Design and evaluation of seismic resilient building structures in China

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ABSTRACT

The "Regulations on Seismic Resistance Management of Construction Projects", which came into effect on September 1, 2021, have put forward more stringent seismic performance requirements for newly - constructed buildings situated in high - intensity seismic fortification areas and key earthquake monitoring and defense zones within China. The buildings mainly include schools, kindergartens, hospitals, elderly care institutions, child welfare facilities, emergency command centers, emergency shelters, and broadcast and television facilities. The requirements have undergone a transformation from merely ensuring safety to maintaining normal functionality, which makes the design of seismic resilience buildings essential. In response, Tsinghua University Tsinghua University, in cooperation with relevant organizations, has developed the “Seismic Technology Guidelines Based on Maintaining Normal Functionality of Buildings (RISN-TG046-2023)” and the “Standards for Seismic Resilience Evaluation of Buildings (GB/T 38591)”. To enable users to have a better understanding of these guidelines and standards, this paper elaborates on the key methods and processes involved in the design and evaluation of seismic resilience buildings. The guidelines introduce, for the first time, a dual-control design concept of displacement and acceleration to ensure the protection of structural, non-structural, and equipment elements. Seismic resilience buildings are categorized into Class I and Class II buildings, with corresponding performance targets. The design demands structural elastic-plastic time-history analysis under fortification and rare earthquakes to calculate inter-story drift. If the drift does not meet the specified limits, the structural design must be adjusted. Additionally, floor horizontal acceleration checks must satisfy the limit requirements; otherwise, the structural design need to be revised, or special measures and studies should be implemented. This paper also elaborates on the process of seismic resilience rating for buildings, seismic resilience evaluation indicators, and their calculation methods.

1 INTRODUCTION

A series of earthquakes across the globe have demonstrated that the anti - collapse design of buildings merely under maximum - considered earthquakes is incapable of meeting the demands of resilient city construction. Building seismic resilience is defined as the building's ability to endure seismic actions and restore its normal functions after an earthquake. Although the most recent building seismic design codes have emphasized structural performance - based design, resilience design encompasses not only the structure but also the performance of non - structural components and equipment(Ryan et al., 2016; Zuo et al., 2024). Some researchers provided methods for building seismic resilience design. Mike W. Mieler. et.al(Mieler et al., 2016) provided a conceptual building seismic resilience design framework to both consider structure and non-structure performance using fault tree, and divided the building function into fire safety, structural integrity, weather tightness, building services and usable space. Gebelein et.al (Gebelein et al., 2017) showed that quantitative resilience-based design approach is limited, however, seismic resilience assessment method is established and promoted, such as FEMA-P58, REDi. Matthew D. Joyner et.al(Joyner & Sasani, 2020) compared different story buildings' performance from repair cost and loss of function, and evaluated the difference influences of stiffness, strength and deformation capacity. Then multi-objective optimization was induced to seismic resilience design considering the complex targets facing building safety, function and cost-benefits. (Joyner, Gardner, et al., 2021). Researchers also revealed that recovery-based design is also a perspective to enhance building seismic resilience(Joyner, Kurth, et al., 2021).

Numerous researchers have delved into the study of seismic resilience assessment methods. FEMA P-58, called Next-generation Building Seismic Performance Assessment Methodology is considered as the starting of seismic resilience assessments. The seismic performance is expressed as probability distributions for repair time, cost and casualties (Hamburger et al., 2012). REDi proposed by Arup company considered detailed downtime for assessment of building seismic resilience(Almufti & Willford, 2013). Samadian et.al (Samadian et al., 2019)proposed a seismic resilience evaluation method considered local economic conditions by conducting vulnerability analysis. Jiang(Jiang et al., 2022) proposed a new framework by assembly-based function loss quantification method, and the building function is quantitative evaluated by logic system and logic trees based on consequences analysis of building components.

The development of building seismic resilience design and evaluation is rapid in China. The Regulations on Seismic Resistance Management of Construction Projects, effective from September 1, 2021, impose higher seismic performance requirements for new buildings located in high-intensity seismic fortification areas and key earthquake monitoring and defense zones in China. The buildings mainly include schools, kindergartens, hospitals, elderly care institutions, child welfare facilities, emergency command centers, emergency shelters, and broadcast and television facilities. The requirements have evolved from ensuring safety to maintaining normal functionality, necessitating seismic resilience building design. In response, Tsinghua University collaborated with relevant organizations to develop the Seismic Technology Guidelines Based on Maintaining Normal Functionality of Buildings (RISN-TG046-2023)(Li et al., 2024) and the Standards for Seismic Resilience Evaluation of Buildings (GB/T 38591-2020)(Ren et al., 2021). To help users better understand the guidelines and standards, this paper details the key methods and processes for seismic resilience building design and evaluation.

2 SEISMIC RESILIENCE BUILDING DESIGN

The Research Institute of Standards and Norms Ministry of Housing and Urban-Rural Development released RISN-TG046-2023 'Technical guideline for maintaining normal functionality of buildings in earthquakes' on May 12th, 2023. The guideline is made for technically supporting the new buildings resilience design located in high-intensity seismic fortification areas and key earthquake monitoring and defense zones in China.The flowchart of seismic design procedure for buildings to meet the requirement to maintain functionality was illustrated in detail.

2.1 Guideline Content Overview

The *Guideline* comprises seven chapters, namely “General Principles” ,“Terminology and Symbols”,Basic Regulations ” , “ Seismic action and seismic verification ” , “ Building non-structure components” , “Building mechanical and electrical equipment and functional instruments” , “Maintenance and monitoring ” . This *Guideline* offers a standardized and unified design approach and requirements for the seismic design of buildings that are required to maintain normal functionality during earthquakes.

2.2 Interpretation of key articles

2.2.1 The connotation of maintaining normal functionality of buildings in earthquakes

To maintain normal function during earthquakes, a building must retain its functionality under a design intensity earthquake. This necessitates that both the structural and non - structural components remain basically intact, and the auxiliary mechanical and electrical equipment as well as the functional instrumentation within the building operate normally. Buildings required to maintain normal function during earthquakes include schools, kindergartens, hospitals, elderly care institutions, child welfare facilities, emergency command centers, emergency shelters, and broadcast and television facilities.

2.2.2 The category of building kept normal function in earthquakes

Eight types of buildings are classified into two categories in accordance with Table 1. Class I buildings refer to those that, once damaged, will trigger serious secondary disasters or exert a substantial impact on earthquake relief during and after an earthquake. Class II buildings are those with a high occupancy rate and housing vulnerable groups. The seismic performance target of Class I buildings is higher than that of Class II. For buildings with multiple functions, the classification shall be determined by the designer based on the actual engineering situation.

Table 1: The category of building kept normal function in earthquakes

Category	Building
I	emergency command center； hospital； emergency shelter； broadcast and television
II	school； kindergarten; hospital subsidiary building； old peoples home; Children's welfare institution

2.2.3 The seismic performance target of building kept normal function in earthquakes

The seismic performance targets for buildings that maintain normal functions during earthquakes are as follows. For Class I buildings, when they subjected to earthquakes equivalent to the local seismic design intensity， they can be used without the need for repair. When encountering a rare earthquake, they can resume use after simple repairs. For Class II buildings, when the subjected to earthquakes equivalent to the local seismic design intensity， they can be also used without repair. When subjected to a rare earthquake, they can continue to be used after moderate repairs. imply that the ratio of building repair costs to construction costs is less than 5% and the repair time is less than 7 days. Moderate repairs mean that the ratio of building repair costs to construction costs is less than 10% and the repair time is less than 30 days.

The seismic performance of components in buildings that maintain normal functions during earthquakes is presented in Table 2 and Table 3. In these tables, "intact" indicates that the components remain elastic; "basically intact" means the components remain essentially undamaged; "minor damage" implies that the components may experience minor plastic deformation without affecting normal use; "mild damage" means the components reach the yield state but without obvious plastic deformation; "moderate damage" means obvious plastic deformation occurs, yet it is controlled within the range allowing continued use after moderate repair; "normal operation" means that dampers, bearings, auxiliary electromechanical equipment, and functional instruments and equipment operate as normal.

For non-structure components and equipment, mild damage indicates that the appearance may be impaired without influencing functionality and fire resistance. The safety glass may crack but will not fall. Moderate damage means that the function is basically normal or can be rapidly restored. The fire - resistance time is reduced by one - quarter, the reinforced glass breaks, yet other glass does not fall.

Table 2: Class I building components' seismic performance target

Components	Design earthquake	Rare earthquake
Structure components	Intact or basically intact	Mild or minor damage
Dampers	normal operate	normal operate
Isolation devices	normal operate	normal operate
Non-structure components	basically intact	minor damage
Auxiliary electromechanical equipment	normal operate	minor damage
Functional instruments	normal operate	minor damage

Table 3: Class II building components' seismic performance target

Components	Design earthquake	Rare earthquake
Structure components	basically intact or mild damage	mild or moderate damage
Dampers	normal operate	normal operate
Isolation devices	normal operate	normal operate
Non-structure components	basically intact	moderate damage
Auxiliary electromechanical equipment	normal operate	moderate damage
Functional instruments	normal operate	moderate damage

2.2.4 Design procedure of building kept normal function in earthquakes

The *Guideline* first proposed the design concept of achieving structural, non-structural, and equipment protection through dual control of displacement and acceleration, and provided the corresponding design process（Figure 1）：

1）Determine the initial design plan：Establish structure finite element model according to building and structure design results;

2）Calculate bearing capacity under intermediate earthquakes: Calculate bearing capacity of structural components under intermediate earthquakes;

3）Structure inter-story drift calculation：Elasto-plastic time history analysis under intermediate and rare earthquake， calculate inter-story drift, if the results couldn't meet the requirement of Table 4 and 5, the initial design should be changed and repeat the procedure, if the results could meet the requirements, then move next step;

4）Floor horizontal acceleration calculation：if the results meet the requirement of Table 6, the design is end. The maximum floor horizontal acceleration limits in Table 6 are determined based on a comprehensive consideration of the seismic intensity classification standards, the normal - use limit requirements of building non - structural components, building auxiliary electromechanical equipment, and functional instruments and equipment.(Cosenza et al., 2015; Di Sarno et al., 2019; Rashid et al., 2021) If the result can't meet the requirements, one way is to change the structure design, and the other way is to take specialized measures and analysis for all building non-structure components and equipment, and consider the influence to building normal function.

5）Building seismic resilience evaluation：The analysis can be conducted according to Building Seismic Resilience Evaluation Standard GB/T 38591-2020， Class I should achieve seismic resilience of three stars， Class II should achieve over seismic resilience of two stars.

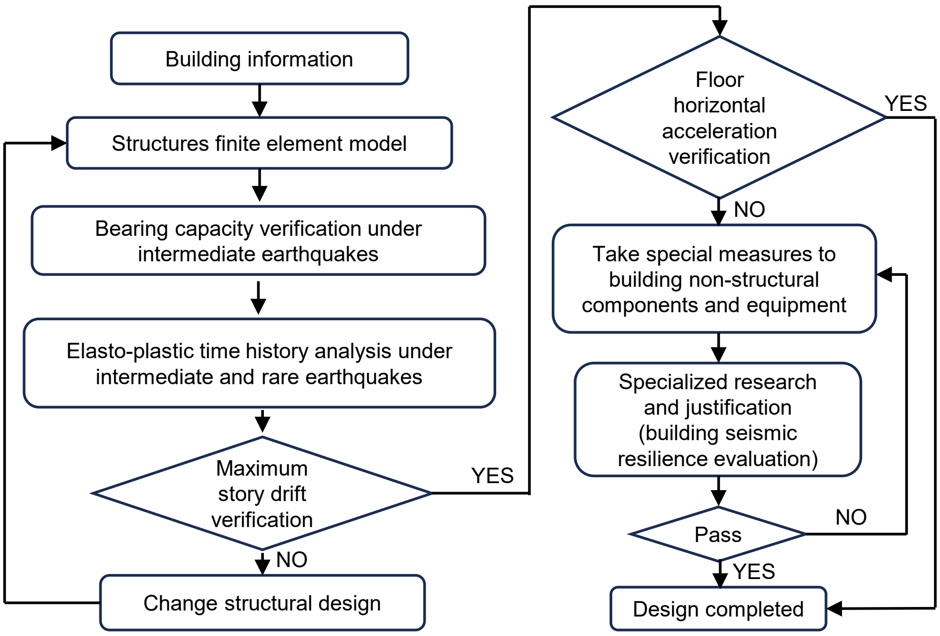

Figure 1: Design procedure of resilient building

Table 4: The drift limiting value under intermediate and rare earthquakes of Class I building

Earthquake level	**Intermediate earthquakes**	**Rare earthquakes**
Reinforced concrete frame	1/400	1/150
Frame-shear walls in bottom frame masonry buildings, Reinforced concrete frame-shear wall, Frame-core tube	1/500	1/200
Reinforced shear wall, slab-column shear wall, core in core, reinforced concrete frame supported layer structure	1/600	1/250

Multi story and high-rise steel structures	1/250	1/100

Table 5: The drift limiting value under intermediate and rare earthquakes of Class II building

Earthquake level	Intermediate earthquakes	Rare earthquakes
Reinforced concrete frame	1/300	1/100
Frame-shear walls in bottom frame masonry buildings, Reinforced concrete frame-shear wall, Frame-core tube	1/400	1/150
Reinforced shear wall, slab-column shear wall, core in core, reinforced concrete frame supported layer structure	1/500	1/200
Multi story and high-rise steel structures	1/200	1/80

Table 6: The limiting value of floor horizontal acceleration of building kept normal function/g

Earthquake level	Intermediate earthquakes	Rare earthquakes
Class I	0.25	0.45
Class II	0.45	-

2.2.5 Building non-structure component, building equipment and functional devices

Building kept normal function in earthquakes need choose suitable building non-structure components and equipment under the results of drift ratio and floor horizontal acceleration in intermediate earthquakes. The non-structure components and equipment should suit the drift ratio and floor horizontal acceleration at its position. When the components couldn't adapt to the drift and floor horizontal acceleration, the component should be changed or specialized measures should be taken. Specialized measures include adding supports, installing energy dissipating and isolation devices, and strengthening anchoring measures. For components lacking data support, specialized experiments should be carried out.

3 SEISMIC RESILIENCE BUILDING EVALUATION

The Standards for Seismic Resilience Evaluation of Buildings (GB/T 38591-2020) in China is developed by Tsinghua University and other universities, design companies and construction companies in China.

3.1 Standard Content Overview

This standard includes 9 chapters, namely "Ranges" " Normative reference documents" "Term and definition" "Requirements" "Determination of Building Damage Status" "Calculation of Building Restoration Costs" "Calculation of Building Repair Time" "Personnel casualty calculation" and "Building seismic resilience evaluation" . This standard is based on on-site investigation experience of earthquake damage and a large amount of experimental data, fully utilizing research results in the field of seismic engineering such as performance-based design of building structures, damage control theory, and reliability evaluation methods. It has formulated evaluation methods for the damage status, repair cost, repair time, and personnel casualties of buildings under the determined level earthquake, and specified the evaluation methods and grading standards for the seismic resilience of buildings.

3.2 Interpretation of key articles

3.2.1 Building seismic resilience evaluation procedure

The building seismic resilience evaluation should be determined according to the rating process shown in Figure 2.

（1）Building information collection. The building is divided into different structure and non-structure components. The design information is collected, and the components are divided into “deformation sensitive components” and “acceleration sensitive components” according to the sensitivity level to engineering demand parameters such as drift ratio and floor acceleration, preparing the subsequent seismic resilience evaluation based on the vulnerability of building components.

（2）Structure model establishment. The model is within the range from the embedded bottom of the structure to the top story. The model is created according to the structure design drawings. For existing building, the standard requires to check actual situation. If there are changes that affect the structural performance, they should be reflected in the structural model.

（3）When employing the time-history analysis, it is required to select at least 11 sets of real seismic waves and artificially created acceleration time history categorized by the type of building site and the design earthquake group. Of these 11 waves, at least two-thirds must be actual seismic recordings. The ground motion is controlled by both peak acceleration and velocity.

（4）Extraction of engineering demand parameters. The engineering demand parameters, which include the inter-story drift ratio in two perpendicular directions and the floor acceleration responses at each level of the structure, are derived from the results of elasto-plastic time-history analysis. By analysing the relationship between structural inter-story drift ratio, floor accelerations, and the corresponding deformations and accelerations of the components, a correlation is established between these engineering demand parameters and the vulnerability data of the components.

（5）Determination of inter-story residual deformation. Inter-story residual deformation refers to the deformation between floors after the seismic event has ended and the structure has stopped shaking. It is recommended to use the average results from elasto-plastic time history analyses conducted at the level of rare earthquakes, and then compare the average of the maximum inter-story residual deformations with the prescribed limit for such deformations. If the average exceeds this limit, the building is deemed irreparable, and the resilience evaluation process is halted. If it is below the limit, resilience evaluation process can proceed. For residential or public buildings made of reinforced concrete or steel, the recommended limit for interstory residual drift ratio is 1/200(McCormick et al., 2008).

（6）Expansion of engineering demand parameter matrix. Using Monte Carlo simulation method to expand the engineering demand parameter matrix, it is required that the mean vector and covariance matrix of the engineering demand parameter matrix remain unchanged before and after expansion. The number of Monte Carlo simulations shall not be less than 1000 times.

（7）Determination of building damage status. The damage status of a building is determined jointly by the damage status of all components. During the evaluation process, the damage status of the components is determined using Monte Carlo simulation based on engineering demand parameters and component vulnerability data.

（8）Evaluation of sub indicators. The seismic resilience index includes building repair cost index, repair time index, and personnel casualties’ index.

（9）Evaluation of seismic resilience level of buildings. Based on the sub indicators obtained from multiple Monte Carlo simulations, a fitting value with an 84% guarantee rate is used to evaluate the seismic resilience level of buildings. To express simply and clearly of the evaluation results, the seismic resilience level of buildings is classified into 3 stars. This standard requires that the level of resilience evaluation be given in the form of signage, which is more conducive to the public's intuitive understanding of building seismic resilience.

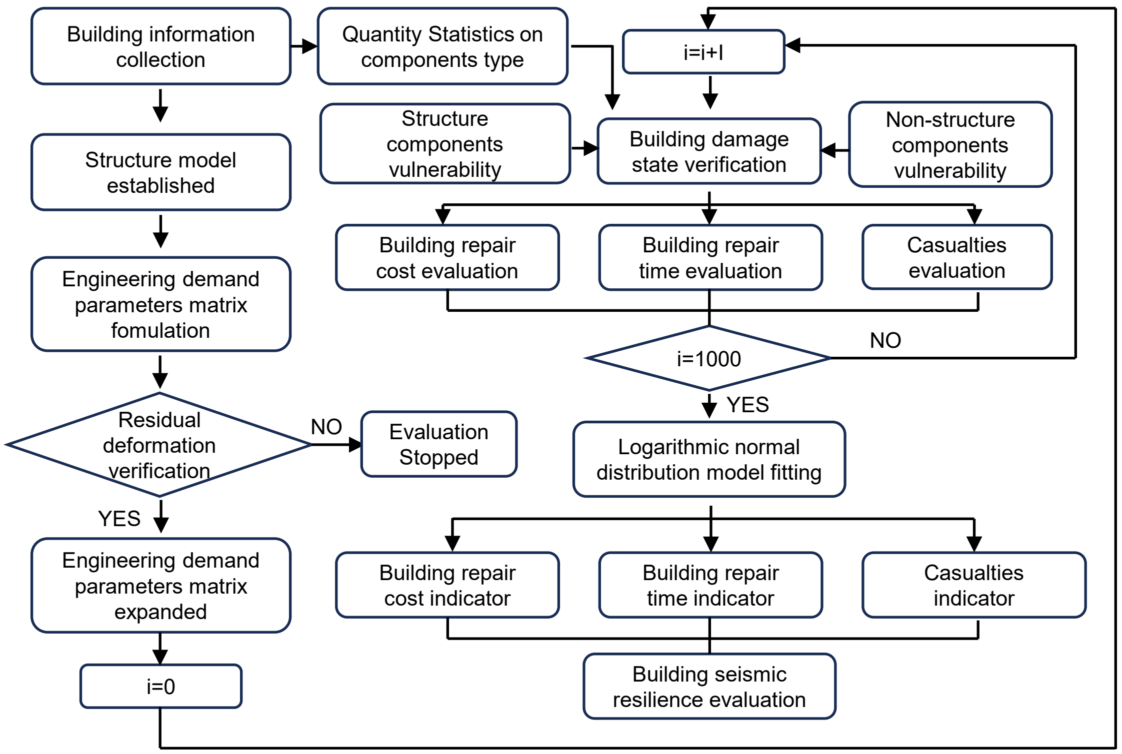

Figure 2: Building seismic resilience evaluation

3.2.2 Building seismic resilience evaluation indicators

（1）Building repair cost

The assessment of building repair costs should consider the comprehensive restoration of functionality for earthquake-damaged components. Among these costs, the proportion of expenses dedicated to decoration and finishing should not be overlooked in the overall repair cost. The indirect economic losses of buildings are not considered in this standard. The building repair costs described in this standard are only related to the direct economic losses incurred by earthquake damaged buildings.

（2）Building repair time

The repair time of the building should be included in the repair time required for all earthquake damaged components and equipment to complete the functional restoration of the building. This standard only calculates the time spent on on-site repair work. The impact of repair strategies should be considered during the on-site repair phase. The repair strategy includes two types: parallel repair and serial repair. Parallel repair strategy is used between layers, and a mixture of serial and parallel strategies is used within layers.

（3）Personnel Casualties

The calculation of casualties is based on the story as the basic unit, and the possible number of injuries or deaths is obtained by multiplying the injury rate or death rate, personnel density, and the number of people on the floor. The emphasis here is on injury and mortality rates, without highlighting the actual number of casualties, which avoids causing psychological impact on users and the public.

3.2.3 Building seismic resilience evaluation standards

Overall, the standard adopts the methods of sub item evaluation and integrated rating to assess the seismic resilience of buildings.

This standard categorizes the seismic resilience levels of buildings into three levels, with one star, two star, and three-star ratings used from low to high. This standard divides the determination of seismic resilience levels into two stages：

1）Firstly，calculate the seismic resilience indicators under intermediate earthquakes（building repair cost，building repair time and casualties）. Compared the results to the standard of one star. If the criteria are not met, further evaluation is unnecessary. However, if the requirements are satisfied, the evaluation process can proceed to the next stage.

2）Based on the seismic resilience evaluation results under rare earthquakes, compare the results to the standard of two star and three star criteria. If the requirements are satisfied, the evaluation level is promoted, otherwise, the resilience level is one star.

4 CONCLUSION

1) The *Guideline* firstly proposed the design concept of achieving structural, non-structure, and equipment protection through dual control of displacement and acceleration, and provided the corresponding design process

2) The *Guideline* aim to ensure that buildings can meet normal usage requirements when subjected to earthquakes equivalent to the intermediate seismic intensity of the local area. They require load-bearing capacity design based on intermediate earthquake, and through structural deformation and floor horizontal acceleration verification, can ensure that the structural and non-structural components of the building are basically intact, as well as the normal operation of the building's ancillary mechanical and electrical equipment and functional instruments.

3) The "Evaluation Standard for Seismic Resilience of Buildings" evaluates buildings as a product for the first time in China, paying more attention to the multi-level effect of building resistance to earthquake action, establishing localized component vulnerability database.

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