.5%. In terms of material consumption, the Isolation Code leads to a 5.94% decrease in concrete usage, accompanied by a 13.97% increase in steel consumption, resulting in an overall cost increase of 4.98%. The findings indicate that seismic isolation design, guided by the Isolation Code, substantially mitigates the seismic response of the superstructure. The damage extent to structural members is reduced by 15–20%, promoting enhanced safety and repairability. The outcomes of this study offer valuable insights for future seismic isolation designs in RC frame structures.

Keywords: seismic isolation design, isolation code, seismic code, RC frame, structural member damage, comparative study

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1. Introduction

Earthquakes, despite their brief duration, wield immense destructive power. Since 2023, there have been a total of 16 global earthquakes with a magnitude of 7 or higher. The frequency of severe earthquakes has surpassed the annual average, and the resultant buildings damage is frequently a significant factor contributing to casualties and economic losses. Particularly notable is the 7.8 magnitude earthquake that struck Turkey this year, resulting in tens of thousands of casualties and causing billions of dollars in losses. Seismic isolation technology, as a cutting-edge research field in disaster prevention and mitigation, has garnered substantial attention from scholars both domestically and internationally over the past two decades. In contrast to conventional seismic r3-1esistance techniques that depend on increasing the strength of structural components through greater material usage, seismic isolation technology provides a more economical, effective, and direct approach to meet seismic requirements [1–4].

In 2001, the seismic isolation design method was initially incorporated into China's *Code for Seismic Design of Buildings* (referred to as "Seismic Code"). This inclusion marked a significant simplification of the seismic isolation design process through the introduction of the separate calculation design method and the incorporation of the horizontal earthquake reduction coefficient. Subsequently, in 2021, the *Code of Design for Seismic Isolated Buildings* (referred to as "Isolation Code") was officially promulgated. It proposed the unitary calculation design method, where the base shear ratio replaced the horizontal earthquake reduction coefficient. In future seismic isolation structural designs, both codes can serve as design references, but variations exist in design methods and control criteria. Wei [5] compared the design methods of the two codes, and the study revealed that structures designed directly based on the "Isolation Code" exhibited better seismic performance. Yin et al. [6] and Zeng et al. [7] conducted research on RC (Reinforced Concrete) frame structures and RC shear wall structures, respectively, comparing the structural responses under different design methods, and clarified that the control criterion of the "Isolation Code" is the base shear ratio. Liu et al. [8] identified the control criterion of the "Isolation Code" for RC framed tube structures as story drift angle and proposed the significance of the "Isolation Code" for structural recoverability. Sun [9] conducted an economic analysis of RC shear wall structures based on the "Seismic Code" and the "Isolation Code", and found that significant post-earthquake damage could lead to an increase in the total life cycle cost. Erdik [10] compared Turkish, European, Japanese and American codes and Becker [11] pointed out the differences in Japanese and American seismic isolation codes.

Currently, the majority of researchers in the field focus on comparing the design methods and structural responses of the Seismic Code and the Isolation Code. They validate their findings through numerical simulations, yet there is a scarcity of analysis on actual engineering projects involving RC frame structures, particularly in terms of comparing member damage. This study addresses this gap by utilizing a real engineering project involving a ceramic jar storage as an example. The design will b1e carried out separately based on the Seismic Code and the Isolation Code, and a comparison will be made regarding the design methods, structural responses, economics, and member of post-earthquake damage.

2. The differences between the seismic code and the isolation code

In comparison to the Seismic Code, the Isolation Code mainly makes adjustments in design methods, response spectra, and key control criteria, as shown in Table 1.

Table 1. Comparison of contents of two design codes (for RC framework)

	Seismic Code	Isolation Code
Design objectives (for earthquake)	Frequent: undamaged Fortification: repairable Rare: uncollapsed	Fortification: undamaged Rare: repairable Extremely rare: uncollapsed
Design method	Separated	Unitary
Response spectrum (5Tg~6 s)	Straight-line descending segment	Curved descending segment
Story drift angle limit (for rare earthquake)	1/50	1/100
Story drift angle limit (for fortification earthquake)	–	1/400
Conditions for reducing 1 degree	Horizontal earthquake reduction coefficient ≤ 0.4	Base shear ratio ≤ 0.5

2.1. Design methods

The Seismic Code's three-level design objective is to achieve a structure that remains "undamaged after frequent earthquakes, repairable after fortification earthquakes, and uncollapsed after rare earthquakes". It employs a "separated calculation design method" based on time history analysis, which divides the entire isolated structure into four parts: upper structure, isolation layer, lower structure, and foundation. The introduction of horizontal earthquake reduction coefficients serves as a "bridge" between these four parts, simplifying the seismic isolation design process and enabling the upper structure to be designed using traditional response spectrum analysis methods. It's worth noting that this design approach may lead to an actual structural failure mode inconsistent with expectations. The seismic isolation design processes for both the Isolation Code and the Seismic Code are illustrated in Figure 1.

The Isolation Code's three-level design objective is to achieve a structure that remains "undamaged after fortification earthquakes, repairable after rare earthquakes, and uncollapsed after extremely rare earthquakes". It employs an "unitary calculation design method" based on mode-acceleration response spectrum, which involves the overall modeling of the structure. The determination of equivalent stiffness and equivalent damping ratio for the isolation layer involves iterative processes or time history analysis, considering the building's
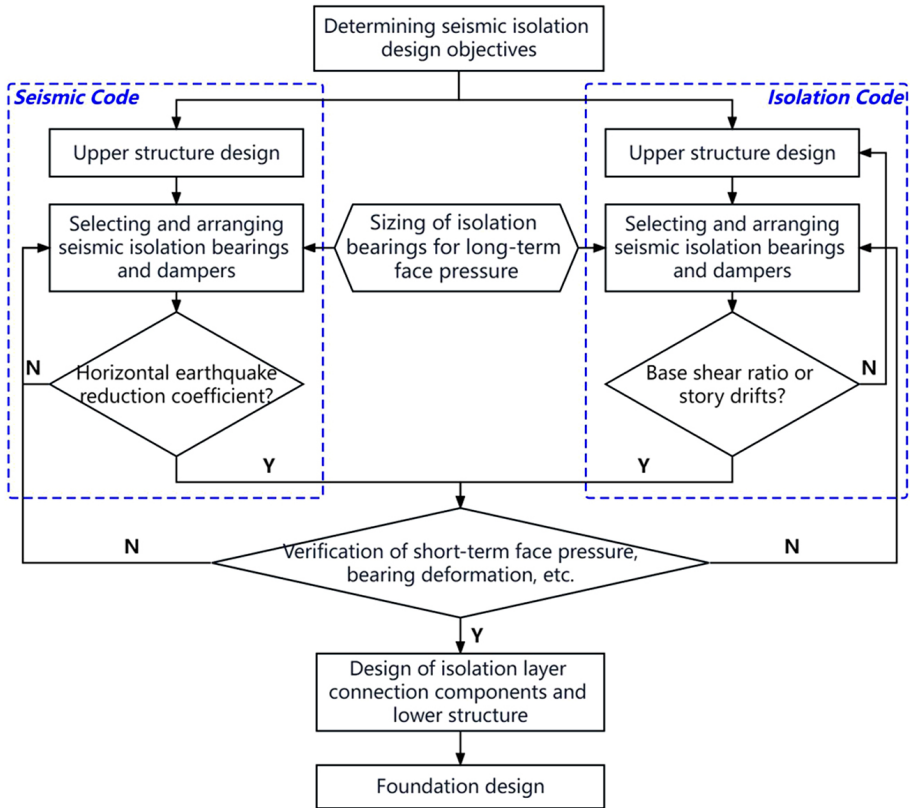
Fig. 1. Seismic isolation design process of two design codes

deformation characteristics and load conditions [6], making it a more practical approach. In contrast to the Seismic Code, the Isolation Code mandates the use of mode-acceleration response spectrum analysis in addition to time history analysis when the building height exceeds 24 meters. Moreover, the Isolation Code designates the fortification earthquake as the seismic level for structural elastic design, leading to significantly enhanced design objectives compared to the Seismic Code. However, this design adjustment may impact on the amount of reinforcement required.

2.2. Response spectrum

The Seismic Code's response spectrum is segmented into four segments, featuring a linear descending segment within the range of 5Tg to 6 s. In contrast, the Isolation Code's response spectrum is divided into three segments, and within the range of 5Tg to 6 s, it still exhibits a curved descending segment. When employing isolation structures to extend the structural period, the reduction in seismic action becomes more pronounced, accentuating

the effectiveness of isolation. This is advantageous for promoting the application of isolation in high-rise building structures and simplifies the selection of seismic records that adhere to the code's response spectrum.

2.3. Design objectives

The Isolation Code has elevated the design objectives from achieving an "elastic response to frequent earthquakes" to an "elastic response to fortification earthquakes", necessitating the verification of structural bearing capacity and deformation during moderate seismic events. Additionally, the objective of "not collapsing in rare earthquakes" has been heightened to "repairable after rare earthquakes", indicating that future isolated buildings will exhibit a higher degree of repairability, thereby offering increased assurance for the safety of lives and properties ultimately contributing to enhanced well-being.

Simultaneously, the Isolation Code introduces elevated requirements for the story drift angle during fortification and rare earthquakes. The upper structure of RC frames is subject to a limit of 1/400 for the story drift angle during fortification earthquakes, and the limit for the story drift angle during rare earthquakes has been increased from 1/50 to 1/100. These modifications are expected to contribute to significantly enhanced structural performance.

2.4. Base shear ratio

The Isolation Code has dispensed with the concept of horizontal earthquake reduction coefficients, introducing the base shear ratio as a replacement to gauge the effectiveness of seismic isolation. Moreover, it has relaxed the requirement, allowing the base shear ratio to be not greater than 0.5, thereby permitting the use of a reduction factor in the design of the upper structure. This change holds significant importance for the advancement and promotion of high-rise seismic isolation technology.

3. Engineering case analysis

3.1. Engineering overview

This case study involves a RC frame structure designed for a seismic design intensity of 8 degrees (0.2 g). The design earthquake group is categorized as the second group, and the site is classified as category III. The characteristic period of the structure is 0.55 s. The building comprises multiple floors with varying heights: the first floor has a height of 6 m, the second floor is 3.6 m, and floors 3 to 6 have a uniform height of 3.3 m. The total height of the building is 18 m (the influence of the partially protruding part on the rooftop can be neglected and has thus not been considered). The concrete strength for all components is designated as C30, and the thickness of the floor slabs is uniformly 120 mm. The reinforcement used throughout the structure is of grade three. The three-dimensional model of the building is shown in Figure 2, and the floor plan is illustrated in Figure 3.
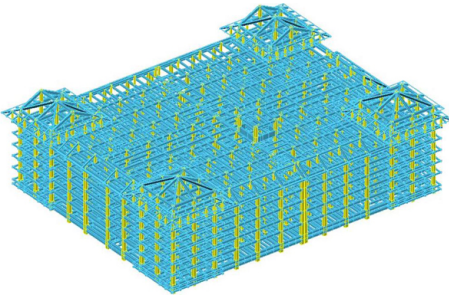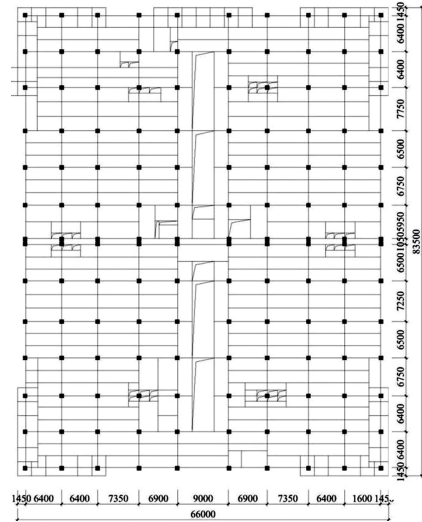
Fig. 2. Architectural 3D model

Fig. 3. Structural layout diagram

3.2. Design principles

To facilitate an effective comparison between the Isolation Code and the Seismic Code, the following design principles are adopted for the seismic isolation design.

1. The seismic isolation design employs the same arrangement of isolation bearings, as illustrated in Figure 4. The chosen isolation bearings consist of LNR (*Linear Natural Rubber bearing*) and LRB (*Lead Rubber Bearing*). Detailed parameters of the selected isolation bearings are provided in Table 2.

2. The seismic isolation design objectives for both codes aim to reduce the seismic intensity by one degree. According to the Seismic Code, the reduction factor for the designed structure should not exceed 0.4. In contrast, for the Isolation Code, the base shear ratio should not exceed 0.5.

3. The structure designed according to the Isolation Code undergoes iterative optimization until the base shear ratio, story drift angle, or any other specified control criterion reaches the code's specified limits. This iterative process aims to determine the control parameters of the model in accordance with the Isolation Code.

4. The structure designed according to the Seismic Code is analyzed using the time history analysis method, whereas the structure designed according to the Isolation Code adopts the mode-acceleration response spectrum method based on complex mode decomposition [12–14]. The equivalent stiffness and equivalent damping ratio of the isolation bearings are determined using an iterative approach.

5. For the purpose of comparison, the design objectives for both cases were set to mid-level elastic response to fortification earthquakes.

Table 2. Properties of the Isolation bearing

Model	LNR800	LNR900	LRB800
Symbol	●	■	▲
Number of supports	48	32	60
Total rubber thickness (mm)	150	160	150
100% equivalent horizontal stiffness (kN/m)	1470	1690	2640
Post-yield stiffness (kN/m)	–	–	1430
Yield force (kN)	–	–	166
Rubber shear modulus (N/mm^2)	0.4	0.4	0.4
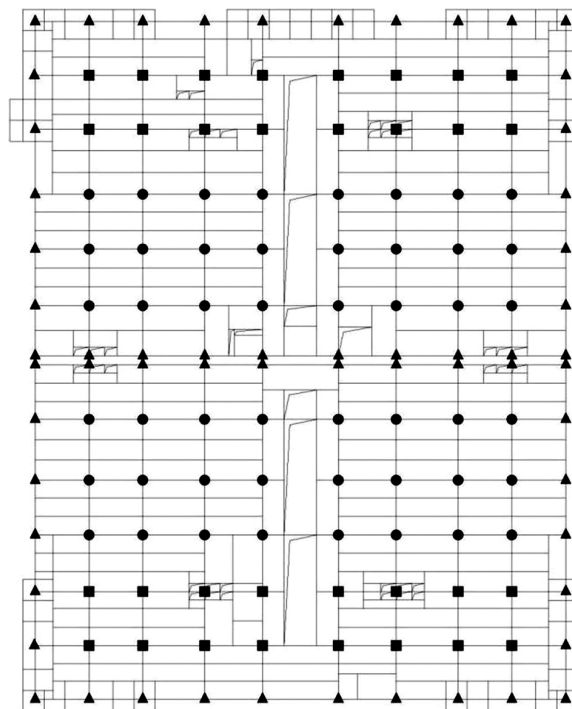
Fig. 4. Vibration isolation pad arrangement plan

3.3. Design results and analysis

3.3.1. Earthquake wave selection

The basic periods of the structure before and after seismic isolation are shown in Table 3. It is evident that the isolation layer has a notable impact on the dynamic characteristics of the structure. The inclusion of the isolation layer results in a reduction in the lateral stiffness of the structure, leading to a considerable increase in the natural period. Importantly, the first three periods of the isolated structure are all more than three times longer than those of the non-isolated structure.

Table 3. Comparison of fundamental periods before and after seismic isolation

Type	Period No.	Period before isolation (s)	Period after isolation (s)
Seismic Code	1	0.913	3.462
	2	0.902	3.410
	3	0.892	3.404
Isolation Code	1	0.947	3.436
	2	0.937	3.407
	3	0.934	3.376

In this study, a total of 7 earthquake records were chosen for elastic time history analysis, comprising 2 artificial waves and 5 natural waves, as shown in Table 4. The comparison between the earthquake acceleration response spectrum and the code design spectrum is illustrated in Figure 5 and Figure 6. From the figures, it is evident that the selected earthquake records satisfy the requirement that the difference between the response spectrum of a single earthquake record and the code spectrum does not exceed 35% at the main periods, and the average earthquake response spectrum does not exceed 20%. The chosen exhibit statistical consistency with the code spectrum.
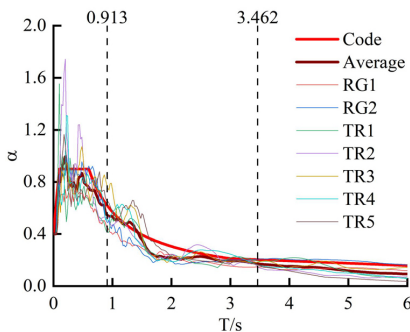

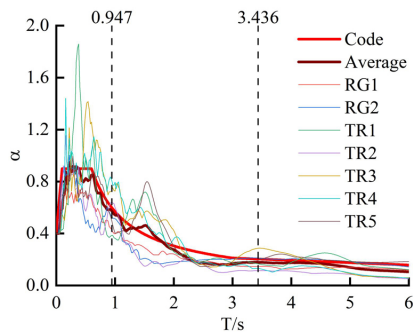Fig. 5. Comparison of seismic wave response spectra of seismic codes and normative spectra

Fig. 6. Comparison of seismic wave response spectra of seismic isolation code and normative spectra

3.3.2. Design results for the upper structure

This paper employs PKPM for seismic isolation design. Following the aforementioned design principles, the cross-sectional dimensions of the main components are shown in Table 4.

Table 4. Dimensions of main components (unit: mm)

Floor No.	Element	Seismic Code	Isolation Code
3–6	Column	700×700	600×600
	Beam	300×500 350×650 350×700	300×450 350×650 350×700
2	Column	750×750	700×700
	Beam	300×500 350×650 350×700	300×450 350×650 350×700
1	Column	900×900	900×900
	Beam	300×600 400×700	300×550 400×700

When designing the structure in accordance with Isolation Code, it is possible to reduce the column cross-sectional area on floors 3 to 6 by 26.53%, and the beam cross-sectional area can be reduced by 10%. On the second floor, the column cross-sectional area can be reduced by 12.89%, and the beam cross-sectional area can be reduced by 10%. On the first floor, the beam cross-sectional area can be reduced by 8.33%. These reductions contribute to an enhancement in space utilization.

3.3.3. Critical response analysis

The critical response results of structures under the Seismic Code and the Isolation Code are shown in Table 5. Under Isolation Code, the story drift angle for the fortification earthquake is calculated to be 1/418, closely approaching the specified limit of 1/400. This value is also 31.14% lower than the story drift angle calculated under the Seismic Code, which is 1/292. Similarly, Under the Isolation Code, the story drift angle for the rare earthquake is calculated to be 1/171, closely approaching the specified limit of 1/100. This value is 19.88% lower than the story drift angle calculated under the Seismic Code, which is 1/137. Therefore, it is evident that the Isolation Code employs the story drift angle as its control criterion, while the Seismic Code utilizes the horizontal earthquake reduction coefficient. This distinction arises due to the relatively large load-bearing capacity of a ceramic jar storage compared to conventional buildings, making it susceptible to loads similar to those experienced by high-rise buildings.

From Table 5, it can be observed that seismic isolation design based on the Isolation Code significantly reduces the seismic response of the upper structure. Consequently, the upper structure can embrace a more flexible design scheme, thereby reducing the intricacy

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of seismic isolation design for high-rise buildings. Additionally, the story drift angle of the isolation layer, based on the Isolation Code, experiences a reduction of 37.5%, indicating that the seismic response calculated according to the Isolation Code is smaller compared to the response calculated according to the Seismic Code.

Table 5. Comparison of main response indicators of two design codes

Key indicators	Seismic Code	Isolation Code	Increase
Horizontal earthquake reduction coefficient (Base shear ratio)	0.35	0.41	17.14%
Maximum story drift angle under fortification earthquake	1/292	1/418	−31.14%
Maximum story drift angle under rare earthquake	1/137	1/171	−19.88%
Average shear force at the first story under fortification earthquake (kN)	23649	15178	−35.82%
Maximum displacement of isolation layer (mm)	504	315	−37.5%

From Figure 7, it can be observed that the elastoplastic story drift angle under the rare earthquake in the X-direction for structures designed according to the Isolation Code and the Seismic Code are generally consistent on floors 5 to 6. In the Y-direction, they are generally consistent on floors 4 to 6. The maximum elastoplastic story drift angle in the X-direction for structures designed according to the Seismic Code occurs on the 2nd floor, with a value
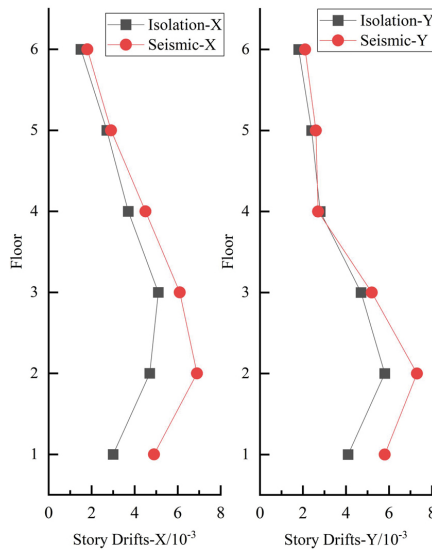

Fig. 7. Comparison of elastic-plastic story drift angle

of 1/144. In the Y-direction, it occurs on the 2nd floor with a value of 1/137. For structures designed according to the Isolation Code, the maximum elastoplastic story drift angle in the X-direction occurs on the 3rd floor, with a value of 1/198. In the Y-direction, it occurs on the 2nd floor with a value of 1/171. Importantly, all of these values meet the code requirements.

3.3.4. Economic analysis

Economic indicators play a crucial role in the selection of structural design schemes [15–17]. The difference between the Isolation Code and the Seismic Code lies in the varying dimensions of beams and columns in the upper structure. Therefore, a comparison of the concrete and steel reinforcement quantities along with their associated costs for beams and columns is shown in Figure 8 and Figure 9.
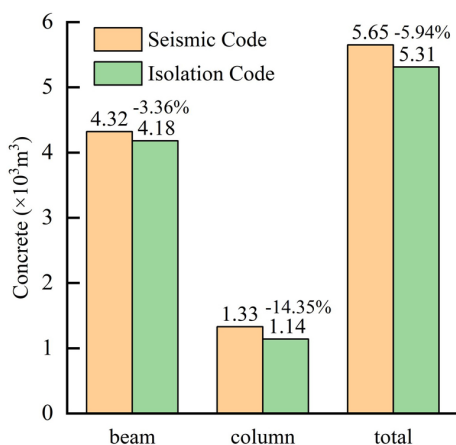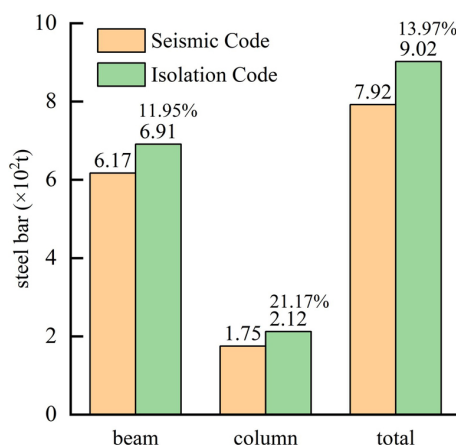

Fig. 8. Comparison of concrete consumption

Fig. 9. Comparison of steel reinforcement quantity

Due to the adoption of a more flexible design scheme for the upper structure, certain structural components have experienced a reduction in dimensions, leading to an overall decrease in concrete usage in the design based on the Isolation Code compared to the design based on the Seismic Code. In comparison to the Seismic Code, the concrete usage for beams has decreased by 3.36%, and for columns, it has decreased by 14.35%.

In terms of reinforcement, the Seismic Code conducts reinforcement design for the entire structure after seismic isolation, based on the frequent earthquake response spectrum under the original seismic design intensity. Conversely, the Seismic Code performs reinforcement design by analyzing the upper structure's fortification earthquake response spectrum with a one-degree reduction. Overall, the reinforcement quantity based on the Seismic Code is higher than that based on the Isolation Code, with an increase of 11.95% and 21.17% in steel reinforcement usage for beams and columns, respectively.

Based on the information obtained from the Nanjing Engineering Cost Information Website in June 2023, the average price of C30 concrete is 517 yuan/m³, and the price of HRB400 steel is 4476 yuan/ton, calculations reveal that the cost of the design based

on the Seismic Code is 6,463,820 yuan. In contrast, the cost of the design based on the Isolation Code is 6,785,464 yuan, resulting in a 4.98% increase compared to the Seismic Code. Therefore, it can be observed that designing the project using the Isolation Code method would incur an additional cost.

3.3.5. Member damage analysis

This paper employs PKPM-SAUSAGE for rare earthquake elastoplastic analysis, utilizing the seismic waves illustrated in Figure 5. In conjunction with relevant literature and specifications, the damage states of components are categorized into 6 levels: undamaged, slightly damaged, moderately damaged, severely damaged, and seriously damaged [18–24]. The damage levels of beams and columns are shown in Figure 10 to Figure 13.
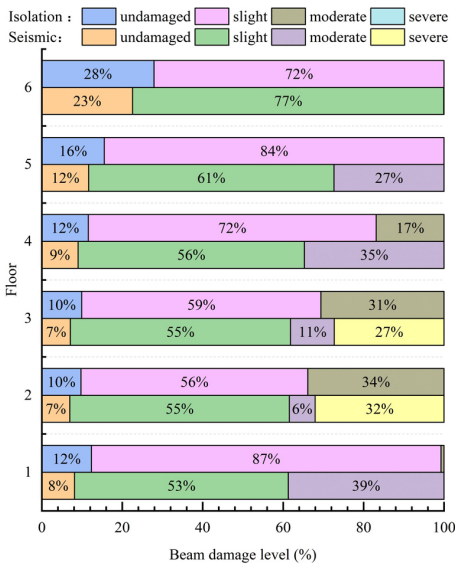
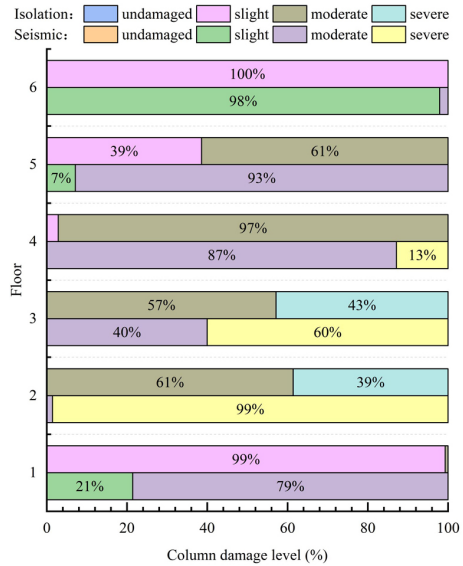Fig. 10. Comparison of beam damage (by floor)

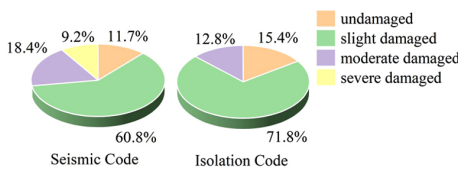Fig. 11. Comparison of column damage (by floor)
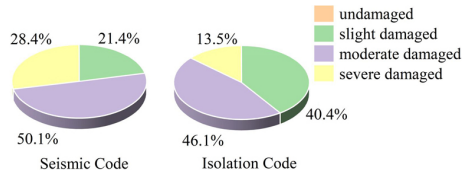

Fig. 12. Comparison of beam damage (total)

Fig. 13. Comparison of column damage (total)

For beams designed based on the Seismic Code, the proportion of undamaged and slightly damaged beams is 72.5%, with only 9.2% of the beams showing moderate damage at performance level 3. In contrast, for beams designed based on the Isolation Code, the

proportion of undamaged and slightly damaged beams is 87.2%, and there are no beams with moderate damage, with a performance level of 2. In both individual and overall comparisons, the damage level of beams designed based on the Isolation Code is relatively lower, indicating a higher level of safety [25]. Additionally, as the number of stories increases, the damage level of beams gradually decreases, aligning with the fundamental theoretical pattern.

For columns designed based on the Seismic Code, the proportion of slightly damaged and moderately damaged columns is 71.5%, with a performance level of 4. In comparison, for columns designed based on the Isolation Code, the proportion of slightly damaged and moderately damaged columns is 86.5%, also with a performance level of 4. Similar to beams, in both individual and overall comparisons, the damage level of columns designed based on the isolation code is relatively lower, indicating a higher level of safety. The damage level of columns from the 2nd to 6th story decreases gradually with the increase in the number of stories, while the 1st-story column has a larger cross-section, resulting in a lower damage level.

The above research indicates that under the same design objectives, structures designed according to the Isolation Code are relatively safer and exhibit better reparability compared to those designed following the Seismic Code.

4. Conclusions

Based on the comparison between the Seismic Code and the Isolation Code, this paper conducted seismic isolation design for an RC frame structure of a ceramic jar storage. The study focused on the design methods, structural responses, economic analysis, and post-earthquake damage assessment. The conclusions obtained are as follows:

1. The Isolation Code elevated the design objectives to "undamaged after fortification earthquakes, repairable after rare earthquakes, and uncollapsed after extremely rare earthquakes". It replaces the horizontal earthquake reduction coefficient with the base shear ratio and employs the unitary calculation design method, which considers the building's deformation characteristics and force state, making it more aligned with practical scenarios.

2. Compared to structures designed following the Seismic Code, structures designed according to the Isolation Code exhibit an overall reduction in cross-sectional dimensions of components by around 10–20%, resulting in improved space utilization.

3. In comparison with the Seismic Code, the Isolation Code results in a 31.14% decrease in maximum story drift angle for fortification earthquake and a 19.88% decrease for rare earthquake, enabling the adoption of a more flexible design approach for the upper structure.

4. The concrete usage for structures based on the Isolation Code is reduced by 5.94%, while the steel reinforcement increases by 13.97%. Consequently, the total cost, calculated based on average market prices, experiences a certain increase.

5. Structures designed under the Isolation Code exhibit a 14.7% relative reduction in damage for beam components with higher performance levels, and a 19% relative reduction in damage for column components. This indicates that the designed

components are safer and possess stronger repairability when compared to those under the Seismic Code.

6. This paper is based on a case study of the ceramic jar storage, which can provide a reference for the design of other ceramic jar storage. Also, the case is applicable to RC frame structures that require seismic isolation design and have large loads.

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