Research Review on Earthquake Resilient Structures

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Abstract. As researchers summarized their experiences with earthquake disasters, they found that the traditional seismic design concept of only regarding preventing collapse of structures under earthquake loads as the primary seismic defense objective for structures, has deficiencies in post-earthquake use and repair. Therefore, the concept of resilient structure design was proposed, which enables structures to quickly repair to pre-earthquake functional levels after earthquakes. Currently, the concept of resilience is gradually becoming the core theory of seismic design. This paper reviews the shortcomings of traditional seismic design concepts, introduces the two core objectives of resilient structure design, namely "reducing post-earthquake residual deformation" and "reducing post-earthquake structural damage and damage concentration." Resilient structures are mainly classified into rocking structures, structures with self-centering braced, and structures with replaceable member according to their implementation methods. The principles and research progress of these three structures are summarized. The deficiencies of existing building structural seismic performance are analyzed, and the reinforcement technology and practical engineering extension applications of the resilience concept in the reinforcement of existing structures are introduced. The prospects of the resilience concept in interdisciplinary research, post-disaster structural damage analysis, practical engineering applications, and other aspects are proposed.

Keywords: earthquake resilient structure; rocking; self-centering structure; structure with replaceable member; existing structural reinforcement.

1. Introduction

The traditional seismic design concept aims to prevent the collapse of structures under earthquake loads as the primary seismic defense objective, in order to ensure the safety of people inside the building and provide them with escape opportunities. To achieve this seismic design concept, structures are allowed to undergo ductile deformation under earthquake loads to dissipate seismic energy and avoid brittle failure. However, a large amount of earthquake disaster experience shows that buildings designed based on traditional seismic design concepts suffer significant damage during earthquakes, with concrete crushed at the bottom of columns, and reinforcing steel at joints yielding. Severe residual deformation after earthquakes makes post-earthquake repair work difficult, even though the objective of "not collapsing in a major earthquake" is achieved. For example, the 7.8 magnitude earthquake that occurred in Kaikōura, South Island, New Zealand in November 2016 caused casualties, severe damage to infrastructure, and deformation and damage to buildings in the central business district, requiring significant cost for structural damage repair [1]. With the summary of earthquake disaster experiences, researchers gradually realize that the traditional seismic design concept, which only considers preventing structural collapse after earthquakes, is incomplete. The resilience of structures after earthquakes should also be considered as one of the main seismic defense objectives.

In 2003, American scholar Bruneau et al. first proposed the concept framework of seismic resilience of communities and supplemented measures to enhance structural resilience [2]. In January 2009, "resilient cities" were identified as the future direction of earthquake engineering cooperation at the second stage of the US-Japan Earthquake Engineering Cooperative Research Conference [3]. In 2011, Chinese scholars Lu et al. proposed the new concept of resilient structure as the seismic design of structures [4]. In November 2015, the 10th Pacific Conference on Earthquake Engineering in Australia proposed new measures for a more resilient society [5]. In January 2016, the annual meeting of the Pacific Earthquake Engineering Research Center (PEER) in the United States emphasized the importance of research in the field of resilience [6]. In September 2016, the First International Resilience workshop (IRW2016) was held in Turin, Italy, exploring new directions based on resilience-based design from scholars in the Americas, Asia, and Europe [7]. In April 2017, the theme conference "The Next Generation of Low Damage and Resilient Structures" was held in Wellington, New Zealand, discussing research directions and trends for improving structural seismic performance [8]. The research focus in the field of earthquake engineering is shifting from resisting earthquakes to reducing post-earthquake damage and impacts. Resilience-based design has become a hot topic at major international conferences on earthquake engineering, and the seismic design concept based on structural resilience is gradually recognized as a new concept and trend for the next generation of seismic structural design.

Currently, many practical engineering projects have adopted seismic defense technologies to enhance structural seismic performance by improving structural resilience, mainly in countries such as the United States, New Zealand, and Japan. For example, in 2001, in the seismic retrofit of a 14-story building in Berkeley, California, Tipping and Mar Company used the rocking shear wall structure for the first time, to reduce earthquake damage to the structure through the wall's rocking motion [9]. In 2007, in the construction of the Santa Clara Medical Center Hospital, as shown in Figure 1, the structure's resilience after earthquakes was achieved by installing viscous dampers for diagonal bracing within the frame structure [10].

Figure 1 Santa Clara Medical Center Hospital construction with damping diagonal braces.

This paper first reviews the shortcomings of traditional seismic design concepts, and then introduces the concept of earthquake resilient structures, which aims to reduce the residual deformation and damage of structures to achieve rapid post-earthquake repairation. Based on different ways of achieving resilience, earthquake resilient structures are classified into rocking structures, structures with self-centering braced, and structures with replaceable member. The principles and research progress of these three types of resilient structures are summarized. Finally, the application of resilience measures in engineering practice is presented, where resilience technology plays an important role in reinforcing existing structures. The overall framework of the paper is shown in Figure 2.

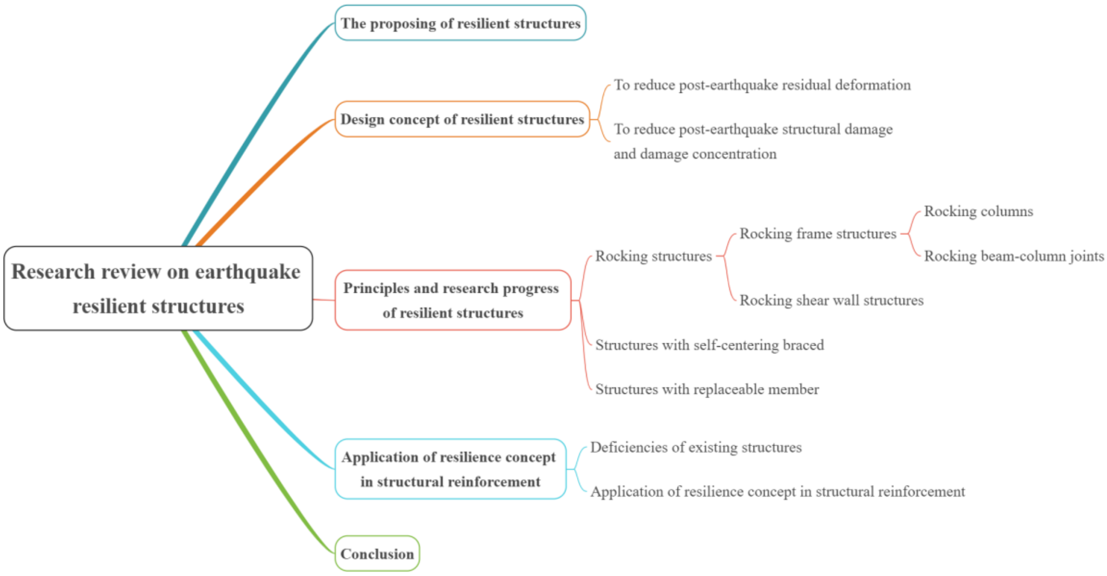


Figure 2 Main research content of the paper.

2. Design Concept of Resilient Structures

Regarding the design concept of earthquake resilient structures, Callister [11] proposed that resilience refers to the ability of a structure to withstand the impact of an earthquake without permanent deformation. Lu et al. [4] defined earthquake resilient structures as structures that can repair their functional use after an earthquake without or with minimal repair. Zhou et al. [12] proposed the concept of earthquake resilience, as shown in Figure 3, where curve A represents a traditional structure, curve B represents a resilient structure, and the shaded area below curve B indicates the size of its resilience. From the figure, it can be seen that the post-earthquake repairation ability of resilient structure B is greater than that of traditional structure A. Specifically, traditional structure A suffers severe functional loss under earthquake action, and the post-earthquake repairing work requires more time. After repairation, its functional use may still not reach the pre-earthquake level. However, resilient structure B has less functional loss under earthquake action, and the repairation time is shorter. After a certain post-earthquake repairation, its functional use can reach the pre-earthquake level. Moreover, if the weaknesses of resilient structure B can be reinforced and improved, the functional use of the repaired structure can exceed the pre-earthquake level, as shown by curve C.

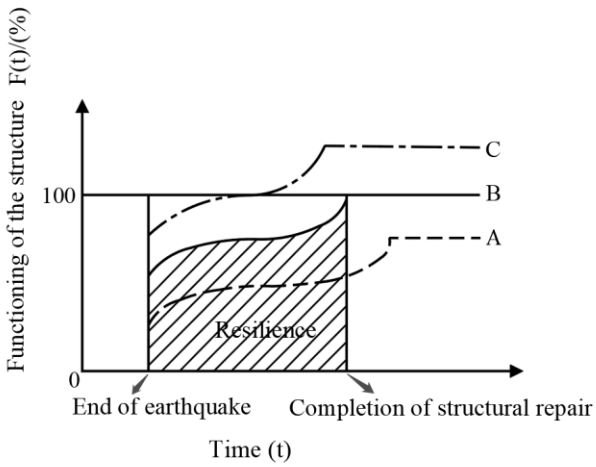


Figure 3 Concept of earthquake resilience.

To achieve post-earthquake resilience, it is necessary to minimize or avoid irreversible residual deformation of the structure after an earthquake, or to allow the structure to dissipate energy at specific locations, where replacement can be done directly after the earthquake. Therefore, the implementation of the earthquake resilient design concept should focus on two aspects: first, to minimize the residual deformation of the structure after an earthquake, and second, to minimize the damage of the structure under earthquake action or to concentrate the damage at specific locations for later replacement. This section will introduce these two aspects in detail.

2.1 To Reduce Post-Earthquake Residual Deformation

In 1965, Newmark proposed a concept for calculating residual deformation [13]. Later, scholars suggested controlling the residual deformation of structures within 0.2%. If the post-earthquake residual deformation of a structure is less than 0.2%, it is considered still usable. For structures designed based on traditional seismic design concepts, Ruiz-Garcia and Miranda [14] calculated the maximum roof residual deformation of four different frame structures with varying numbers of floors and spans (Christidis et al. [15] supplemented the calculation results), as shown in Table 1 [14,15].

Table 1 Maximum roof residual deformations of frame structures.

Case	Maximum roof residual deformations (%)
3-story and 6-span	0.45
6-story and 6-span	0.80
6-story and 3-span	1.17
9-story and 6-span	1.58

The calculation results show that the residual deformation values increase with the decrease of the frame structure span and the increase of the number of stories, and all significantly exceed the 0.2% residual deformation control range. Therefore, structures designed based on traditional seismic design concepts have a large degree of residual deformation after an earthquake, which has an adverse effect on the normal use of post-earthquake structures.

In May 1960, an earthquake in Chile caught the attention of Housner. The unstable golf-ball-on-a-tee types of elevated water tanks survived the earthquake due to their rocking motion, while the stable reinforced concrete elevated water tanks suffered severe residual deformation and damage. Based on this phenomenon, Housner [16] simplified the stiff block as a rocking motion, as shown in Figure 4 [16]. By analyzing the dynamic characteristics of the rocking motion and calculating the overturning force of acceleration pulses and half-sine wave pulses on objects, it was found that the vibration characteristics of the rocking motion were different from those of linear elastic structures. Moreover, the stability of tall and slender structures under earthquake action was greater than that under horizontal constant force. With the discovery of this phenomenon, researchers gradually began to focus on how to use the rocking motion of structures at the epicenter and the self-centering brace of post-earthquake structures to reduce residual deformation.

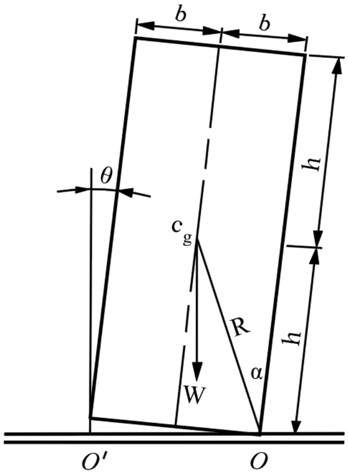


Figure 4 A rocking block.

The reduction of residual deformation in structures emphasizes the active resilience of post-earthquake structural systems, meaning that the structure should always remain in an elastic deformation state as much as possible. The mechanisms for achieving post-earthquake deformation repairation can be divided into rocking mechanisms and self-centering mechanisms, but usually the two are combined to form a resilient structure. In terms of implementation measures, the rocking mechanism is more about relaxing the constraints between the upper structure and the foundation or between the component joints to increase degrees of freedom, allowing the upper structure to undergo rocking motion at the junction with the foundation or relative movement between component joints [9], and utilizing the weight of the components themselves to achieve structural reset. The self-centering mechanism is more about adding post-tensioned reinforcement to structural components such as columns, beams, and shear walls, and using the high yield strength of the post-tensioned reinforcement in combination with concrete components to ensure that the structure always remains in an elastic deformation state under earthquake action, ensuring that the concrete is primarily under compression and not under tension at the junction interface, fully utilizing the mechanical properties of concrete's resistance to compression but not to tension, and ensuring that there is no permanent irreversible residual deformation after the earthquake.

2.2 To Reduce Post-Earthquake Structural Damage and Damage Concentration

Wang [17] analyzed the damage to reinforced concrete structures after the 2008 Wenchuan earthquake in China and found that structures based on traditional seismic design concepts suffered severe component damage and destruction after the earthquake, mainly manifested in global deviation of the upper structure, wall cracking, ductile hinged joints formed at column ends, frame column inclination, Reinforcing steel yielding, concrete detachment of beams and columns, and formation of weak story throughout the entire structure, which are irreversible structural damage after the earthquake. MacRae et al. [18] analyzed the damage to steel structures after the 2010-2011 Christchurch earthquake in New Zealand and found that post-earthquake steel structural components suffered irreversible component damage such as yielding, buckling, and fracture. A large number of actual earthquake damage cases have shown that structures based on traditional seismic design concepts suffer from serious structural damage after earthquakes, and the damage is dispersed and complex, which is very unfavorable for the rapid repairation of the structure after the earthquake.

Reducing and repairing structural damage focuses on the passive resilience of the post-earthquake structural system. Usually, local weakening strategies are adopted, and replaceable components with low yield points are used to promote ductile deformation and passive energy dissipation under earthquake action, thereby reducing structural damage. After the earthquake, components with large residual deformation or serious damage are quickly and conveniently replaced to repair the structure. The purpose of the replaceable device for energy dissipation is to reduce the non-elastic energy dissipation demand of the structural frame system, thereby reducing the damage of earthquake action on the structural system [19,20,10]. Symans et al. [10] proposed a damage measure coefficient (DM) that can quantify the degree of earthquake damage to structures, and the specific calculation method is shown in the following formula.

$$\mathrm{DM} = \frac{\mu_{\mathrm{Demand}}}{\mu_{\mathrm{Capacity}}} + 4\rho \frac{\mathrm{E}_{\mathrm{Demand}}}{\mathrm{E}_{\mathrm{Capacity}}}$$

In the formula, μ_{Demand} represents the maximum displacement ductility demand, μ_{Capacity} represents the ductility capacity, ρ represents the calibration factor, $\mathrm{E}_{\mathrm{Demand}}$ represents the cumulative hysteretic energy dissipation demand, and $\mathrm{E}_{\mathrm{Capacity}}$ represents the hysteretic energy capacity for one full cycle of inelastic deformation. By calculating the DM of single-story frame structures with and without energy dissipation devices under historical earthquake records, it was found that the DM of single-story frame structures without energy dissipation devices is larger under earthquake action, resulting in severe damage and a greater demand for inter-story displacement angle and displacement ductility demand. However, single-story frame structures with energy dissipation devices can resist relative inter-story displacement and velocity through damping devices, thereby greatly reducing the DM coefficient, that is, reducing the degree of damage. From the results, it can be seen that replaceable damping devices can reduce the degree of damage to structures under strong earthquake action.

3. Principles and Research Progress of Resilient Structures

Based on different principles of implementing post-earthquake resilience, existing resilient structures can mainly be divided into three categories: rocking structures, structures with self-centering braced, and structures with replaceable member. This section mainly introduces the working principles and related research progress of these three types of structures.

3.1 Rocking Structures

Rocking structures emphasize loosing rotational constraints and reducing structural damage by allowing column footings to lift and relative motion to occur at nodal interfaces under earthquake action. Self-centering devices are added to achieve post-earthquake resilience, and energy dissipation devices are attached to increase structural energy dissipation capacity. This subsection mainly divides rocking structures into rocking frame structures and rocking shear wall structures according to their rocking types, and introduces these two types of structures.

3.1.1 Rocking Frame Structures

For rocking frame structures, rotational constraints between column bases and foundations, and between beam-column joints are relaxed, allowing column bases to undergo rocking rotation and beam-column joints to undergo rotation under earthquake action, thereby increasing the overall frame structure's deformation capacity. Self-centering and energy dissipation devices are added to enhance the seismic resilience of the structure. In 1997, Clough and Huckelbridge [21] connected the structure and foundation in the form of hinge joint, as shown in Figure 5 [21], and analyzed the effect of column uplift on the structure under earthquake action through shake table tests on steel frame structures. The analysis results showed that the connections of hinge joints between the structure and foundation can significantly reduce the impact of earthquake loads and the demand for structural ductility caused by column uplift.

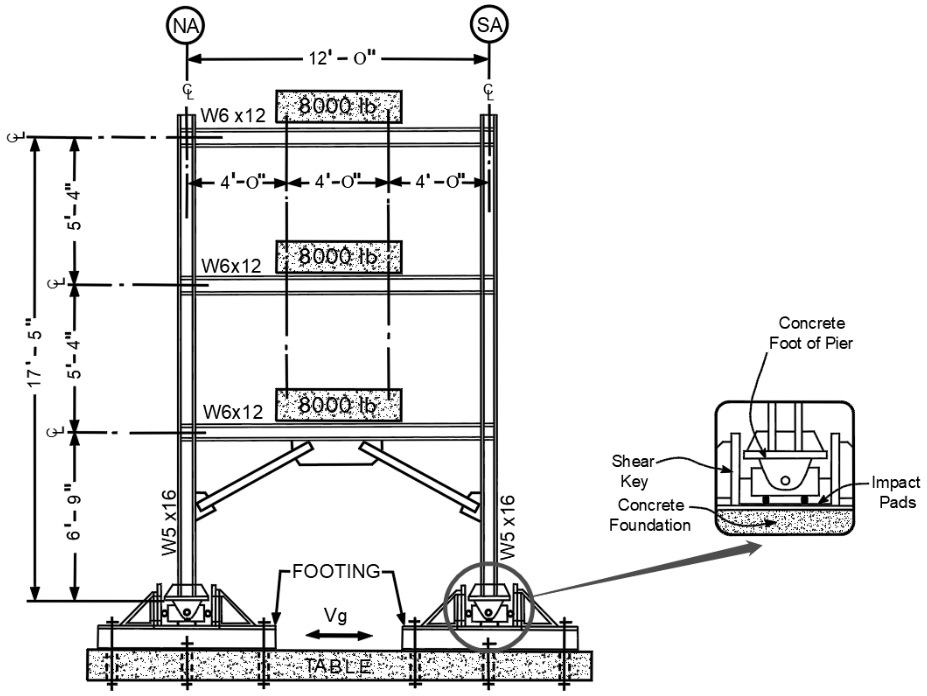


Figure 5 The connection form of hinge joint of rocking frame structures.

Based on the theory of implementing structural rocking motion by relaxing constraints, some scholars have established calculation models and conducted experimental analysis verification on rocking columns in rocking frame structures. In 2009, Roh and Reinhorn [22] studied the calculation model and strength influencing factors of rocking columns without post-tensioned reinforcement. They proposed using macro-model analysis to model the changes in strength and stiffness before rocking motion and established the lateral force-displacement relationship diagram and macroscopic analytical model from the initial point to the cracking point, yielding point, rocking point, and overturning point as shown in Figure 6 [22]. The figure shows that after entering the rocking state, the lateral force resisting force decreases, and the lateral strength of the rocking column is related to the aspect ratio of the column and the external axial load and is proportional to the external axial load. In 2010, Roh and Reinhorn [23] simplified the macro-model to simulate the overall performance of rocking structures. By comparing the analysis results of the 1:3 scale rocking column model loaded with axial static loads of 5%, 10%, and 20% of the reference strength and the IDARC2D computer simulation model, they verified the rationality of the simplified analysis model.

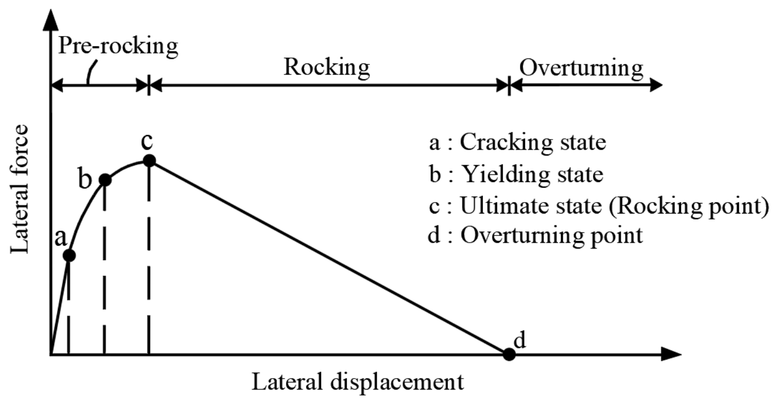


Figure 6 Lateral force-displacement diagram of rocking cracked column.

With the in-depth research on rocking frame structures, some scholars have further proposed the strategy of combining structural rocking with energy dissipation devices. Viti et al. [24] studied the strategy of reducing the acceleration response and deformation of rocking structures. They evaluated the inelastic response of the structure through nonlinear dynamic analysis based on Monte Carlo simulations and proposed using a combination of rocking mechanism and damping devices to control deformation and reduce the inertial load acting on the structure, and verified the effectiveness of this strategy. Roh [25] proposed the strategy of using viscous dampers in combination with structural rocking motion to form rocking structures.

With a large number of experimental tests and analyses on rocking frame structures, the problem of rocking motion and overturning risk has gradually been exposed. Some scholars have proposed corresponding solutions and devices to reduce rocking motion and overturning risk. Makris and Zhang [26] studied the transient rocking motion response of anchored blocks subjected to horizontal pulse-like motion, as shown in Figure 7 [26]. Through numerical simulation analysis, they found that limiters with elastic pre-yielding behavior and finite strength can effectively limit the overturning of slender blocks subjected to low-frequency ground excitation.

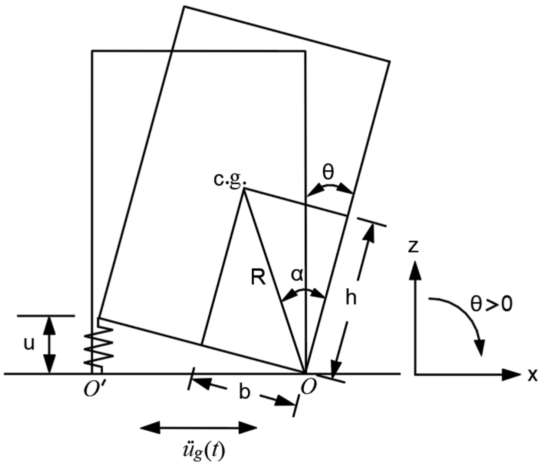
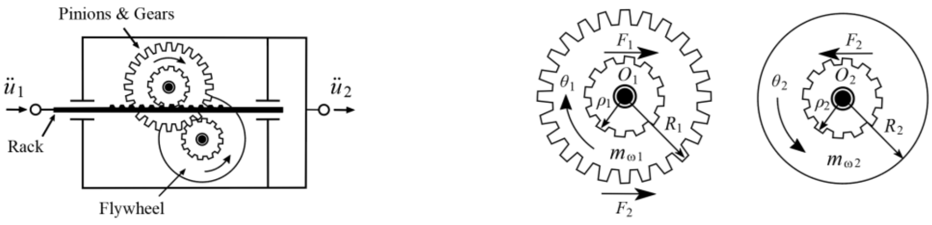


Figure 7 Schematic of anchored block in rocking motion.

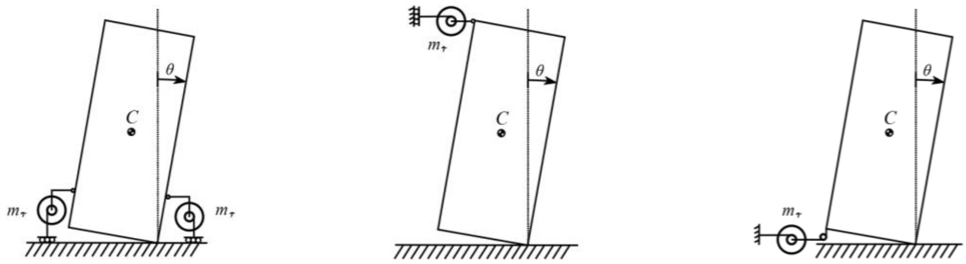
Based on the research approach of anchor blocks, Dimitrakopoulos and DeJong [27] conducted in-depth research on adding damping to constrain rocking motion and limit overturning, and supplemented the research of Makris and Zhang [26]. By analyzing the overturning envelopes of bilateral and unilateral linear viscous dampers and nonlinear dampers, it was found that the overturning regions of bilateral linear viscous dampers are smaller and have better anti-overturning effects.

Building on the above research, Thiers-Moggia and Málaga-Chuquitaype [28] studied a new measure to mitigate the effects of earthquakes on the overturning of rocking structures by using supplemental rotational inertia. They proposed using a Rack-pinion-flywheel and block-inerter mechanical device, as shown in Figures 8 and 9 [28], to generate resistance force proportional to the relative acceleration, thereby reducing the overturning region in the frequency-amplitude acceleration space and significantly reducing the probability of overturning of the rocking frame columns.



(a)Two-flywheel configuration. (b)Free-body diagram of the flywheels.

Figure 8 Rack-pynion-flywheel supplemental rotational inertia system.



(a)Vertical pair of inerters. (b)Horizontal inerter. (c)Pulley-inerter system.

Figure 9 Example of stiff block-inerter configurations.

At the same time, for the rocking beam-column joints in the rocking frame structure, some researchers have proposed the idea of using rotating beams to construct them. In 1993, Priestley and Tao [29] studied pre-stressed integral frame joints and proposed using debonded tendons to connect beam-column joints, using diagonal braces to transmit horizontal joint shear forces to resist applied shear loads. By allowing the beams connected by pre-stressed tendons to undergo relative rotation, i.e., forming "rotating beams," rocking beam-column joints were constructed, as shown in Figure 10 [29].

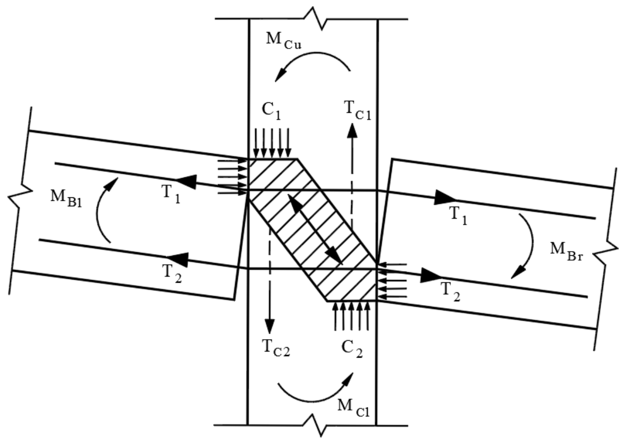
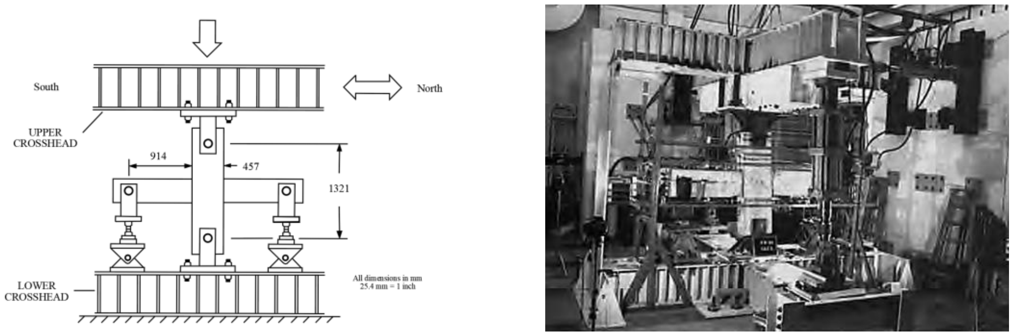


Figure 10 Diagram of rocking beam-column joints in rocking frames.

Based on the above idea of rocking beam-column joints, some researchers have conducted experimental tests and proposed improvement measures. In 1993, Cheok and Lew [30] conducted low-cycle reciprocating loading tests on eight 1:3 scale steel reinforced concrete frame pre-stressed rotational joints, as shown in Figure 11 [30]. They found that the failure characteristics of the joints were post-tensioned steel strand yielding, beam crushing, and opening of the beam-column connection interface. Through comparative experiments, they proposed that post-tensioned steel strands have better strength reserves and cyclic energy dissipation than post-tensioned high-strength bars.



(a) Schematic diagram of low-cycle reciprocating loading test.

(b) Actual test.

Figure 11 Low-cycle reciprocating loading test of pre-stressed rotational joints in 1:3 scale steel reinforced concrete frames.

With the deepening of research on rocking beam-column joints, more and more scholars have proposed new types of combined connection forms and devices. In 2005, Rojas et al. [31] established a fiber element-based analysis model and proposed introducing friction plates into the steel frame beam-column connection rotational joints. Friction plates were set on the beam flange and post-tensioned steel strands were set parallel to the beam web, as shown in Figure 12 [31]. The friction device was used to dissipate energy, and the post-tensioned steel strands were used to provide self-centering ability and reduce ductile deformation of the beam-column. The research showed that this rotational joint has good energy dissipation ability, self-centering ability, and sufficient strength, as shown in Figure 13 [31].

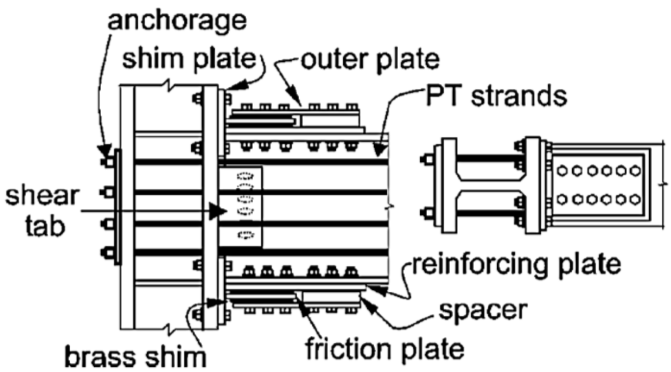


Figure 12 Rocking of post-tensioned friction damped connection details.

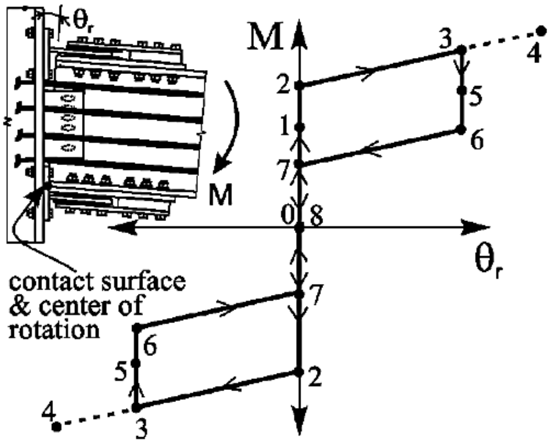
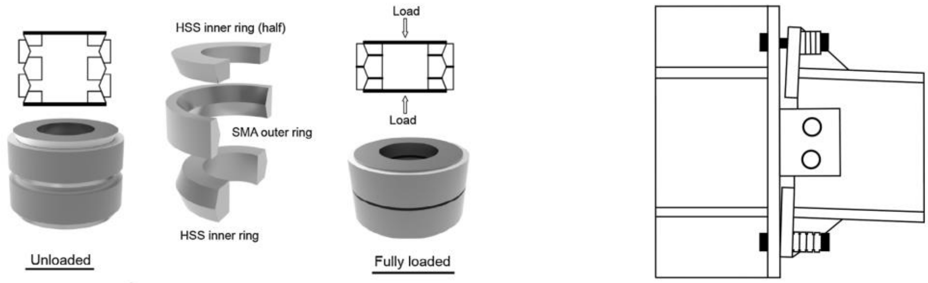


Figure 13 Ideal moment-relation rotation behavior of post-tensioned friction damped connection.

In 2017, Wang et al. [32] conducted innovative research on the application of superelastic shape memory alloys (SMAs) in rocking structures. They installed SMAs at the connection joints between the beam end and the column, as shown in Figure 14 [32], and found through cyclic loading tests that SMAs have good self-centering ability and energy dissipation ability, which can achieve the combination of self-centering and energy dissipation in rocking.



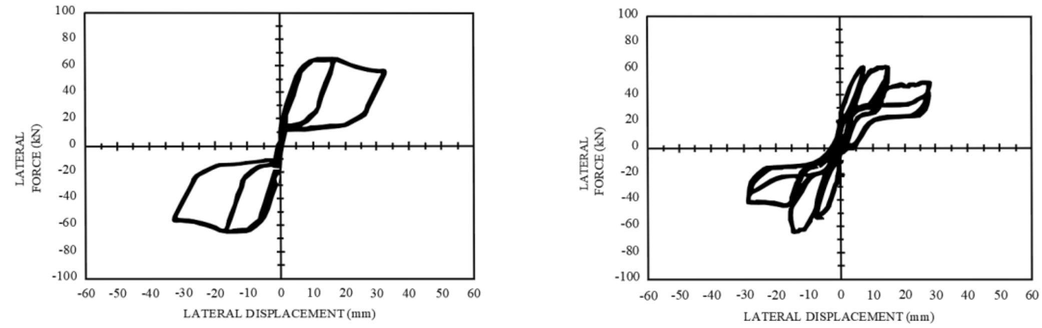
(a) Superelastic shape memory alloy (SMA).

(b) Working principle schematic.

Figure 14 Superelastic shape memory alloy and its working principle.

3.1.2 Rocking Shear Wall Structures

In a shear wall structure, the shear wall serves as the main or even the entire lateral resistance system. A rocking shear wall structure refers to relaxing the rotational restraint between the wall base and the foundation. Under earthquake action, the wall drives the entire structure to rock, and self-centering and energy dissipation devices are added. Madan et al. [33] conducted experimental research and analysis modeling on the hysteretic behavior of rocking concrete masonry shear walls without post-tensioned tendons. They proposed a fiber element model (micro-element model) and used this calculation model to analyze the force-displacement performance of the masonry shear wall without post-tensioned tendons under in-plane cyclic loading. The rationality of the fiber element model was verified by comparing the force-displacement curves of the model with the experimental hysteresis curve (specific experimental details can be found in Madan et al. [34] in 1996), as shown in Figure 15 [33].



(a)Fiber element model force-displacement curve.

(b)Experiment force-displacement curve.

Figure 15 Comparison of force-displacement curves between the model and experiment.

As research on rocking shear walls deepens, scholars have proposed combining post-tensioned steel strands with rocking structures to enhance the self-centering capacity of shear walls. Kurama et al. [35,36] conducted systematic research on self-centering shear walls with unbonded post-tensioned tendons and proposed combining unbonded post-tensioned steel strands with reinforced concrete shear walls, as shown in Figure 16 [36]. Dynamic analysis shows that self-centering shear walls with unbonded post-tensioned tendons have strong nonlinear lateral displacement resistance and self-centering ability. Under severe earthquake action, they can withstand significant damage and displacement without collapsing. Based on experimental analysis, seismic design recommendations have been proposed.

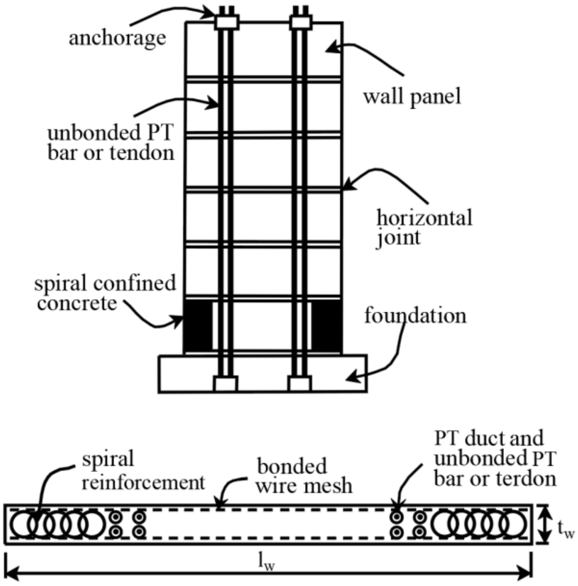


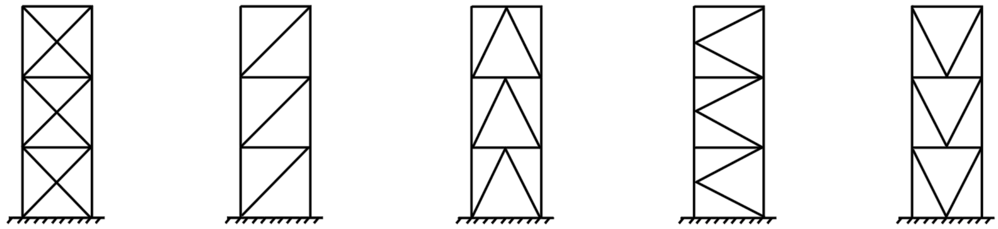
Figure 16 Rocking shear wall with unbonded post-tensioned steel strands.

Based on the concept of combining rocking shear walls, scholars have improved the post-tensioned steel strands. Holden et al. [37] proposed combining carbon fiber post-tensioned tendons and energy-dissipating bars with reinforced concrete cantilever shear walls. Through quasi-static reversed cyclic loading tests on half-scale models, they found that carbon fiber post-tensioned tendons can reduce the loss of prestress caused by creep and shrinkage by maintaining elasticity until failure. They also have good corrosion resistance and can address the issue of exposed post-tensioned tendons corroding due to rocking interface opening. Meanwhile, energy-dissipating bars added to the wall can dissipate energy when the wall undergoes certain lateral deformation, reducing permanent damage to the system.

3.2 Structure with Self-centering Braced

Self-centering braced structures emphasize the use of self-centering devices, elastic dampers, pre-stressed or elastic brace materials to brace structures, so that buildings can actively return to their pre-earthquake positions after earthquakes, reducing residual deformation and repairation time, and lowering post-earthquake structural damage.

The main traditional seismic brace forms for frame structures are central brace and eccentric brace, with commonly used central brace types including cross-shaped, single diagonal rod-shaped, herringbone-shaped, K-shaped, V-shaped, etc., as shown in Figure 17. Based on traditional seismic brace forms, the brace rods are disconnected and self-centering devices are installed at the disconnects, transforming the brace rods from immovable to relatively movable self-centering rods, thus forming structures with self-centering braced that prevent structural collapse and achieve post-earthquake structural self-centering effect, reducing residual deformation and structural damage.



(a)cross-shaped. (b)single diagonal rod-shaped. (c)herringbone-shaped. (d)K-shaped. (e)V-shaped.

Figure 17 Types of central brace.

In 2007, Zhu and Zhang [38] proposed a structure with self-centering braced similar to the post-tensioned steel strands embedded in rocking shear walls, called the reusable hysteretic damping brace (RHDB). This brace device constrains the sliding surface relative movement by anchoring post-tensioned steel strands on both sides of two sliding blocks and achieves self-centering effect after sliding, as shown in Figure 18 [38]. However, due to the strong tensile elastic performance of post-tensioned steel tendons but the susceptibility to buckling under compression, this device is more effective in achieving self-centering effect when the brace components are under tension at both ends.

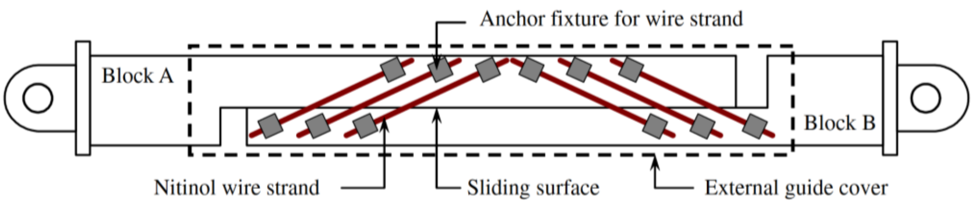


Figure 18 Hysteretic damping brace (RHDB).

Based on the self-centering concept, scholars have improved the one-way self-centering mode of post-tensioned steel strands to achieve two-way self-centering effect. In 2016, Kitayama and Constantinou [39-41] proposed a fluidic self-centering device that can brace frame structures, as shown in Figure 19 [39,40] and Figure 20(a) [41]. Under earthquake action, the pressurized fluid in the device provides resilience, and the fluidic self-centering device can return to its initial position regardless of the direction of tensile or compressive loading, as shown in Figure 20(b) [41], meeting the requirements of structural self-centering.

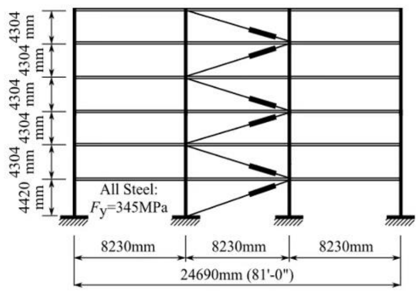
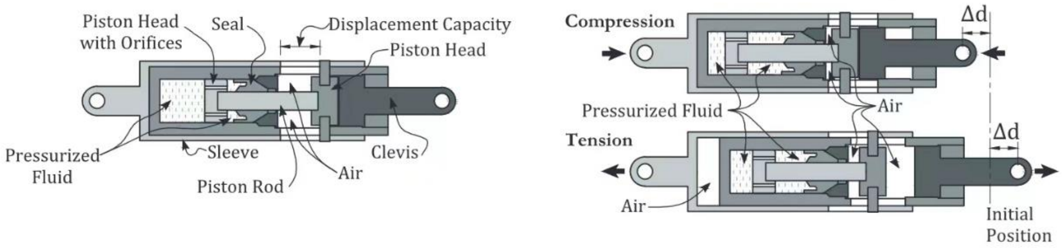


Figure 19 Schematic diagram of structure with self-centering braced for frame structures.



(a) Fluidic self-centering device details. (b)Working mechanism under tensile and compressive loading.

Figure 20 Fluidic self-centering device.

In 2019, Hashemi et al. [42] applied a new shape memory alloy to structure with self-centering braced and proposed a Resilient Slip Friction Joint (RSFJ) for steel frame structures, as shown in Figure 21 and Figure 22(a) [42]. This device uses the characteristic of shape memory alloy to return to its initial position under tensile and compressive loading, achieving structure with self-centering braced that can achieve self-centering effect under bidirectional loading, as shown in Figure 22(b) [42]. Through cyclic tests on the RSFJ brace device, it was found to have good energy dissipation performance and can reduce residual deformation and structural damage under earthquake action.

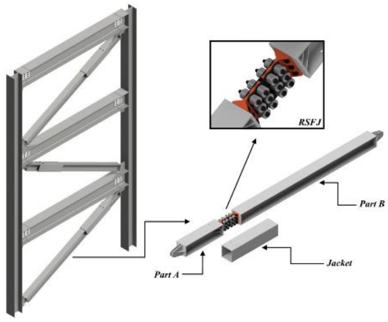


Figure 21 Schematic diagram of structure with self-centering braced.

(a) Resilient Slip Friction Joint (RSFJ) details. (b) Working mechanism of RSFJ.

Figure 22 Resilient Slip Friction Joint (RSFJ).

3.3 Structures with Replaceable Member

Structures with replaceable member emphasize weakening replaceable components locally to allow them to undergo ductile deformation or damage under earthquake action to dissipate energy, reducing structural damage. After earthquakes, components with significant residual deformation or serious damage can be quickly repaired or replaced to achieve post-earthquake structural resilience.

Different scholars have proposed different replaceable devices and combination forms for replaceable structures and verified their performance through experiments. In 2011, Deierlein et al. [43] proposed combining post-tensioned tendons with replaceable steel-plate butterfly-shaped fuses to provide elastic resilient force under earthquake action. The steel-plate butterfly-shaped fuse can dissipate energy through non-elastic yield and repair or replace components that exceed its energy dissipation capacity after a major earthquake, as shown in Figure 23 [43]. Two combination forms were proposed for single-span and double-span frames, as shown in Figure 24 [43]. The rationality and effectiveness of the combination forms were verified through quasi-static tests on large-scale models and shake table tests at E-Defense, and the structure can remain undamaged and repair after a major earthquake.

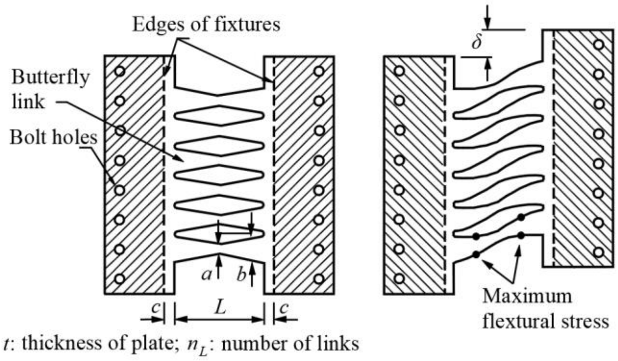


Figure 23 Energy dissipating steel butterfly-shaped fuses.

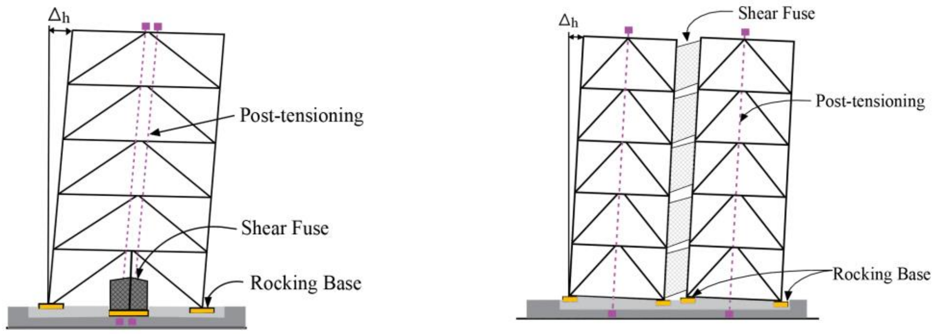


Figure 24 Two combination forms for single frame and dual frames.

In 2015, Sritharan et al. [44] proposed a replaceable O-shaped mild steel connector that is vertically installed at the joint between rocking columns and rocking walls, as shown in Figure 25 [44]. The O-shaped connector undergoes bending yield within the connector plane under earthquake action to dissipate energy and can be replaced after the earthquake. The good energy dissipation performance of the replaceable O-shaped connector was verified through vertical cyclic loading tests, as shown in Figure 26 [44], and it can be used in the structural system and replaced after an earthquake.

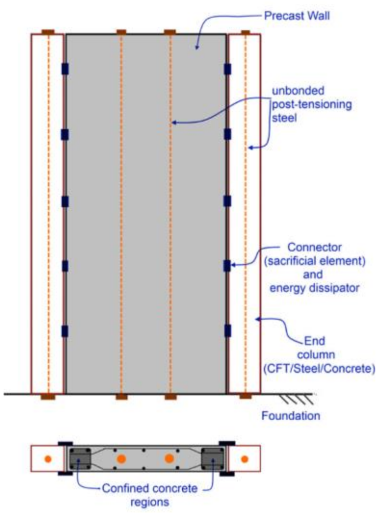
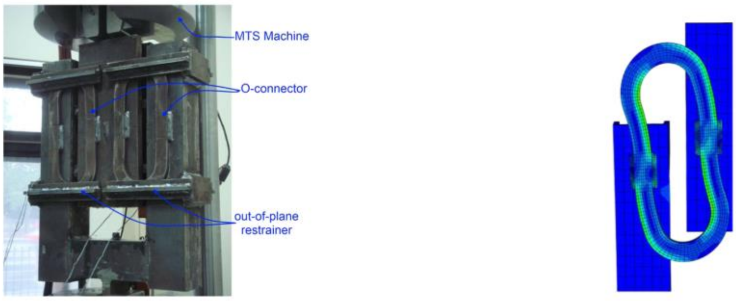


Figure 25 Combination connection of replaceable O-type low-carbon steel connectors and rocking structure under vertical cyclic loading test.



(a)Vertical cyclic loading test. (b)Deformed shape.

Figure 26 Loading test and deformation shape of O-type connectors.

In 2018, Aghlara and Tahir [45] proposed a new passive bar-fuse damper (BFD) for frame structures, as shown in Figures 27 and 28(a) [45]. The round steel bars are used as sacrificial elements to dissipate energy through ductile deformation under seismic action, as shown in Figure 28(b) [45]. The stable hysteretic behavior of the BFD has been verified through vertical cyclic loading tests, and the fuses can be replaced in the structures with replaceable member.

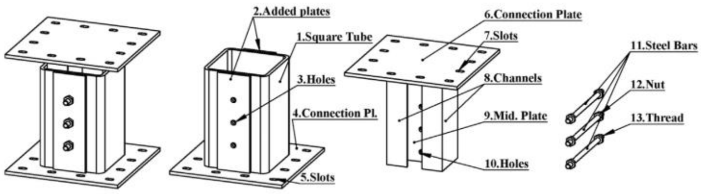
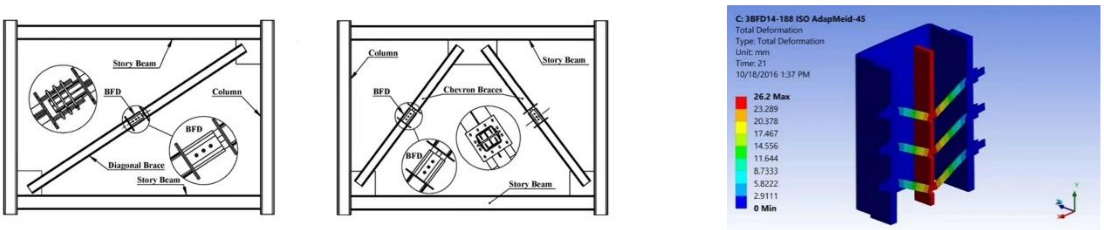


Figure 27 Bar-Fuse Damper details.



(a)Application example of Bar-Fuse Damper in frame structures.

(b)Schematic working form of Bar-Fuse Damper.

Figure 28 Application and working form example of Bar-Fuse Damper.

4. Application of Resilience Concept in Structural Reinforcement

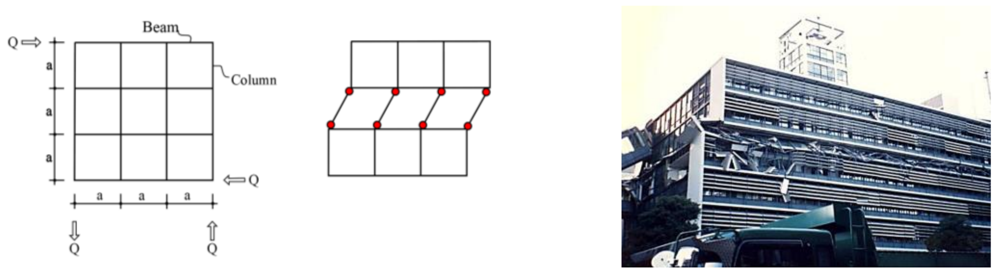
The resilience design concept has been widely applied in practical engineering, including two aspects: designing structures with better seismic resilience and reinforcing existing structures with poor seismic performance. The previous section mainly introduced the resilience design concept and types of resilient structures, while this section focuses on the application of resilience measures in structural reinforcement.

4.1 Deficiencies of Existing Structures

With the deepening of seismic research and the gradual unification of local codes, relatively mature seismic design codes began to emerge internationally in the 1970s. In the United States, seismic design codes were proposed earlier, but it was not until 1978 that the Applied Technology Council (ATC) proposed the National Seismic Design Guidelines [46], i.e., ATC 3-06 [47]. In Europe, the first generation of European building design technical specifications, EuroCode, was not formed until the 1980s. In China, the first trial seismic design code was promulgated in 1974, i.e., Technical

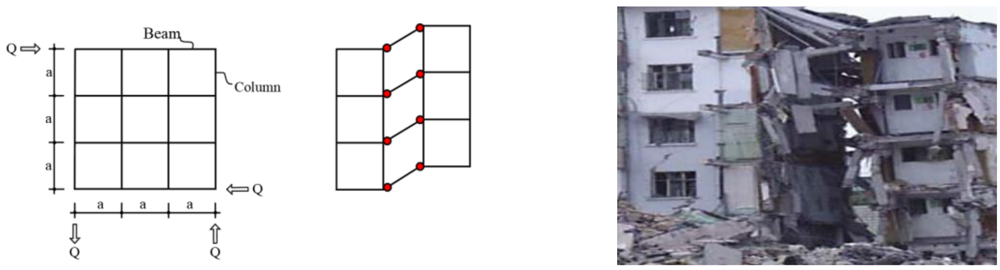
Specification for Industrial and Civil Buildings Seismic Design (TJ11-74), and a more mature seismic design code was not promulgated until 1989, i.e., Code for Seismic Design of Buildings (GBJ-89) [48].

Mature and unified seismic design codes were proposed relatively late, and there were already a large number of buildings that did not meet modern seismic fortification requirements, with frame structures as the main structural system. Based on a large amount of earthquake disaster experience, the ductile hinge joints were formed at both ends of the frame columns due to irregular vertical arrangement, leading to the failure of the moment-resisting frame or the earlier failure of columns than beams under seismic action. Existing frame structures did not meet the requirements of "strong columns and weak beams" and "strong joints and weak components" in modern seismic design codes, resulting in the collapse of the entire weak story after the earthquake, as shown in Figure 29 [49]. Due to the irregular layout of the plane, the eccentric stiffness of the plane caused the frame structure to twist and collapse after the earthquake, as shown in Figure 30 [49]. With the gradual maturity of seismic research and the proposal of resilience concepts, theoretical foundations have been established for the reinforcement of existing structures, and it is urgent to reinforce the weak aspects of frame structures to improve the seismic performance of existing structures with poor seismic performance.



(a)Collapse of weak story illustration. (b)Actual post-earthquake disaster map of weak story collapse.

Figure 29 Weak story collapse caused by irregular vertical arrangement.



(a) Twisting collapse illustration. (b)Actual post-earthquake disaster map of twisting collapse.

Figure 30 Twisting collapse caused by irregular planar arrangement.

4.2 Application of Resilience Concept in Structural Reinforcement

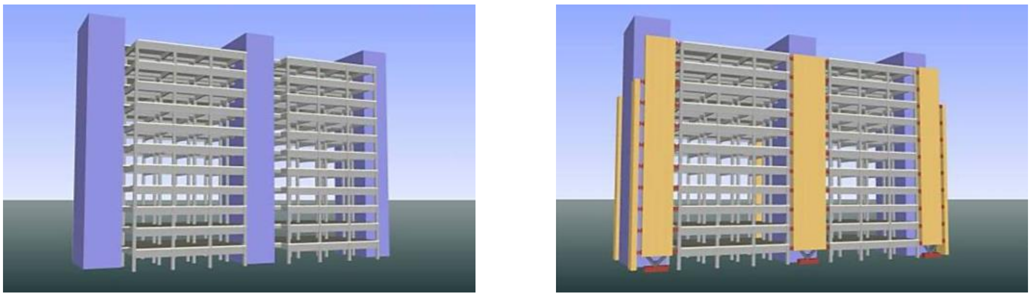
Based on the analysis of weak points in frame structures mentioned above, many scholars have proposed theoretical schemes for structural reinforcement and improvement based on the concept of resilience design, which have been applied in actual reinforcement projects. In 1997, Seible et al. [50] proposed a resilient reinforcement method using continuous carbon fiber jackets (in 2007, Colomb et al. [51] proposed a CFRP material), which were wrapped around the periphery of existing reinforced concrete columns to constrain the concrete columns, enhance their compressive capacity, and prevent damage to the column foot caused by rocking under compression.

In 2009, Wada et al. [49] proposed a reinforcement scheme that connects a strong rocking shear wall to a bending-resistant frame structure, as shown in Figure 31 [49]. The strong rocking shear wall has the advantages of dissipating energy to the greatest extent and minimizing ductile residual deformation under earthquake action. By connecting the frame structure to the shear wall, strong control of the weak structure can be achieved during earthquake action, thus avoiding structural damage and achieving the goal of resilient reinforcement after the earthquake.

(a) Frame with rocking wall. (b) Global failure mode.

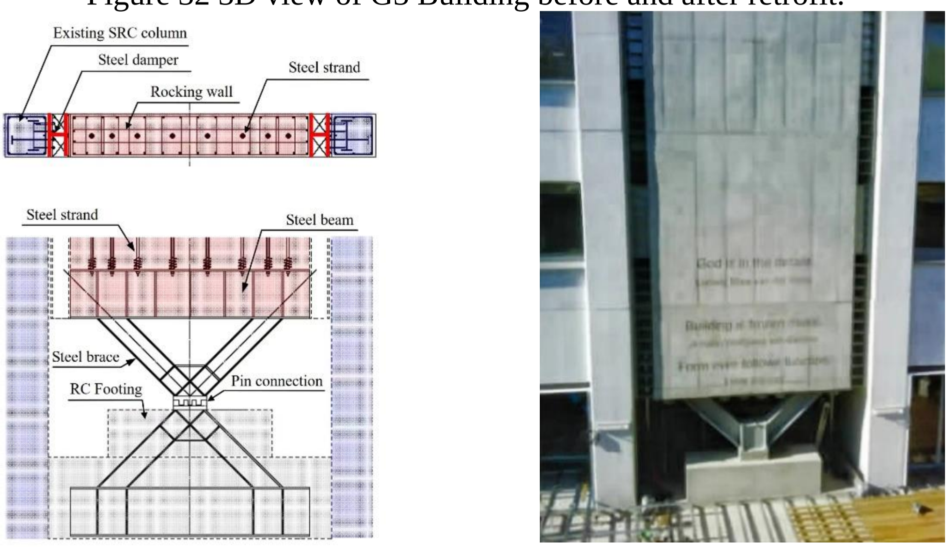
Figure 31 Moment resisting frame with strong rocking walls.

This theory of resilient reinforcement was applied in the structural reinforcement project of Building G3 at the Tsuda Campus of Tokyo Institute of Technology, which was built in 1979 (before the Building Standard Law of Japan), as shown in Figure 32 [49]. The existing structure is an 11-story reinforced concrete frame structure (RCF), and the reinforcement scheme is to set a strong rocking shear wall outside the existing structure and connect it to the existing frame structure to achieve overall control of the frame structure through the rocking shear wall, thus avoiding collapse in the weak story. Steel dampers were installed at the connection gaps to achieve energy dissipation under earthquake action, and they can be replaced after the earthquake, as shown in Figure 33 [49]. Vibration table tests on the reinforcement model proved that the reinforced structure can effectively reduce seismic response under different earthquake inputs.



(a)Existing. (b)Retrofitted.

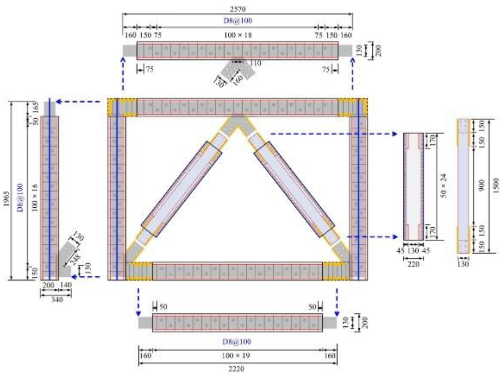
Figure 32 3D view of G3 Building before and after retrofit.



(a) Details of reinforcement joints. (b) Actual reinforcement joints.

Figure 33 Joint reinforcement diagram of G3 Building.

In 2021, Cao et al. [52] improved the existing rigid external diagonal bracing to enhance its resilience, and proposed a new external frame-brace sub-structure system reinforcement theory, as shown in Figure 34(a) [52], and verified the feasibility of this improved theory through experiments. The external sub-structure reinforcement system consists of rocking prefabricated beams, rocking prefabricated columns, and damping braces connected by assembly bolts. The prefabricated columns are internally threaded with post-tensioned bars to allow them to achieve self-centering effect after the earthquake and reduce residual deformation of the structure after the earthquake. The damping diagonal brace can stabilize the frame structure and dissipate energy under earthquake action. Structural reinforcement based on this theory has been applied in actual engineering projects, as shown in Figure 34(b) [52].



(a) External frame-brace details.

(b) Actual reinforcement engineering application.

Figure 34 External frame-brace sub-structure system.

Regarding the application of replaceable components and centralized energy dissipation and seismic reduction technology in the reinforcement of existing structures, Black et al. [53] statistically analyzed some engineering application cases of this reinforcement technology, which utilizes partially weakened components to yield under earthquake action and can be replaced after the earthquake, as shown in Table 2 [53].

Table 2 Cases of replaceable components and centralized energy dissipation and seismic reduction technology applied in the reinforcement of existing structures.

Building and location	Type of construction and building size
Marin County Civic Center Hall of Justice, County of Marin	Reinforced concrete, 3-6 stories, 600,000 ft2
Hildebrand Hall, University of California	Reinforced concrete, 3 stories + basement, 138,000 ft2
Wallace F. Bennett Federal Building, Salt Lake City	Reinforced concrete, 8 stories, 300,000 ft2
King County Courthouse, King County	Reinforced concrete, 12 stories, 500,000 ft2
Building 5, HP Corvallis Campus, Hewlett-Packard	Steel, 2 stories, 160,000 ft2

From the above structural reinforcement cases, it can be seen that the introduction of resilience design concept into structural reinforcement projects has good effects. Without affecting the normal use of existing buildings, it can improve the following performance of existing structures:

(1) Improve fatal defects caused by irregular vertical or horizontal arrangement of existing frame structures;

(2) Reduce damage to building structures and components under earthquake action;

(3) Improve the seismic resilience of structures and provide the ability for building structures to repair after the earthquake.

5. Conclusion

Extensive experience of seismic damage has shown that structures designed based on traditional design concepts are not conducive to post-earthquake repairation and have poor seismic resilience. In order to improve the shortcomings of traditional seismic design concepts, researchers have gradually proposed the concept of resilient structures and extended it to the structural reinforcement of existing buildings. This paper has summarized the principles and research progress of resilient structures and studied the application of the resilience concept in the reinforcement of existing structures, and the following conclusions have been drawn:

(1) The goal of resilient structural design is to achieve full repairation of structural use function in the shortest possible time after an earthquake-induced structural functional loss, even surpassing the pre-earthquake structural functional level, through pre-designed active or passive mechanisms or measures to reduce residual deformation after earthquakes and lower and repair post-earthquake structural damage. In order to achieve this goal, the concept of resilient design is mainly studied from two aspects, that is, "reducing post-earthquake residual deformation" and "reducing and repairing post-earthquake structural damage".

(2) Resilient structures can be mainly divided into rocking structures, structures with self-centering braced, and structures with replaceable member according to their implementation principles or measures. Among them, rocking structures allow frames or shear walls to rock by relaxing constraints, and are combined with pre-stressed materials or new shape memory alloy materials with good elastic properties to restrain violent rocking motion to prevent structural overturning and achieve self-centering after rocking. Self-centering braced structures mainly incorporate self-centering and energy-absorbing devices on the basis of traditional seismic braces, which not only prevent structural collapse, but also reduce residual deformation and structural damage. Structures with replaceable member use pre-designed construction measures to utilize weakened component damage to dissipate energy under seismic action, and are easily replaceable after earthquakes, thus achieving structural resilience in a short time.

(3) This paper analyzes and lists the shortcomings of the seismic performance of existing building structures and innovatively introduces the extension technology and practical reinforcement engineering application of the resilience design concept. The reinforcement engineering of existing structures mainly addresses the problems of irregular vertical or horizontal arrangement of frame structures, and incorporates the three core technologies of resilience (rocking, self-centering, and replaceable) to enhance the seismic resilience of existing structures.

The resilience design concept is currently in a rapidly developing stage, and many scholars have proposed different theoretical methods and equipment devices to achieve post-earthquake structural resilience. Regarding the future development direction of resilient structures, research can be conducted in the following aspects:

(1) More implementation ideas for resilient mechanisms. Currently, the resilience concept mainly focuses on rocking, self-centering, and replaceable mechanisms, and more implementation ideas for resilient mechanisms are worth exploring.

(2) Development of new low-cost materials or devices. The use cost of materials or equipment devices that achieve structural self-centering effect and replaceability is currently high, and it is still insufficient to realize large-scale construction and reinforcement engineering applications.

(3) Integration of intelligent sensing and control technology with resilient structures. Resilient structure measures mainly emphasize post-earthquake detection and repair, and the real-time sensing ability of the health status of resilient materials or equipment devices under seismic action is still insufficient.

In summary, resilient structures have become the core concept of future structural design and structural reinforcement. There is still a lot of work to be done in interdisciplinary theoretical research, post-disaster structural damage analysis, and practical engineering applications.

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