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# Seismic Retrofitting of Precast Concrete Structures with Energy-Dissipation and Self-Centering Systems: A Critical Review

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**Abstract** **Review Article**

Existing precast concrete structures are vulnerable to earthquake damage due to weak connections, limited ductility, and insufficient energy dissipation capacity. Traditional retrofitting methods can improve structural strength and stiffness, but they may not effectively control residual deformation or prevent severe damage during strong earthquakes. To address these problems, researchers have increasingly focused on energy-dissipation and self-centering systems to improve seismic performance and post-earthquake recovery. This paper reviews the development and application of these systems in precast concrete structures based on findings from experimental studies, numerical analyses, and performance-based seismic assessments. The review discusses different technologies, including metallic yielding dampers, buckling-restrained braces (BRBs), friction and viscous dampers, unbonded post-tensioning systems, rocking mechanisms, and shape memory alloys (SMAs). Special attention is given to hybrid systems that combine energy dissipation and self-centering mechanisms to control both peak displacement and residual drift. Previous studies have shown that energy-dissipation devices can reduce seismic demands on vulnerable precast connections, while self-centering systems provide restoring forces that help structures return toward their original positions after earthquakes. Combining these technologies can reduce structural damage, improve repairability, and increase overall seismic resilience. The paper also examines externally attached retrofitting systems, experimental and numerical evaluation methods, and design approaches such as Direct Displacement-Based Design (DDBD) and probabilistic seismic loss assessment. However, several challenges still require further investigation, including structural response under near-fault ground motions, interaction with non-structural elements, long-term durability, and practical construction requirements. Further experimental and numerical studies are needed to improve the reliability, cost-effectiveness, and long-term performance of these systems. Overall, this review summarizes current developments and identifies important research gaps to support the design of safer, more sustainable, and earthquake-resilient precast concrete structures.

**Keywords:** Precast concrete structures; Seismic retrofitting; Energy-dissipation systems; Self-centering systems; Buckling-restrained braces; Residual drift; Seismic resilience.

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## 1. Introduction

### 1.1 Seismic Vulnerability of Precast Concrete Structures

Precast concrete structures are widely used in modern construction because they offer several advantages, including faster construction, better quality control, and lower overall construction costs. However, many older precast concrete buildings, especially those constructed before modern seismic design codes were introduced, have shown poor

seismic performance during strong earthquakes[1]. One of the main weaknesses of these structures is often found in the connections between precast elements rather than in the individual structural members[2]. Unlike cast-in-place concrete structures, where reinforcement is continuous and the members are connected to form a monolithic system, precast concrete structures depend mainly on dry or semi-rigid connections to transfer forces between structural members. A common example is the dowel-based beam-to-column connection, where steel dowels are inserted into oversized ducts filled with grout to connect the precast members. In these connections, forces are transferred through the dowels, friction, and local bearing resistance of the surrounding materials.

During strong earthquakes, traditional precast concrete connections are vulnerable to sudden and brittle failure. One of the most common failure modes is dowel shear failure, which occurs when repeated lateral forces cause yielding, fatigue damage, and eventually fracture of the steel dowels[2]. Once the dowels fail, the connection may lose its ability to transfer lateral forces between structural members. This can lead to beam unseating and, in severe cases, collapse of the surrounding floor system. Another important weakness in older precast concrete frames is the lack of sufficient transverse reinforcement in the joint regions[3]. This reduces the ductility and energy dissipation capacity of the connections, making them more likely to experience severe damage during earthquakes. Failure of these connections can also affect nearby structural members and may lead to progressive collapse of a larger part of the building.

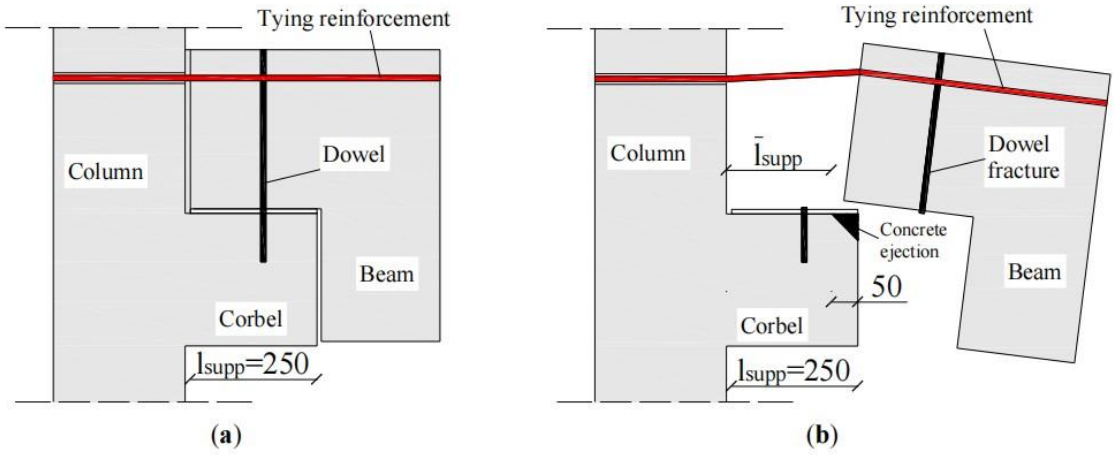



*Figure 1-Schematic representation of support loss assumption: (a) undeformed joint; (b) deformed joint with support loss (PLS4) and concrete ejection. (Dimensions in mm)[4].*

Therefore, there is an increasing need to develop and apply effective seismic retrofitting methods to improve the safety and seismic performance of existing precast concrete structures, especially those located in earthquake-prone regions.

### 1.2 Need for Advanced Seismic Retrofit Strategies

Traditional seismic retrofitting methods mainly focus on increasing the strength and initial stiffness of existing structures. Common methods include

reinforced concrete jacketing, steel plate strengthening, and the use of composite materials such as fiber-reinforced polymers (FRP) and textile-reinforced mortars[4]. These techniques can improve the load-carrying capacity of individual structural members, but they also have some limitations. For example, reinforced concrete jacketing increases the overall weight of the building, which can lead to higher inertial forces during earthquakes. Similarly, a large increase in structural stiffness can change the dynamic behavior of the building and may increase seismic force demands on the existing foundations. As a result, additional foundation strengthening may be required, which can increase construction costs and make the retrofitting process more complicated.

Another limitation of traditional retrofitting methods is that they do not always meet the broader goals of modern performance-based earthquake engineering. In modern seismic design, preventing structural collapse is an important requirement, but it is not the only objective. Seismic resilience also focuses on reducing damage, limiting repair costs, shortening building downtime, and allowing buildings to return to normal use as quickly as possible after an earthquake[5]. For this reason, researchers have increasingly focused on advanced seismic retrofitting methods that can control structural deformation and dissipate seismic energy rather than simply increasing strength and stiffness. These approaches aim to improve both the seismic safety and post-earthquake recovery of existing structures.

### 1.3 Energy-Dissipation and Self-Centering Concepts

To improve the seismic resilience of existing precast concrete structures, modern retrofitting methods mainly focus on two mechanisms: energy dissipation and self-centering. Energy dissipation systems use devices such as metallic yielding dampers, friction slip plates, and fluid viscous dampers to absorb and dissipate seismic energy, reducing force and deformation demands on primary structural members[6], [7]. Some devices are also designed for easy replacement after damage. By concentrating energy dissipation in these components, the main gravity-load-bearing members can experience less damage and are more likely to remain elastic.

However, systems relying only on elastoplastic energy dissipation devices may develop significant residual drifts after strong earthquakes, potentially causing permanent deformation, increased P-Delta effects, and costly repairs. Self-centering mechanisms address this limitation by helping structures return toward their original position. Combining energy dissipation and self-centering can produce flag-shaped hysteretic behavior, allowing structures to dissipate seismic energy during cyclic loading while limiting residual drifts[8]. This combined approach improves seismic performance and post-earthquake recovery, making it promising for retrofitting existing precast concrete structures.

### 1.4 Scope, Objectives, and Research Questions

This paper provides a detailed review of recent developments in the seismic retrofitting of existing precast concrete structures using energy-dissipation and self-centering systems. The main objectives of this review are to examine the working mechanisms of different retrofitting technologies, compare their advantages and limitations, and summarize findings from experimental studies and numerical analyses related to their seismic performance. The paper also discusses how these systems can be applied within modern design approaches, including probabilistic loss-based design and direct displacement-based design methods. In addition, it identifies several research gaps that need further investigation, particularly the effects of near-fault velocity pulses and the interaction between structural members and non-structural cladding during earthquakes. By reviewing both the behavior of individual structural components and the overall performance of retrofitted buildings, including life-cycle costs, this paper aims to provide useful information for researchers and structural engineers. The findings may also help guide future research and support the development of more effective and practical seismic retrofitting methods for existing precast concrete structures.

## 2. Seismic Retrofit Technologies for Precast Concrete Structures

### 2.1 Conventional versus Advanced Retrofit Approaches

The development of seismic retrofitting methods has gradually shifted from strengthening individual structural members to improving the overall seismic response of buildings. Traditional retrofitting methods mainly focus on correcting weaknesses in the materials or structural details of individual members. For example, wrapping weak precast concrete columns with carbon-fiber-reinforced polymer (CFRP) jackets or strengthening them with ultra-high-performance concrete (UHPC) can improve their confinement and load-carrying capacity. Previous studies have shown that UHPC jacketing can significantly increase the initial stiffness and peak strength of damaged columns, while textile-reinforced mortar (TRM) can improve displacement ductility and energy dissipation capacity[4]. However, these methods mainly improve the performance of individual structural members and may not significantly reduce the overall displacement demands of the building during earthquakes.

In comparison, advanced seismic retrofitting methods focus on controlling the overall dynamic response of the structure and improving the transfer of seismic forces. Instead of strengthening every weak precast column or beam-column joint, which can require extensive construction work and disturb normal building activities, researchers have increasingly explored externally attached sub-structures and distributed damping systems[9]. For example, precast bolt-connected steel-plate reinforced concrete frames and external steel exoskeletons can be installed along the exterior of existing buildings[10]. These systems provide additional lateral load-resisting capacity and help transfer a large portion of the seismic forces from the existing precast concrete frame to specially designed energy dissipation devices. As a result, they can reduce the force and deformation demands on vulnerable structural members and limit damage during earthquakes. External retrofitting systems can also reduce the need for major modifications inside the building, simplify on-site construction, and, in some cases, allow the building to remain in use during the retrofitting process.

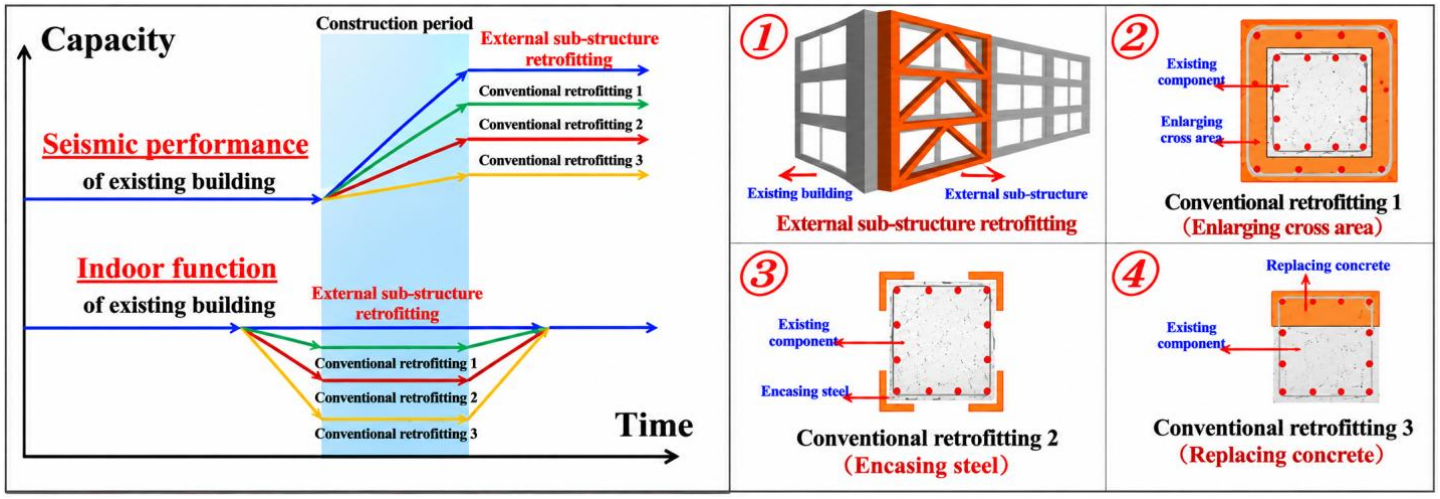



*Figure 2-The superiorities of the external sub-structure retrofitting method in comparison with the traditional approaches. [9]*

### 2.2 Energy-Dissipation Systems

Energy-dissipation systems reduce seismic demands by absorbing and dissipating earthquake energy. They are particularly useful for precast concrete structures, where connections may have limited energy dissipation capacity compared with well-designed monolithic reinforced concrete connections. These systems improve seismic performance by reducing structural deformation and damage[6]. They are generally classified as displacement-dependent or velocity-dependent devices. Displacement-dependent devices include metallic yielding dampers, buckling-restrained braces (BRBs), and friction slip dampers, while velocity-dependent devices include fluid viscous and viscoelastic dampers.

Displacement-dependent systems can also provide additional lateral stiffness and limit forces transferred to primary structural members after yielding. During strong earthquakes, metallic yielding devices are designed to yield at a specified force level and develop stable hysteresis loops, dissipating seismic energy through plastic deformation[11]. This behavior reduces demands on vulnerable precast concrete connections and helps prevent severe structural damage. These devices therefore act as mechanical fuses, protecting the main load-bearing members.

### 2.3 Self-Centering and Low-Damage Systems

The main idea behind self-centering and low-damage systems is that buildings may experience large movements during strong earthquakes, but these movements should not cause severe permanent damage. In precast concrete structures, this can be achieved through controlled rocking mechanisms[12]. Instead of using fully rigid connections between precast walls or columns and their foundations, these systems allow the structural members to uplift slightly and rock at their bases when subjected to strong lateral forces. This controlled movement helps reduce damage to the structural members and their connections during earthquakes.

To prevent overturning and help the structural members return to their original positions, unbonded post-tensioned tendons are commonly used[8], [13]. These tendons are anchored to the foundation and extend vertically through the precast structural members. Since the tendons are unbonded along their length, the deformation caused by gap opening at the base is distributed over the full tendon length rather than being concentrated in a small region. This allows the tendons to undergo elastic deformation and reduces the risk of yielding. As the tendons remain elastic, they provide a restoring force that helps the precast members return toward their original positions after an earthquake. When unbonded post-tensioning systems are combined with replaceable external energy dissipators, they can provide both self-centering capability and energy dissipation[14]. This combination helps limit residual drifts and structural damage, reducing the need for major repairs even after strong earthquakes, including maximum considered earthquake (MCE) events.

### 2.4 Evolution and Classification of Retrofit Technologies

Seismic retrofitting of precast concrete structures has evolved from conventional internal steel bracing to advanced external systems incorporating energy dissipation and self-centering mechanisms. Earlier methods used concentric steel braces within existing frame bays, but these braces were prone to compression buckling, resulting in asymmetric energy dissipation, stiffness degradation, and increased demands on vulnerable precast concrete connections.

To address these limitations, buckling-restrained braces (BRBs) were developed with a restraining system that prevents steel core buckling under compression, providing stable hysteretic behavior and reliable energy dissipation during cyclic loading[15]. Subsequent developments introduced hybrid braced frames combining BRBs with self-centering pendulum or rocking mechanisms to improve energy dissipation and residual drift control[16]. More recently, multi-stage and hybrid

damping systems have been developed to provide different responses depending on earthquake intensity[17]. Friction or viscoelastic components control structural response during low-intensity earthquakes, while sacrificial metallic components activate during stronger events. This approach provides multiple levels of seismic protection while limiting damage and unnecessary component replacement.

*Table 1- Classification of Seismic Retrofit Technologies [18].*

| **Retrofit Technology Category** | **Primary Mechanism** | **Impact on Stiffness** | **Impact on Strength** | **Residual Drift Control** |
|---|---|---|---|---|
| **Conventional Jacketing** (RC, TRM, UHPC) | Local cross-section enlargement and confinement. | High Increase | High Increase | Poor / None |
| **Metallic Yielding Dampers** (Slit, Shear Links) | Inelastic deformation of mild/LYP steel. | Moderate Increase | Moderate Increase | Poor |
| **Buckling-Restrained Braces** (BRB) | Core yielding in tension and compression without buckling. | High Increase | High Increase | Poor |
| **Friction & Viscous Dampers** | Sliding friction or fluid velocity resistance. | Variable / Dependent | Force Capping | Moderate |
| **Self-Centering Rocking Walls** | Gap opening with unbonded post-tensioning. | Moderate Decrease | Force Capping | Excellent |
| **Hybrid SC-ED Exoskeletons** | External framework combining PT tendons and replaceable fuses. | High Increase | High Increase | Excellent |

## 3. Energy-Dissipation Systems

### 3.1 Hysteretic and Metallic Dampers

Hysteretic metallic dampers dissipate seismic energy through the inelastic deformation of metals, mainly mild structural steel and low-yield-point steel. In precast concrete structures, these devices include steel slit dampers, shear links, and U-shaped flexural plates[6]. They can be installed at beam-to-column joints, wall bases, or within external bracing systems to reduce seismic demands on primary structural members.

Steel slit dampers consist of steel plates with parallel vertical slits that form narrow strips[11]. During earthquakes, lateral displacement causes these strips to bend in double curvature and undergo repeated plastic deformation, dissipating energy through stable cyclic yielding. Low-yield-point steel is particularly suitable due to its low yield stress and high ductility, allowing dampers to yield at relatively low force levels and protect vulnerable precast concrete members. Metallic dampers are also compact and can be designed as replaceable components. After strong earthquakes, damaged units with bolted connections can often be replaced without major structural repairs, reducing costs and disruption to building occupants[19].

### 3.2 Buckling-Restrained Braces (BRBs)

Buckling-restrained braces (BRBs) are an important development in energy-dissipation technology and are widely used to improve the seismic performance of structures. A conventional BRB consists of a slender steel core surrounded by a concrete-filled steel tube that provides lateral restraint[15]. An unbonding layer, usually made from a low-friction material or formed by a small air gap, is placed between the steel core and the surrounding concrete. This layer allows the steel core to deform independently and helps prevent axial forces from being transferred to the restraining casing through friction or bonding. As a result, the steel core can undergo stable yielding under both tension and compression while the surrounding casing prevents global and local buckling. This allows BRBs to maintain stable cyclic behavior and avoid the sudden loss of load-carrying capacity commonly observed in conventional steel braces under compression [20].

Buckling-restrained braces (BRBs) offer several advantages for retrofitting existing precast concrete structures. Older precast frames often lack sufficient lateral stiffness, resulting in excessive inter-story drifts and non-structural damage during earthquakes. Installing BRBs within existing frame bays or externally attached steel frameworks can improve lateral stiffness and energy dissipation, reducing deformation and damage to vulnerable structural members. Recent developments in assembled bolt-connected BRBs have simplified installation and reduced on-site welding, making them suitable for occupied buildings[15]. Bolted connections also allow damaged braces to be replaced more easily after earthquakes, improving repairability and maintenance.

However, BRB-retrofitted structures may still experience significant residual drifts after strong earthquakes due to the low post-yield stiffness of conventional BRBs and their limited restoring capacity[22]. Large seismic displacements, particularly under near-fault ground motions with strong velocity pulses, can leave permanent deformations that increase repair costs and delay building recovery. To address this limitation, researchers have combined BRBs with self-centering systems that provide additional restoring force, reduce residual drifts, and improve post-earthquake recovery.

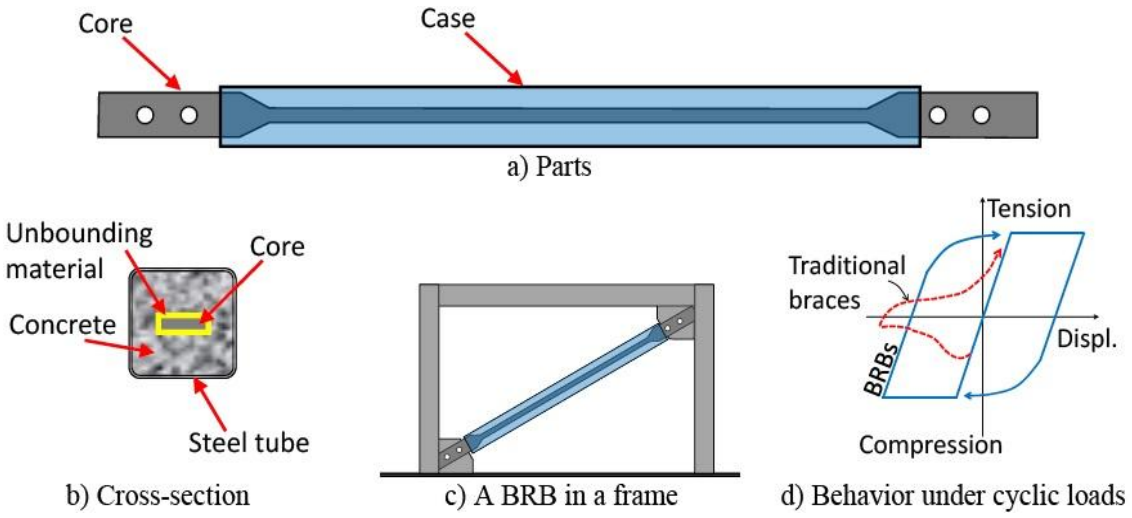



*Figure 3-Buckling-Restrained Braces (BRBs)[21].*

### 3.3 Friction and Viscous Dampers

Unlike metallic yielding dampers, which dissipate energy through plastic deformation, friction dampers use sliding between contact surfaces held together by high-strength pre-tensioned bolts[23]. These surfaces may include friction pads made of brass, non-asbestos organic materials, or treated steel. Friction dampers provide high initial stiffness and limit forces transferred to primary structural members. Their behavior is often represented by an idealized rigid-plastic model, where sliding begins once the applied force exceeds a specified slip load. This produces nearly rectangular hysteresis loops, dissipating seismic energy while limiting force demands on vulnerable precast concrete connections and foundations.

Viscous dampers dissipate seismic energy by forcing a highly viscous silicone-based fluid through small openings inside a cylinder. Unlike friction dampers, their resisting force depends on relative velocity rather than directly on displacement. The damping force reaches its maximum at peak velocity and approaches zero when relative velocity becomes zero at maximum displacement. This allows viscous dampers to dissipate energy without significantly increasing lateral stiffness. Consequently, they can reduce seismic displacement without necessarily causing a large increase in peak base shear, making them suitable for precast concrete buildings with limited foundation capacity where strengthening may be difficult or costly.

### 3.4 Hybrid and Multi-Stage Systems

To address the limitations of individual dampers, researchers have developed hybrid and multi-stage systems that combine different energy dissipation mechanisms. For example, a multi-stage damper may integrate a friction slip mechanism with a metallic yielding core that activates at higher force levels[17]. During low-intensity earthquakes or strong winds, friction sliding dissipates energy and reduces cyclic demands on the metallic core, limiting low-cycle fatigue damage. Under stronger earthquakes, the metallic core begins to yield once the designed activation threshold is reached. Both mechanisms then provide additional resistance and energy dissipation, helping control structural deformation.

Hybrid systems combining velocity-dependent viscous dampers with displacement-dependent buckling-restrained braces (BRBs) have also attracted attention for precast concrete structures, particularly in near-fault regions with strong velocity pulses[24]. Viscous dampers dissipate energy associated with high relative velocities, while BRBs increase lateral stiffness and dissipate energy through stable hysteretic behavior. Together, these mechanisms can reduce structural deformation and seismic demands on vulnerable precast concrete connections, limiting damage and improving seismic performance under complex earthquake loading.

## 4. Self-Centering and Low-Damage Systems

### 4.1 Prestressed and Self-Centering Frames

The high repair costs associated with residual drifts have encouraged the development of self-centering frames for retrofitting precast concrete buildings. These systems typically use unbonded post-tensioning technology, with high-strength steel tendons anchored at both ends and passing through ducts in precast beams or columns[8]. Their unbonded configuration allows tendon elongation to be distributed along their length during seismic loading.

During strong earthquakes, lateral forces may overcome the initial pre-compression, causing gaps to open at beam-to-column or column-to-foundation connections and enabling controlled rocking[25]. The tendons are designed to remain elastic and provide a restoring force that closes these gaps as seismic demands decrease. This mechanism reduces localized strain, limits residual drifts, and improves post-earthquake recovery.

When installed as external sub-structures, self-centering frames provide additional lateral load resistance and reduce seismic demands on vulnerable precast concrete columns and connections[14]. This helps existing members maintain their gravity-load-

bearing function while limiting structural damage and improving seismic resilience.

### 4.2 Replaceable and Damage-Control Components

An important goal of structural resilience is to design buildings that can be repaired quickly and return to normal use after an earthquake. Advanced self-centering systems help achieve this by separating the restoring force mechanism from the energy dissipation mechanism. The restoring force is usually provided by elastic unbonded post-tensioned tendons or Shape Memory Alloys (SMAs), while energy dissipation is achieved through replaceable components such as mild steel bars, friction pads, or steel slit dampers[26]. By combining these two mechanisms, the structural system develops a flag-shaped hysteresis loop in its force-displacement response. The restoring force provided by the post-tensioned tendons or SMAs helps the structure return toward its original position, while the width and enclosed area of the hysteresis loop reflect the energy dissipated by the yielding or friction-based components. This behavior allows the structure to reduce residual drifts while maintaining effective energy dissipation during seismic loading.

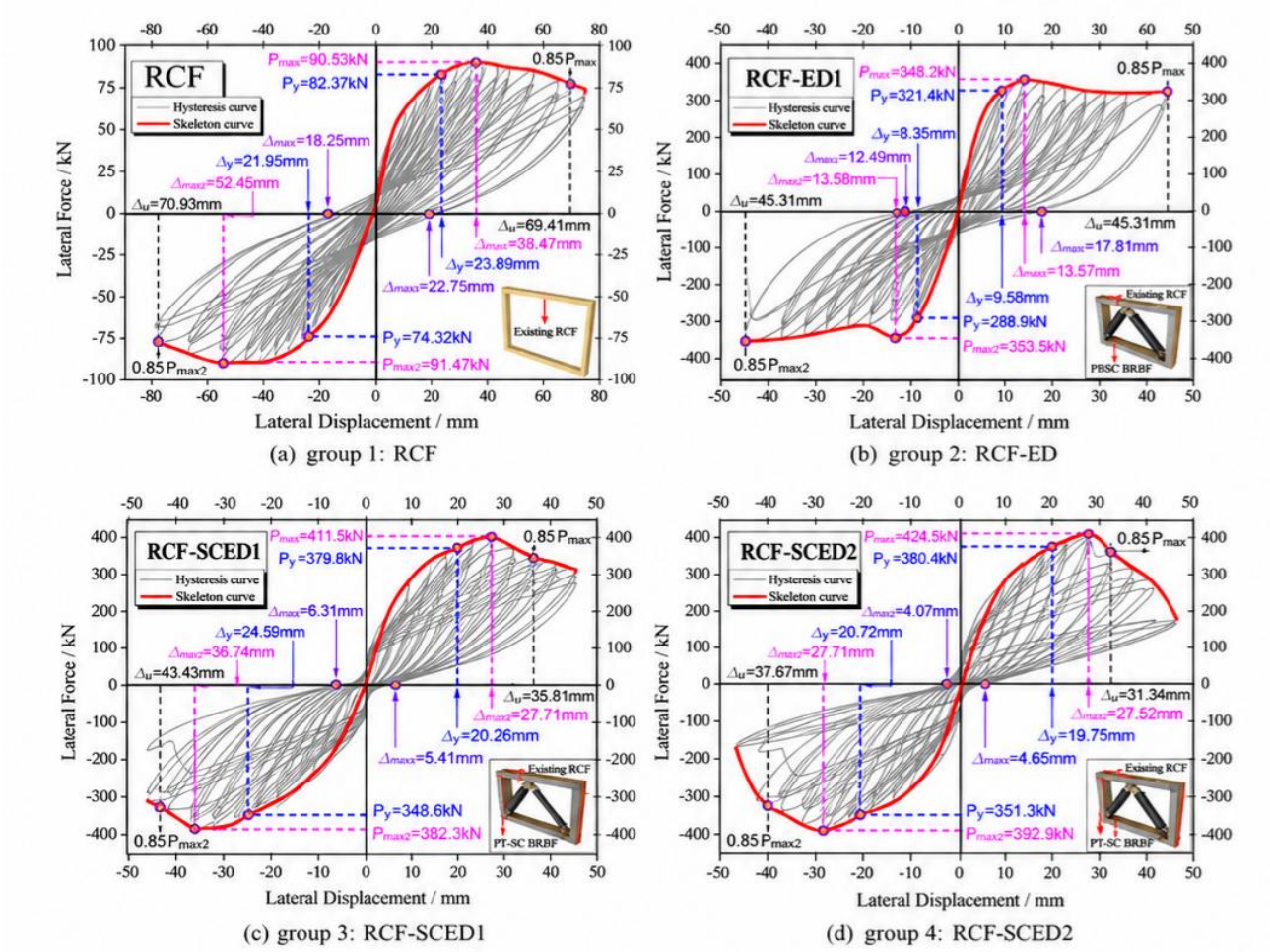



*Figure 4-Comparison of conventional energy-dissipating and self-centering hysteretic responses, illustrating energy-dissipation capacity, restoring force, and residual deformation[14].*

An important feature of these systems is that the energy-dissipating components are designed as external structural fuses that can be easily replaced after an earthquake[27]. For example, in post-tensioned precast beam-column joints, steel angles or specially shaped dog-bone plates can be connected to the beams using bolts[28]. During an earthquake, gaps open at the joints, allowing the unbonded post-tensioned tendons to stretch while remaining within their elastic range. At the same time, the external steel plates undergo plastic deformation and dissipate seismic energy. When the earthquake forces decrease, the restoring force from the tendons helps close the joint gaps and return the structure toward its original position. After the earthquake, the damaged steel plates can be removed by unbolting their connections and replaced with new components, provided that the surrounding structural members remain in good condition. This makes the repair process easier and faster than conventional methods that require removing and reconstructing damaged concrete members. As a result, replaceable energy-dissipating components can help reduce repair costs, shorten building downtime, and improve the post-earthquake recovery of precast concrete structures.

### 4.3 Experimental and Numerical Evidence

The seismic performance of self-centering and low-damage systems has been evaluated through experimental studies, including cyclic loading and shake-table tests. One of the important standards used to assess unbonded post-tensioned precast concrete wall systems is ACI ITG-5.1. This standard provides testing requirements for evaluating the behavior of special unbonded post-tensioned precast structural walls under repeated lateral loading. The tests consider large lateral drift demands, which may exceed 3%, along with energy dissipation capacity and residual deformation. Important performance measures include the relative energy dissipation ratio, with a commonly specified minimum value of 1/8 (12.5%), and the ability to limit residual drifts after large cyclic deformations. These requirements help assess whether the structural system can maintain sufficient strength, energy dissipation, and self-centering capability during strong earthquakes.

Experimental studies using shake-table tests and pseudo-static cyclic loading have shown that self-centering systems can reduce damage to the main structural members by concentrating plastic deformation in specially designed, replaceable energy-dissipating components[14], [29]. Numerical studies using OpenSees have also been carried out to evaluate the seismic response of these systems under different earthquake loading conditions[30]. Advanced material and deterioration models, such as the Modified Ibarra-Medina-Krawinkler model, can be used to represent stiffness and strength degradation during cyclic loading. Detailed numerical models may also consider important mechanisms such as gap opening, rebar bond-slip degradation, and concrete joint-shear deformation[31]. These analyses help researchers better understand the interaction between structural components and evaluate the effectiveness of self-centering systems in reducing damage. The findings suggest that properly designed self-centering retrofitting systems can reduce the risk of brittle connection failures, including dowel shear failure, and improve the overall seismic performance of existing precast concrete structures.

*Table 2-Experimental Validation and Component Functions of SC Precast Systems [14].*

| Component Function | Common Material/Device | Hysteresis Shape | Primary Role in System | Replaceability |
|---|---|---|---|---|
| **Energy Dissipation** | Mild Steel Slit, LYP Plates | Plump / Elastoplastic | Absorb kinetic energy, cap forces | High (Bolted Fuses) |
| **Energy Dissipation** | Friction Pads (Brass/Steel) | Rectangular / Rigid-Plastic | Absorb energy, provide stiffness | Moderate (Requires retorquing) |
| **Self-Centering** | Unbonded PT Strands | Non-linear Elastic | Provide restoring force to zero drift | Low (Designed to remain elastic) |
| **Dual Function** | Shape Memory Alloys (NiTi) | Flag-Shaped | Energy absorption + restoring force | High (If used as external bars) |

## 5. Seismic Performance, Resilience, and Design

### 5.1 Strength, Stiffness, Ductility, and Energy Dissipation

Evaluating the seismic performance of retrofitted precast concrete structures requires more than initial elastic stiffness and ultimate load-bearing strength. Displacement ductility and the relative energy dissipation ratio are also important indicators. Energy-dissipation devices, particularly buckling-restrained braces (BRBs), can shift the lateral load-resisting mechanism from bending-dominated frame action toward axial-force resistance through truss action[10]. This increases initial lateral stiffness and helps reduce lateral displacement and wind-induced vibrations.

Unlike rigid concrete infill walls that may experience brittle damage, energy-dissipation devices can provide controlled yielding and stable energy dissipation, reducing seismic demands on vulnerable precast concrete connections[15]. The relative energy dissipation ratio evaluates this behavior by comparing the area enclosed by a hysteresis loop with a reference area based on force and displacement values. For self-centering systems, energy dissipation must be balanced with restoring force. Sufficient energy dissipation helps control peak displacement, while restoring force must overcome frictional and yielding resistance to limit residual drifts. This balance improves the seismic performance and post-earthquake recovery of retrofitted precast concrete structures.

### 5.2 Drift, Residual Drift, Damage, and Reparability

In performance-based earthquake engineering, maximum inter-story drift is one of the most important parameters used to evaluate structural and non-structural damage during earthquakes[32]. Traditional strength-based retrofitting methods can reduce peak inter-story drift by increasing the stiffness of the building. However, they may not effectively control residual drift, which is the permanent lateral deformation remaining after an earthquake. Residual drift is an important factor in determining whether a damaged building can be repaired and returned to normal use. Buildings with large residual drifts, particularly those exceeding 0.5%, may face serious repair challenges and higher costs. In some cases, the remaining deformation can make repairs economically impractical. Large residual drifts can also increase secondary forces caused by P-Delta effects, which may further reduce

structural stability[32].

Self-centering retrofitting systems are designed to reduce these permanent deformations by providing a restoring force that helps the structure return toward its original position after an earthquake[22]. By controlling residual drift, these systems can improve post-earthquake performance and support higher performance objectives, such as Immediate Occupancy and Functional Recovery, rather than focusing only on Life Safety. Reducing permanent deformation can also help protect important building components, including elevators, doors, and internal partitions, although their performance also depends on other earthquake-related damage. This can reduce the need for major repairs, shorten building downtime, and allow occupants to return to normal activities sooner. As a result, self-centering systems offer an effective approach for improving the seismic resilience and long-term functionality of existing precast concrete structures.

### 5.3 Fragility, Seismic Risk, Losses, and Recovery

The economic and social benefits of seismic retrofitting can be evaluated using probabilistic seismic risk and loss assessment methods, particularly FEMA P-58. This methodology links structural response to earthquake damage and economic consequences using Engineering Demand Parameters (EDPs), such as maximum inter-story drift, and seismic intensity measures, such as Peak Ground Acceleration (PGA). Key outcomes include Expected Annual Loss (EAL), repair costs, and building downtime, providing insight into both structural performance and post-earthquake consequences.

Seismic fragility curves estimate the probability of different damage states in precast concrete buildings, considering vulnerabilities such as dowel-connection shear failure and exterior cladding detachment[33]. Older buildings without adequate seismic retrofitting may face a high risk of severe damage or collapse. Hybrid systems combining energy dissipation and self-centering, including externally attached self-centering buckling-restrained braces, can reduce peak and residual inter-story drifts[34]. Lower peak drift limits damage to displacement-sensitive components, while reduced residual drift improves repairability. Probabilistic studies have reported EAL reductions exceeding 60% compared with certain conventional retrofit methods, depending on structural configuration, seismic hazard, and retrofit design.

Advanced retrofitting can also provide environmental benefits by limiting earthquake damage and reducing demolition, reconstruction, and material consumption. Environmental Life Cycle Assessment (LCA) evaluates these impacts, including embodied carbon emissions, across construction, maintenance, repair, and replacement stages. Combining energy dissipation and self-centering can therefore improve seismic resilience, reduce long-term economic losses, and support sustainable retrofitting of existing precast concrete structures.

### 5.4 Design, Optimization, and Practical Implementation

Designing structures that combine energy dissipation and self-centering using conventional force-based methods can be challenging due to their complex nonlinear behavior. These methods typically rely on initial elastic stiffness and response modification factors (R-factors), which may not fully capture changes in secant stiffness, energy dissipation, and hysteretic damping in self-centering systems.

Direct Displacement-Based Design (DDBD) addresses these limitations by focusing on target displacement and effective secant stiffness at the design displacement[35]. Engineers first select a drift limit based on the required performance level, such as 2% inter-story drift for life safety where appropriate. The equivalent viscous damping ratio is then estimated from the system's hysteretic behavior, including the flag-shaped response of self-centering components. These parameters are used to calculate the required effective stiffness and design base shear, guiding the selection of post-tensioned tendons and the strength and dimensions of metallic energy-dissipating components. By directly considering displacement demands and energy dissipation,

DDBD offers a performance-oriented approach for designing self-centering retrofit systems and may reduce repeated design adjustments.

## 6. Critical Synthesis, Research Gaps, and Conclusions

### 6.1 Comparative Assessment of Retrofit Technologies

Seismic retrofitting methods offer different advantages and limitations for existing precast concrete structures. Traditional methods, such as concrete jacketing and fiber-reinforced polymer (FRP) wrapping, improve the strength and stiffness of individual members but may have limited effects on overall structural deformation. Energy-dissipation devices, including buckling-restrained braces (BRBs), metallic yielding dampers, and friction dampers, reduce seismic demands on vulnerable connections. However, systems relying mainly on plastic deformation may still experience significant residual drifts after strong earthquakes.

Self-centering systems address this limitation by using unbonded post-tensioning or shape memory alloys (SMAs) to provide restoring forces and reduce residual deformation. When combined with replaceable energy-dissipating components, they can improve both energy dissipation and post-earthquake recovery. Externally attached hybrid sub-structures also minimize interior construction and major modifications to existing members[9]. However, their effectiveness depends on connection detailing, force transfer, and the balance between energy dissipation and restoring forces. Therefore, retrofit selection should consider seismic performance, structural conditions, construction feasibility, costs, and post-earthquake repairability.

### 6.2 Current Limitations and Unresolved Challenges

Although experimental and numerical studies have shown promising results, several challenges remain before advanced seismic retrofitting systems can be widely applied to existing precast concrete structures.

Near-fault ground motions: Strong velocity pulses during near-fault earthquakes can cause large, sudden structural displacements, potentially damaging post-tensioned tendons and reducing their restoring force and self-centering capacity. Further experimental and numerical studies are needed to evaluate hybrid systems combining self-centering mechanisms and viscous dampers under near-fault ground motions.

Interaction with non-structural elements: Although self-centering systems reduce residual drift, gap opening and rocking may damage masonry infill walls, precast cladding, and internal partitions that cannot accommodate large movements[36]. Future research should focus on deformation-compatible connections and sliding interfaces to minimize damage and maintain post-earthquake building functionality.

Long-term durability: Prestress losses caused by concrete creep, shrinkage, and steel relaxation can gradually reduce tendon restoring forces. Corrosion and material aging may also affect the performance of tendons and shape memory alloys (SMAs). Long-term testing and field monitoring are needed to assess these effects and establish maintenance guidelines for reliable performance throughout the building's service life.

### 6.3 Future Research Directions

Future research should focus on improving the seismic performance, durability, and practical application of energy-dissipation and self-centering systems. Key priorities include developing smart multi-stage dampers that adapt to different earthquake intensities, evaluating hybrid systems under near-fault ground motions, and studying the interaction between rocking structures and non-structural components to minimize damage[17].

Another important direction is integrating seismic loss assessment with Environmental Life Cycle Assessment (LCA) to evaluate repair costs, building downtime, material consumption, and embodied carbon emissions over a structure's service life[35]. Clearer design guidelines are also needed for hybrid

systems incorporating shape memory alloys (SMAs), friction dampers, and unbonded post-tensioning. Further development of Direct Displacement-Based Design (DDBD) methods could improve their practical implementation. Addressing these gaps can support more reliable, cost-effective, and sustainable seismic retrofitting of existing precast concrete buildings?

### 6.4 Conclusions

This review discussed the application of energy-dissipation and self-centering systems to improve the seismic performance of existing precast concrete structures. Previous studies have shown that conventional strengthening methods may not be sufficient to address weak connections and residual deformation in older precast concrete buildings. Energy-dissipation devices, particularly buckling-restrained braces (BRBs) and friction dampers, can help reduce seismic forces and deformation demands on vulnerable structural members. At the same time, self-centering mechanisms provide restoring forces that help structures return toward their original positions after earthquakes, reducing permanent deformation.

Combining energy-dissipation and self-centering systems can improve seismic resilience by reducing structural damage, residual drift, and the need for major repairs after earthquakes. Externally attached hybrid systems also offer practical advantages, such as easier installation, shorter construction time, and less disturbance to building occupants. However, their overall performance depends on proper structural design, connection details, and the long-term durability of materials. More experimental studies, reliable numerical models, improved design guidelines, and life-cycle performance assessments are needed to better understand these systems and support their practical application. Overall, these technologies offer useful solutions for improving the safety, repairability, and sustainability of existing precast concrete structures in earthquake-prone regions.

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