Available online at www.garmian.edu.krd

Passer Journal of Basic and Applied Sciences

Passer 7 (Issue 1) (2025) 211-230

Original Article

Advances in Enhancing Earthquake Resilience of Concrete Infrastructure: A State-of-the-Art Review

Diyar Nasih Qader[1*], Hind Mahmood Khudhur[1], Pshtiwan Shakor[2], Ghazi Bahroz Jumaa[3], Sarwar Hasan[2], Sathvik Sharath Chandra[4]

[1]*Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq.*
[2]*Technical College of Engineering, Sulaimani Polytechnic University, Sulaymaniyah, Iraq.*
[3]*Civil Engineering Department, University of Garmian, Sulaymaniyah, Iraq.*
[4]*Department of Civil Engineering, Dayananda Sagar College of Engineering, Karnataka, India.*

Received 23 December 2024; revised 06 March 2025;
accepted 23 March 2025; available online 22 May 2025

DOI: 10.24271/PSR.2025.495371.1868

ABSTRACT

This study presents a comprehensive review of state-of-the-art seismic retrofitting techniques for reinforced concrete (RC) structures, focusing on structural resilience, economic feasibility, and sustainability. By systematically analyzing over 100 experimental, numerical, and case studies, this work benchmarks conventional methods—such as concrete and steel jacketing—against advanced solutions, including fiber-reinforced polymers (FRP), shape memory alloys (SMA), and base isolation systems. The findings indicate that FRP retrofitting increases lateral load capacity by up to 40%, shear strength by 30-80%, and ductility by 100-200%, while reducing overall structural weight by 50-75% compared to steel jacketing. SMA components exhibit up to 8% strain recovery, a 30-40% improvement in energy dissipation, and a 70% reduction in post-earthquake residual deformations, effectively enhancing self-centering capabilities. Base isolation systems reduce inter-story drift by 50-75%, floor accelerations by 65-85%, and overall structural damage by 40-60%, though their high initial cost (20-50% of total project costs) limits widespread adoption. Hybrid systems, such as SMA-FRP combinations, achieve 50-60% increased energy absorption and 90% recovery of deformation, further optimizing seismic resilience. Sustainability assessments show that FRP and SMA retrofitting reduce embodied carbon emissions by 20-40% and lifecycle maintenance costs by 30-50% compared to traditional methods. To address challenges such as cost, durability concerns, and standardization gaps, this review introduces a performance-based framework integrating lifecycle cost analysis, seismic risk assessment, and material efficiency to optimize retrofitting strategies for diverse structural applications, from heritage conservation to critical infrastructure.

Keywords: Seismic retrofitting; reinforced concrete structures; fiber-reinforced polymers; shape memory alloys; base isolation systems.

1 Introduction

Seismic retrofitting of current reinforced concrete (RC) structures has emerged as a critical engineering challenge in recent decades. The importance of this issue has been highlighted by several factors that have fundamentally changed our approach to structural safety and seismic resilience. The evolution of seismic design codes and regulations has revealed significant vulnerabilities in structures designed and built under older standards. This recognition has led to a widespread need for structural upgrades to meet current safety necessities [1]. The challenge is further compounded by the global issue of aged infrastructure. A substantial portion of existing RC buildings worldwide were built prior to the application of contemporary seismic design principles, making them particularly vulnerable to earthquake damage. The vulnerability is concerning after the increasing concentration of populations in cities, Numerous of which are in seismically active areas. Recent seismic activity in crowded regions has shown the catastrophic consequences of inadequate seismic resistance in existing of dense structures [2]. The financial implications of seismic retrofitting are substantial. The cost of seismic upgrading of vulnerable structures often needs to be balanced against the potential losses from earthquake damage, making the selection of appropriate retrofitting strategies that are crucial for both safety and economic perspectives [3]. This economic consideration becomes particularly significant in developing regions, where resources for structural upgrades may be restricted.

* Corresponding author
E-mail address diyar.nasih@uokirkuk.edu.iq (Instructor).
Peer-reviewed under the responsibility of the University of Garmian.

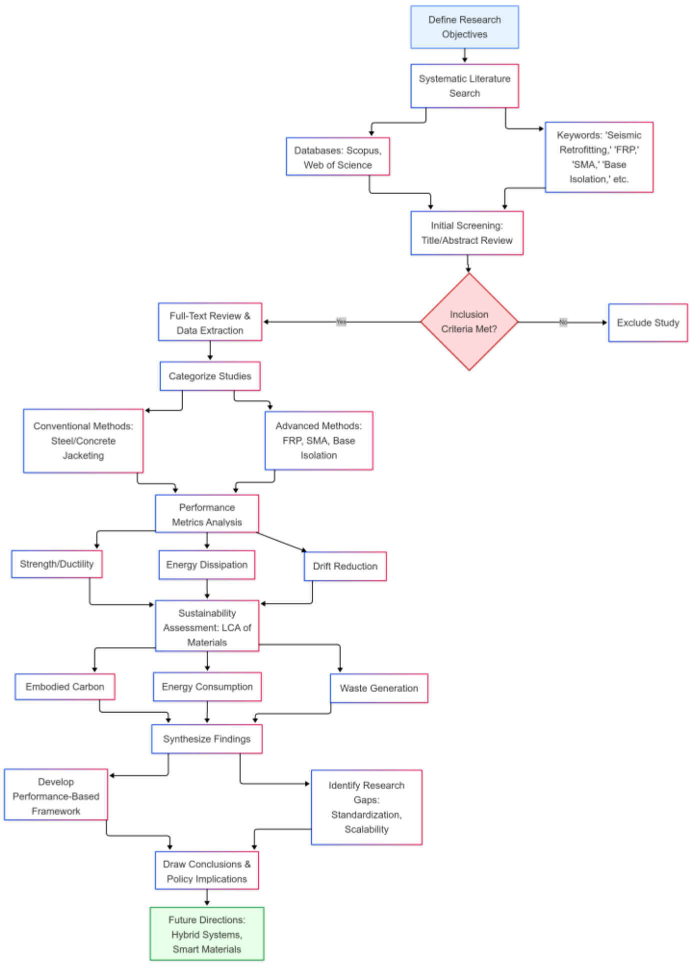

Figure 1: Flowchart illustrating the research methodology adopted in this review.

The seismic vulnerability of aging RC infrastructure, particularly structures built before modern seismic codes, poses a critical global challenge amplified by urbanization and climate change. While existing studies have explored retrofitting techniques, prior reviews often fragmentedly address material performance, economic feasibility, or sustainability, neglecting their interconnectedness in real-world applications. This gap leaves engineers and policymakers without actionable frameworks to prioritize strategies that reconcile safety, cost-effectiveness, and environmental impact—a pressing need as outdated infrastructure in seismically active regions faces intensifying seismic and climatic threats. This review bridges these gaps through a holistic synthesis of over 100 experimental, numerical, and case studies, advancing three novel contributions. First, it critically benchmarks conventional methods (e.g., steel/concrete jacketing) against advanced systems (FRP, SMA, base isolation), quantifying performance gains (40-100% strength increase, 50-75% drift reduction) against practical barriers like labor intensity and durability concerns. Second, it introduces a sustainability-driven retrofitting paradigm, integrating lifecycle cost analyses, low-carbon materials, and energy-efficient designs—an underexplored dimension in current literature. Third, it proposes a performance-based decision framework that aligns regional seismic risks, structural typologies, and retrofit objectives to optimize solutions for diverse contexts, from heritage conservation to critical infrastructure resilience. By dissecting emerging innovations (e.g., SMA-FRP hybrids) and unresolved challenges (e.g., standardization gaps), this work not only informs codes and funding priorities but also catalyzes a paradigm shift from strength-based to resilience-driven retrofitting. The subsequent sections systematically unravel these themes, beginning with conventional techniques and culminating in pathways for adaptive, sustainable infrastructure, ultimately equipping stakeholders to navigate the complexities of modern seismic resilience. This review objects to synthesize the latest advances in retrofitting techniques, providing a systematic analysis of their effectiveness and applicability across different structural contexts. The emphasis is on practical implementation while considering the various constraints that engineers face in real-world applications. The methodology flowchart of the current review investigation is displayed in Figure 1.

1.1 Research Significance

Among the most crucial engineering challenges is seismic retrofitting of RC structures, especially those constructed before the current seismic regulations were put into action. The old buildings are frequently unable to withstand the seismic demands of today, which presents serious safety hazards in earthquake-prone urban areas. In order to address these issues, this review investigated conventional retrofitting methods that have been shown to improve structural ductility, strength, and durability, such as steel jacketing and concrete. Even if these techniques are still useful, their drawbacks—such as higher dead loads, labor-intensive setup, and size augmentation—make it necessary to look at other options.

The state of art investigation emphasizes the revolutionary potential of cutting-edge technologies such as base isolation systems, shape memory alloys, and fiber-reinforced polymers (FRPs). Improved energy dissipation, self-centering capabilities, and notable decreases in structural drift and accelerations are only a few of the greater advantages that these contemporary methods offer. They are especially appropriate for high-risk areas and important infrastructure because of their flexibility in addressing different structural issues. By emphasizing performance indicators and practical limitations, the study highlights how these cutting-edge methods might be applied to meet changing seismic resilience requirements.

The review also highlights how retrofitting procedures could incorporate sustainability. Reducing environmental effect while maintaining economic viability requires the use of resource-efficient designs, lifespan cost assessments, and environmentally friendly materials. By bridging the gap between conventional and cutting-edge retrofitting techniques, this review offers insightful information to researchers, engineers, and policymakers. It advances seismic retrofitting procedures and helps construct more sustainable and safe infrastructure in seismically active areas across the world by optimizing strategies suited to particular structural and geographical demands.

2. Conventional retrofitting techniques

2.1 Concrete Jacketing

Among the first and most well-liked methods for upgrading RC structures is concrete jacketing. Using this technique, a fresh layer of concrete reinforced with stirrups and longitudinal bars (as shown in Figure 2) is applied over the previous structural element [4]. The method increases the structural element's cross-sectional area, which improves its stiffness, ductility, and load-bearing capability. According to [5], the extra concrete layer, which is usually 50-100 mm thick, works in composite with the current member to increase structural performance. Table 1 shows the benefits and drawbacks of this conventional method.

The efficiency of restoring RC circular columns with jackets of self-compacting concrete was investigated experimentally by Dubey and Kumar [6]. The study looked at the refit and strengthening of RC columns using self-compacting concrete (SCC) jackets reinforced by welded wire mesh. Forty-two cylindrical column specimens were examined in the investigation utilizing two distinct SCC mixes for jacketing, comprising 36 pre-stressed specimens and 6 control specimens. The findings demonstrated that SCC jackets successfully improved the columns' ductility and load-bearing capacity.

Table 1: Comparison of the benefits and challenges associated with concrete jacketing.

Advantages	Limitations
High strength enhancement	Increases member size
Excellent fire resistance	Labor intensive
Good durability	Additional dead load
Cost-effective	Requires surface preparation
Familiar to contractors	Building downtime
Local materials available	Weather dependent

A parametric analysis of RC jacketing retrofits for medium span bridges was carried out by Jara, et al. [7]. The seismic susceptibility of medium-span RC bridges was investigated in this study, with an emphasis on buildings constructed decades ago with little regard for seismic design. The researchers examined the effects of various RC jacketing parameters (changing thicknesses and reinforcement ratios) on the seismic performance of restored bridges of 30-meter spans and pier heights ranging from 5 to 25 meters using dynamic nonlinear analysis. The study measures the impact of steel reinforcement and jacket thickness on the likelihood of bridge collapse during seismic events by creating fragility curves and assessing structural demands. Its ultimate goal is to determine the ideal jacketing parameters for increased seismic resistance while also taking into account the impact of hysteresis degradation in the performance of repaired bridges.

Figure 2: Diagram showing the process of applying concrete jacketing to an existing RC structural element [8].

2.2 Steel Jacketing

To produce a composite action between existing part and steel jacket, structural elements are wrapped with steel plates or shells. In the 1990s, this method became well-liked for seismic retrofitting [9]. As illustrated in Figure 3, they are usually made from mild steel plates that are 4-10 mm thick, steel jackets are either bolted through the existing element or welded together around the member. To guarantee adequate stress transfer, It is common practice to fill the gap between the jacket and the old component with non-shrink grout. [10]. Table 2 lists this technique's application and requirements.

The effectiveness of retrofitting seismically damaged RC frames with steel jacketing was examined experimentally by Chong, et al. [11]. Using testing on a half-scale PC frame structure, the study examined the influence of steel jacketing on the seismic functioning of damaged frame structures. After being damaged by pseudo-static loading, the structure was refitted with steel jacketing and put through another test. The results discovered that although the damage patterns of the old and modified constructions were identical, the modified version showed notable enhancements, such as a 33% increase in starting stiffness, a 72% growth in peak load, and an 85% growth in yield load. Lower energy-dissipation coefficients than the original construction was the result of the retrofitting's disadvantages, which included large diagonal cracks in non-retrofitted beam sections and a pinching phenomenon in the hysteretic curve brought on by weld degradation.

High-strength steel bar mesh and engineered cementitious composite (ECC), a fiber-reinforced cementitious material with high tensile ductility and damage tolerance, were the foundations of a novel retrofitting technique put out by Hung, et al. [12]. When paired with jacketing materials, high-strength steel bar mesh significantly decreases the needed expansion of retrofitted joints and improves structural performance, according to their findings on steel jacketing in seismic retrofitting of beam-column joints. Table 3 shows this method's performance characteristics. Moreover, the difference between concrete and steel jacketing techniques is illustrated in Table 4.

Table 2: Technical specifications for steel jacketing, including plate thickness, steel grade, grout strength, and surface preparation requirements.

Parameter	Typical range	Comments
Plate thickness	4-10mm	Depends on required strength
Steel grade	S235-S355	Based on Eurocode 3 [13]
Grout strength	40-60 MPa	Non-shrink type
Surface preparation	Sa 2.5	As per ISO 8501-1 [14]
Corner radius	20-50mm	For stress concentration

Table 3: Summary of the improvements achieved through steel jacketing, including enhancements in axial capacity, shear strength, ductility, and overall structural confinement.

Aspect	Improvement range	Reference
Axial capacity	30-80%	Wu, et al. [15]
Shear strength	40-100%	ChaiI, et al. [16]
Ductility	100-200%	Priestley [9]
Confinement	Significant	Xiao and Wu [10]

Table 4: Comparison of the two retrofitting techniques, evaluating cost, installation time, strength improvements, durability, fire resistance, maintenance requirements, and size implications.

Feature	Concrete jacketing	Steel jacketing
Cost	Moderate	High
Installation time	Long	Moderate
Strength increase	Very high	High
Durability	Excellent	Good (with protection)
Fire resistance	Excellent	Poor
Maintenance	Low	Moderate
Size increase	Significant	Minimal
Skill requirement	Moderate	High

3 Advanced Materials and Techniques

Two cutting-edge materials and methods that have demonstrated potential for seismic retrofitting of RC structures are FRPs [17-19] and shape memory alloy (SMA) [20-23]. To improve RC elements' strength, ductility, and energy dissipation capacity and make them more resistant to deformations brought on by earthquakes, FRP composites can be externally connected to them. Conversely, SMAs are a category of intelligent materials that can go through reversible phase changes, which enables them to recover significant deformations and give structures the ability to center themselves, minimizing damage and residual drifts following an earthquake. These cutting-edge materials and procedures are useful instruments for boosting the seismic resistance of existing RC infrastructure because they provide benefits over conventional retrofitting techniques, including better performance, lower installation costs and times, and increased aesthetic appeal.

Figure 3: Illustration of steel jacketing as a retrofitting technique, where steel plates are wrapped around an existing structural element [8].

3.1 FRP

Significant developments in material science and application methodologies have characterized the growth of seismic retrofitting technology. Composite materials are increasingly being used to retrofit and renovate RC buildings during the past few decades. FRPs have several advantages over other building materials, including excellent corrosion resistance, low specific weight, strong tensile strength, and simplicity of use. When compared to other conventional techniques like bracing and shear walls, these benefits make FRP a better option for upgrading RC buildings [24].

Numerous experts from around the world have looked into the seismic strengthening and repair of structural elements using FRP materials. The use of FRP in fortification of beams [25-27], columns [28-32], and beam-to-column connections [33-37] has been the subject of numerous previous studies. Related issues including de-bonding failure and the interface contact of FRP layers and concrete material have also been studied by researchers [38-42]. Figure 4 shows the utilization of FRP in the shape of fabrics, which are connected to the concrete substratum utilizing epoxy resins.

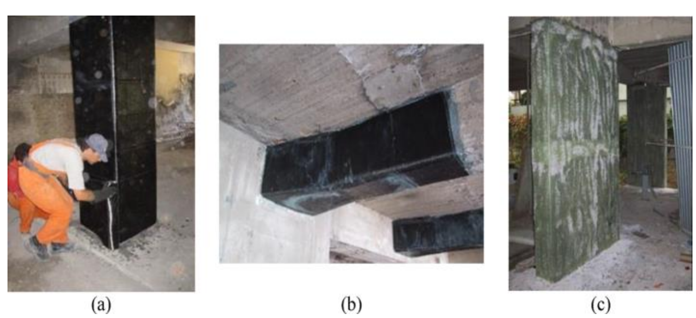

Figure 4: Wrapping of RC (a) columns and (b) beams with CFRP; (c) shear wall with GFRP [49].

Few studies examined FRP-rehabilitated RC structures as a whole, even though there is a wealth of investigation on the FRP strengthening of individual RC components. Full-scale testing by Balsamo, et al. [43]revealed that while shear wall deformability decreased, FRP-repaired structures retained their strength and displacement capacity. Di Ludovico, et al. [44] upgraded a structure from 0.2g to 0.3g PGA resistance by demonstrating the efficacy of FRP wrapping in enhancing structural ductility and energy dissipation. The benefits of FRP for seismic performance were further supported by research by Garcia, et al. [45] and Niroomandi, et al. [46], the latter of which demonstrated that, despite practical restrictions, web-bonded FRP retrofitting boosted lateral load capacity by 40% and seismic behavior factor by 100%.

Using FRP wrapping to increase ductility, Eslami and Ronagh [24] conducted a numerical investigation to evaluate the seismic enhancement of RC buildings. To evaluate seismic performance, nonlinear static analyses utilizing the lumped plasticity approach were conducted. The results indicated that while beam ductility augmentation was more advantageous for intermediate frames, column wrapping was ineffective for code-compliant constructions because of adequate existing confinement. FRP wrapping greatly increased ground motion resistance for poorly restricted structures (PGA = 0.52g). Buildings built to older standards could require reinforcement due to the more stringent criteria of more recent codes such as UBC97 [47] and IBC2006 [48]. Table 5 lists the performance measures for several FRP types.

Table 5: Overview of different FRP materials (CFRP, GFRP, AFRP) with their respective strength properties, advantages, and common applications in seismic retrofitting.

FRP type	Strength properties	Advantages	Common applications
Carbon (CFRP)	- Ultimate strength: 1500-3500 MPa - Elastic modulus: 150-250 GPa	- Superior fatigue resistance - Excellent chemical resistance - Low creep	- Critical structural elements - High-load areas - Corrosive environments
Glass (GFRP)	- Ultimate strength: 1200-2000 MPa - E-modulus: 35-75 GPa	- Cost-effective - Good impact resistance - Higher strain capacity	- Secondary structures - Indoor applications - Moderate load requirements
Aramid (AFRP)	- Ultimate strength: 1000-2500 MPa - E-modulus: 70-120 GPa	- Excellent impact resistance - Good fatigue properties - Light weight	- Dynamic loading conditions - Impact-prone areas - Blast protection

FRP materials are a popular choice for seismic retrofitting because of its high strength-to-weight ratio, corrosion resistance, and ease of application. The two main FRP techniques used are External Bonding (EB) and Near-Surface Mounted (NSM).

3.1.1 External Bonding (EB)

EB involves attachment FRP sheets or laminates to the external surface of concrete or masonry structures, providing increased flexural and shear capacity. This method is relatively simple to apply but can be limited by the surface preparation required and potential debonding issues [50]. Table 6 outlines the key steps for applying FRP as an external bonding element.

Table 6: Key steps for applying FRP as an external bonding element [51-54].

Step	Description	Key considerations	Research findings
Surface Preparation	Cleaning and roughening	CSP 3-5 profile required	Surface roughness significantly impacts bond strength
Primer Application	Penetrating sealer	Moisture content <4%	Proper primer application can increase bond strength by 30%
Putty Application	Surface leveling	Voids < 1 mm	Even distribution reduces stress concentrations
Resin Application	Adhesive layer	Temperature 10-35°C	Humidity control critical for proper curing

Kaptan [55] looked into the restoration of existing buildings using FRP materials that are externally bonded. The paper's first section details an experimental program the author created to assess the cyclic response of previously damaged RC specimens that were restored with carbon-FRP reinforcements. When compared to undamaged control specimens evaluated without external reinforcement, the test findings demonstrated that the chosen reinforcing systems were capable of significantly increasing the strength and deformation capacity of the restored specimens. Nevertheless, there was a noticeable loss of stiffness in the restored specimens. The study conducted an inelastic dynamic analysis of spatial structures in order to assess the impact of damaged columns. According to the numerical results, the seismic performance of structures with repaired elements was superior to that of equivalent structures with undamaged members.

3.1.2 Near-Surface Mounted (NSM)

Because NSM procedures have advantages over externally bonded methods, they are being used more often worldwide. These benefits include greater environmental protection, higher degrees of strengthening with less area, and superior bond qualities that lead to larger FRP strain utilizations before debonding. [50]. A study by Bilotta, et al. [56] has emphasized a number of benefits of NSM reinforcement. These include improved fire resistance, increased endurance in challenging climatic conditions, improved bond performance by 20-30%, and improved aesthetic results. Table 7 lists the procedures of applying NSM-FRP in RC structures. Moreover, Table 8 shows the different configurations of applying FRP in strengthening the structural elements.

Table 7: Performance metrics of NSM-FRP reinforcement, including strength increase, ductility enhancement, and strain capacity.

Parameter	Performance metrics	Research findings
Strength increase	40-120%	Dependent on fiber orientation and layers
Ductility enhancement	60-150%	Significantly affected by corner radius
Strain capacity	0.6-1.2%	Higher with multi-directional fibers

Table 8: Evaluation of different FRP configurations (U-wrapping, full wrapping, side bonding).

Configuration	Effectiveness	Design considerations
U-wrapping	40-80% increase in shear capacity	Anchorage critical for performance
Full wrapping	60-120% increase in shear capacity	Access requirements may limit application
Side bonding	30-50% increase in shear capacity	Most sensitive to debonding

As a result, to increase the flexural or shear capability of components, FRPs can be utilized as prefabricated sheets, strips or bars as shown in Figure 5. In already-existing elements, this is to serve as exterior longitudinal or transverse reinforcement.

(a) (b)

Figure 5: (a) flexural and shear strengthening by FRP laminates; (b) flexural strengthening by NSM reinforcement [49].

3.2 SMA

In the field of seismic retrofitting, SMAs have become innovative smart materials. These novel materials have special qualities that give them especially useful for structural engineering purposes [57]. The most important of these characteristics is their capacity to withstand severe deformations and regain their previous shape. Depending on the material's thermal-mechanical state, heating or spontaneous room temperature could permit this special characteristic. Super-elasticity (SE) refers to the former, whereas shape memory effect (SME) refers to the latter, as illustrated in Figure 6. Based on a study carried out by DesRoches, et al. [58], SMAs behave super elastically, recovering deformations up to 8% strain after unloading-far more than traditional materials can do. They are perfect for ambient circumstances in building constructions because of this feature as well as their temperature-dependent behavior. Consequently, this material's damper may overcome the drawback of significant residual deformation [59].

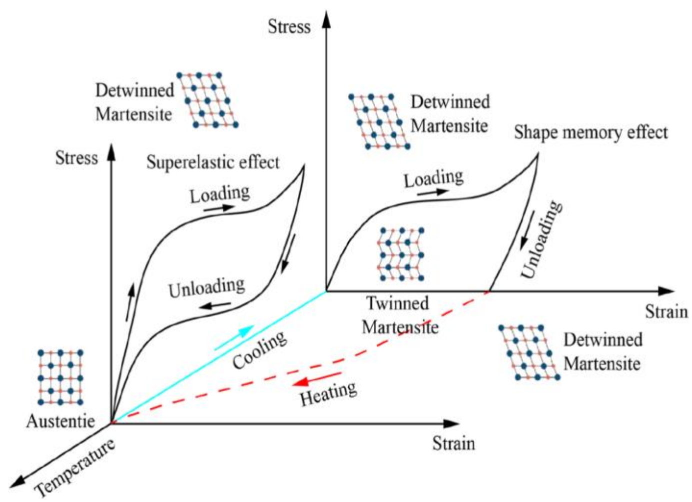

Figure 6: Graphical representation of the shape memory effect (SME) and superelasticity (SE) of SMAs [58].

For energy dissipation devices, SMA material is far superior to conventional metal material due to its superelasticity. Conventional metal materials typically have a 2% strain tolerance before permanently deforming. Many researchers have developed intelligent self-centering dampers via SMA for passive vibration management in civil engineering, these include center trapped type [60], tension and scissor type [61], double cylinder type [62], etc.

The first passive damping device utilizing SMA wires was created in 1995 by Clark, et al. [63] from the University of California's Earthquake Engineering Research Center, setting the stage for further advancements. Later, Dolce, et al. [64] presented a self-centering damper that divided into two different parts: a reset part that leverages the super-elastic property of SMA for self-centering, and an energy dissipation part made of SMA wires. After unloading, this design enables the damper to revert to its initial condition.

Using a large-diameter SMA rod, Miller, et al. [65] presented a self-centering buckling restrained brace (BRB) that dissipates energy and provides self-centering force as shown in Figure 7. Even with significant deformations, the method guarantees that the SMA rods maintain their tension, allowing for self-centering. According to test data, the highest distortion was around half of the residual deformation following unloading.

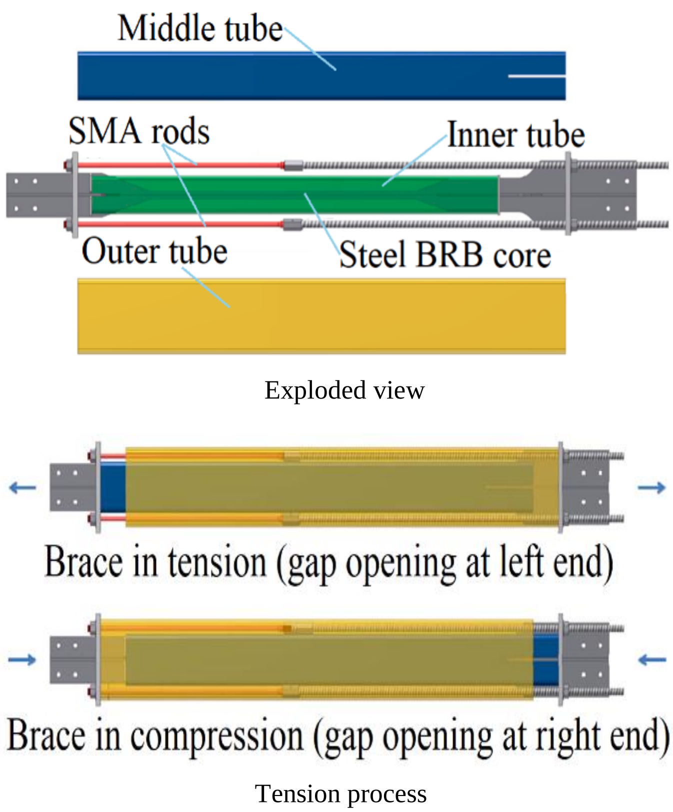

Figure 7: Self-Centering Buckling Restrained Brace (BRB) with SMA Rods [65].

A hybrid SMA viscous damper was created by Zhao, et al. [66] by fusing the energy dissipation of viscous dampers with the superelastic qualities of SMA wires. A hydraulic cylinder in this system improves damping performance by converting kinetic energy into heat. A hybrid SMA friction damper was further developed by Hui, et al. [67], whose performance could be altered by altering the friction force and SMA wire's initial strain. Using SMA and viscoelastic materials, also, they created a viscoelastic coupling beam damper that self-centers [68] which was used on a 10-story coupled shear wall construction. In comparison to conventional viscoelastic beams, this damper showed increased energy absorption, stiffness, and decreased residual deformation, minimizing plastic damage to the shear wall. The major attributes of typical SMA compositions are summarized in Table 9. Moreover, Table 10 presents key performance metrics for various self-centering applications.

Table 9: Comparison of different SMA materials (Ni-Ti, Fe-Mn-Si, Cu-Al-Ni, stainless steel) [69].

Property	Ni-Ti	Fe-Mn-Si	Cu-Al-Ni	Stainless steel
Density (kg/m³)	6450-6500	7200-7500	7100	7850
Poisson's ratio	0.33	0.359	0.3	0.265-0.3
Young's modulus (GPa)	28-83	160-200	30-85	190-120
Specific heat capacity (J/kg °C)	450-620	540	500	420-510
Thermal conductivity (W/m °C)	8.6-18	8.4	30-43	8.9-16.2
Ultimate tensile strength (MPa)	895-1900	680-1200	1000	480-1450
Yield stress (MPa)	70-690	475	950	170-850
Yield strain (%)	5-10	2.5-13	4-6	0.2-1.6
Ultimate strain (%)	5-50	12.4-20	10-30	1-40
Corrosion resistance	Very good	Good	Fair	Low
Cost	High	Low	Low	Low
SME	High	Moderate	Low	-
Workability	Moderate	Low	Good	Good
Fabrication	Low	Good	Moderate	Good
Processing	Demanding	Easy	Easy	Easy

Table 10: Assessment of SMA applications in beam-column joints, base connections, and bracing systems.

Application type	Recovery capacity	Drift reduction		Service life	Installation complexity
Beam-column Joints	95%	80-90%		25+ years	Moderate
Base connections	90%	75-85%		30+ years	High
Bracing systems	85%	70-80%		20+ years	Low

One of the most effective uses of SMAs in seismic retrofitting is in energy dissipation devices. SMA-based dampening devices were shown to significantly increase structural responsiveness by Casciati and Faravelli [70]. According to their research, these devices might dissipate energy 30-40% more effectively than traditional systems. Table 11 illustrates the improved performance characteristics of some types of hybrid systems.

Table 11: Performance properties of several hybrid systems.

System type	Energy dissipation capacity	Recovery rate	Cost-effectiveness	Maintenance requirements
Traditional dampers	Baseline	None	High	Regular
Pure SMA dampers	+30-40%	95%	Moderate	Minimal
Hybrid SMA systems	+40-50%	85%	High	Low
Multi-component SMA	+50-60%	90%	Moderate	Minimal

Numerous studies have established the long-term advantages of SMA applications in seismic retrofitting. Under the right design conditions, Eggeler, et al. [71] showed remarkable durability features, such as fatigue life exceeding 10^6 cycles. SMAs are especially appealing for long-term structural applications because of their endurance, excellent corrosion resistance, and temperature stability. According to Dolce, et al. [64], cost-benefit evaluations showed notable benefits in terms of lifecycle and maintenance expenses, which are shown in Table 12. Moreover, recent study by Alam, et al. [72] highlighted the important considerations for implementing SMA-based solutions as shown in Table 13.

Table 12: Economic evaluation of SMA applications, demonstrating maintenance cost, repair requirements, service life, and post-earthquake recovery times [64].

Benefit category	Performance improvement	Economic impact	Time frame
Maintenance cost	60% reduction	High initial cost offset	5-10 years
Repair requirements	40% decrease	Significant savings	Post-event
Service life	25-30 years	Long-term value	Lifecycle
Recovery time	70% reduction	Business continuity	Post-event

Table 13: Crucial considerations for implementing SMA-based solutions [72].

Factor	Challenges	Solutions	Impact on design
Initial cost	3-5x higher than traditional	Hybrid systems, targeted use	Optimization required
Temperature effects	Performance variation	Environmental controls	Additional systems
Installation	Specialized knowledge needed	Contractor certification	Project planning
Material selection	Property validation	Standardized testing	Quality

Figure 8 illustrates how SMA has been progressively utilized in the industry of constructing structures as research and technology have advanced. 1: The SE of SMA gives the structure with superior energy dissipation and self-resetting ability, which makes it easy to suppress cracks and displacements in the building. 2: Due to its SME, SMA is able to produce a significant driving force that can enhance the structure's overall performance, raise the cracking load, and impart prestress to the structure. 3: Reasonably using SMA's high damping characteristics can result in significant energy consumption. As a result, shock absorption and a decrease in the structural vibration response are possible.

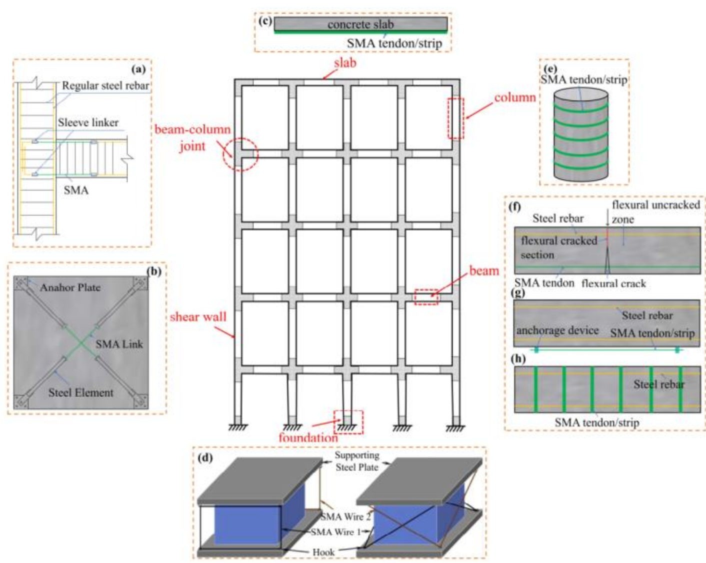

Figure 8: SMA applications in construction structures: (a) Beam-column joints strengthened with SMA; (b) Shear walls strengthened with SMA; (c) Slabs strengthened with SMA; (d) Components of SMA damping energy dissipation; (e) Columns strengthened with SMA; (f) SMA beams' capacity to self-heal; (g) Beams strengthened using SMA bending; (h) Shear-reinforced beams using SMA [73].

Two installation methods for SMA self-healing are depicted in Figure 9. One option is to use SMA in place of beam tensile reinforcement, and the other is to use anchors to secure SMA in the beam's tensile region. The SMA is thermally stimulated following component deformation or cracking under load conditions. Concrete beam fractures may now be repaired by the returning force produced by SMA acting on the structure.

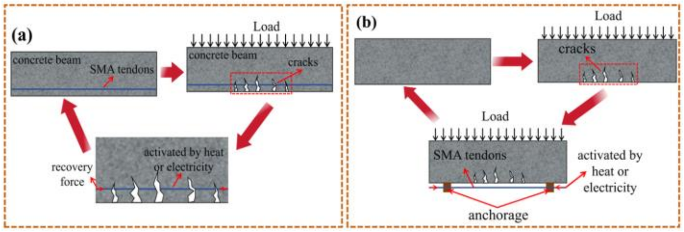

Figure 9: Methods for installing SMA in concrete beams that self-heal: (a) internal: tension reinforcement replacement; (b) external: fastening with anchors in the beam's tensile zone [73].

Relevant research on the seismic resistance of SMA concrete beam-column joints has been conducted. As seen in Figure 10a, Alam, et al. [72],Youssef, et al. [74],Alam, et al. [75],Nahar, et al. [76] carried out finite element analysis and experimental investigation while burying SE SMA bars as beam flexural reinforcements. The findings demonstrated that the SE SMA considered a decent self-leveling, distortion, and plastic hinge turning capabilities and decreased the enduring twist of beam-column joints when compared to conventional joints of beam-columns. Later, in order to improve the concrete's self-centering capacity and decrease the materials' direct cost, Oudah and El-Hacha [77],Oudah and El-Hacha [78] thought about reinforcing the plastic hinge zone with SMA. SMA shifted the plastic hinge section far from the cylinder and decreased joint deformation.

As seen in Figure 10b, Pei, et al. [79] offered a new self-centering junction that utilizes steel plates and SE SMA rods as fundamental elements in the node's core zone. The new steel plate and SMA reinforcement joint construction increased the joint's bearing capacity, postponed the deterioration of its stiffness, and enhanced its ductility and self-centering ability. As seen in Figure 10c, Zafar and Andrawes [80] investigated a novel FRP integrated with SE SMA fibers. According to the findings, the application of SMA-FRP rebar's in the plastic hinge region greatly decreased the buildup of irreversible damage and enduring distortion, enhancing the frame's whole achievement in the event of an ongoing seismic disaster.

To enhance the structure's seismic performance, Navarro-Gómez and Bonet [81] included ultra-high-performance concrete (UHPC) and SMA bars at strategic locations. The findings demonstrated that SMA and UHPC together decreased deformation. The seismic behave of reinforced frame joints reinforced by SE SMA rebar and high toughness, fiber reinforced, engineered cement composite (ECC), as seen in Figure 10d, was examined by Qian, et al. [22],Qian, et al. [82],Qian, et al. [83]. According to the findings, the failure approach and ductility of the beam-column junction were considerably enhanced by applying ECC after the plastic hinge area. SMA-ECC-reinforced beam-column joints demonstrated superior self-healing performance in internal damage repair and crack healing, as well as improved functional self-healing ability following earthquakes.

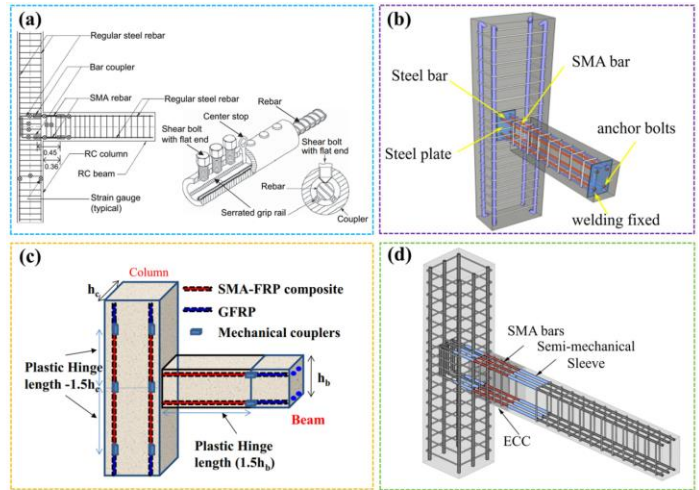

Figure 10: Beam-column junctions strengthened with SMA: (a) diagrammatic representation of the SMA joint [74,75]; (b) The self-centering joint in three dimensions [79]; (c) An illustration of the SMA-FRP joint [80]; (d) diagrammatic representation of the beam–column joint [83].

Finite element analysis is the primary focus of SMA-reinforced shear wall member research. Wang and Zhu [84] adopted the finite element program OpenSees to mimic and examine the self-resetting presentation of SMA shear walls, as seen in Figure 11a, by substituting SMA for the steel bar in the edge-constrained key range depending on the shear wall test model put forth by Thomsen IV and Wallace [85]. Even when interstory displacement is 2.5%, the analysis's findings demonstrated that the SMA shear wall's residual displacement considered minimal. SMA could accommodate the structure's seismic response in the event of a significant earthquake. The SMA constitutive model was created by Ghassemieh, et al. [86], Ghassemieh, et al. [87] in the Fortran program and integrated into the ABAQUS finite element program. In order to confirm the model's efficacy, they examined the seismic response of a two-story shear wall structure and a five-story coupled shear wall, comparing the investigational findings. Abraik and Youssef [88] assessed the seismic performance and sensitivity of 10 and 20-story buildings using the vulnerability curve. Even if SMA was only applied to the essential portions of the edge constraint, the results of interlayer dislocation, residual displacement, and vulnerability demonstrated that it greatly enhanced the structure's seismic performance and decreased its residual displacement.

Cortés-Puentes and Palermo [89], Cortés-Puentes and Palermo [90], Cortés-Puentes and Palermo [91] created a SMA tension bracket, which is represented in Figure 11b. Experiments and simulations demonstrated that this equipment increased the strength of RC shear walls while minimizing the strength and stiffness deterioration produced by shear failure. Abdulridha and Palermo [92] created a SMA-reinforced shear wall component, as illustrated in Figure 11c. The cyclic loading test revealed that SMA considerably increased the fracture healing performance of the component, even when the residual crack was 12%. SE SMA reinforcement resulted in decreased energy usage for the SMA shear wall compared to the standard shear wall.

Cortés-Puentes, et al. [93] restored damaged concrete in a SMA shear wall and tested it under cyclic pressure. The restored shear wall's yield and ultimate loads remained similar with the original, indicating that the SMA shear wall may be utilized afterward the earthquake with minor repairs. Soares, et al. [94] analyzed the seismic presentation of the SMA shear wall using arithmetic simulations. SMA shear walls outperformed standard steel-reinforced walls in terms of energy dissipation and self-resetting capacities.

Tolou Kian and Cruz-Noguez [95] presented three new forms of shear walls: FRP, steel wire, and SMA. The seismic behave of the three types of shear walls was compared using quasi-static loading experiments, and the recoverability mechanism of shear walls was investigated. Later, Abraik and Assaf [96] examined the seismic performance of several types of SMA-reinforced shear walls (NiTi, FeNCATB, and CuAlMn) with varying ground motion durations, and found that Cu-based RC walls performed better. In addition, Abraik and Asteetah [97] employed slotting technology to build a SMA-reinforced shear wall in 2022 and investigated its seismic performance under uniaxial and cyclic loads. This approach boosted the wall's bearing capacity and ductility, while also delaying strength loss. Tabrizikahou, et al. [98] utilized Abaqus software to evaluate a SMA-ECC shear wall made of Ni-Ti SMA strips and ECC to address brittle cracking in conventional concrete. Figure 11d illustrates the results. The study found that combining the two approaches enhanced the shear wall's energy absorption, self-resetting, and self-healing capabilities, leading to increased seismic routine and durability.

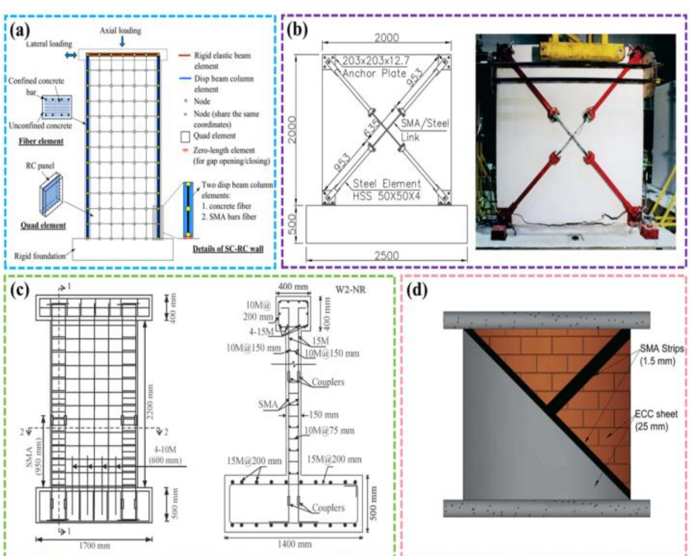

Figure 11: Shear walls strengthened with SMA: (a) Finite element simulation of the SMA-reinforced shear wall's plastic zone [84]; (b) SMA shear wall with external reinforcement [89-91]; (c) Design of shear walls reinforced with SMA [92]; (d) SMA-ECC shear wall [98].

In 2017, the Swiss business re-fer AG carried out the world's first use of Fe-SMA strips for building reinforcement in Villages [99]. The static bearing capacity of the building's RC floor had to be increased when load-bearing walls were removed. The faults of insufficient bending steel bar configuration at the position of the destroyed wall are solved by compounding the usage of steel beams, Fe-SMA strips, and non-prestressed CFRP strips, while also meeting the criteria of normal usage and ultimate bearing capacity. Figure 12a depicts an arrangement of reinforcing materials. The business employed nail fixation Fe-SMA strip machinery to manage fractures in concrete slabs of a school building in Nieppe, France [100]. Figure 12b illustrates how the Fe-SMA strip was nailed to the concrete slabs and calculated with resistance heating equipment. Prestressing led to a 0.14 mm reduction in crack width.

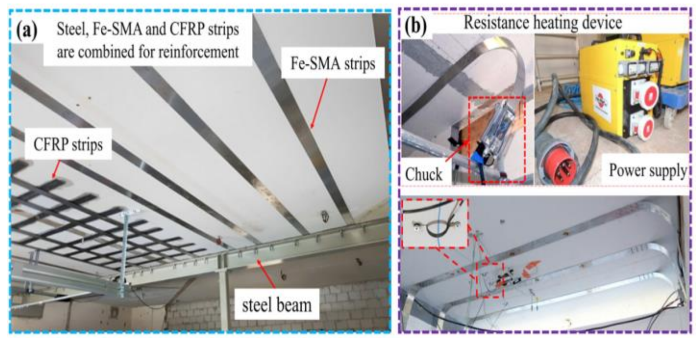

Figure 12: Fe-SMA-RC slabs: (a) example of reinforcing following the elimination of a load-bearing wall; (b) crack control of concrete slabs [100].

4 Innovative System-Level Approaches

4.1 Base Isolation System

Base isolation technology has evolved significantly since its first modern implementation in the 1970s. According to Warn and Ryan [101], this approach fundamentally alters the structure's dynamic response to seismic excitation by establishing a bendable interface between the structure and its foundation. This decoupling mechanism substantially decreases the transfer of seismic forces to the superstructure, making it particularly effective for critical facilities and historic buildings.

An example building situated on frictionless rollers, as depicted in Figure 13(b), is used to illustrate the base isolation principle. The rollers roll freely when the ground trembles, while the structure above stays still. Therefore, the lateral movement of the ground does not transfer any kind of force to the structure; in other words, the earthquake has no effect on the building. Now, a portion of the ground shaking will be transferred to the building above if that particular building is positioned on flexible pads that prevent horizontal movements (Figure 13(c)). Properly designed flexible pads can reduce ground shaking forces compared to fixed base buildings (see Figure 13(a)) [102]. Base isolation systems can be broadly categorized into two major types, as shown in Table 14.

Table 14: Categorization of elastomeric and sliding isolation bearings.

Type	Subtypes	Key characteristics	Notable applications
Elastomeric bearings	Lead rubber bearings (LRB)	High vertical stiffness, moderate damping (15-35%)	Pasadena City Hall (2007)
	High-damping rubber bearings (HDRB)	Enhanced damping properties (15-20%)	Oakland City Hall (2000)
Sliding systems	Friction pendulum systems (FPS)	Low friction coefficient (5-7%), self-centering	San Francisco Airport (2000)
	Triple pendulum bearings	Adaptive behavior, multiple sliding surfaces	Apple Park, California (2017)

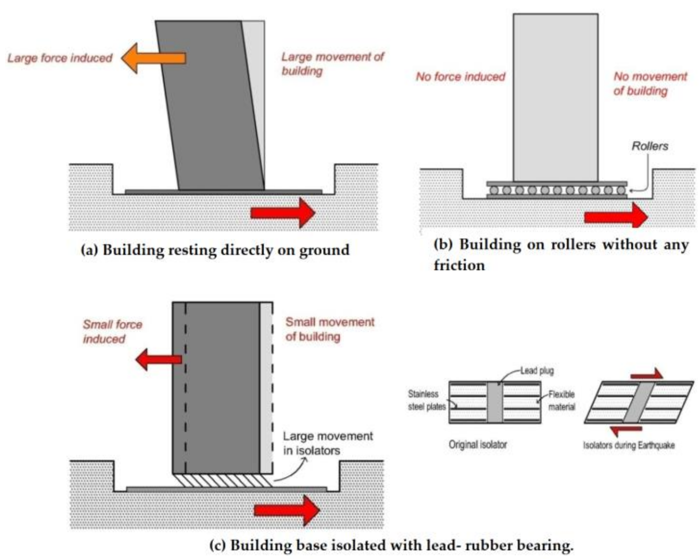

Figure 13: Illustration comparing fixed-base, friction roller, and elastomeric bearing isolation systems [102].

4.1.1 Elastomeric Bearings

The usage of elastomeric bearings, which are comprised of either neoprene or natural rubber, is indicative of the base isolation method that has gained the especially popularity in the past few years. By sandwiching the base and the structure with a layer of low horizontal rigidity, this method decouples the building or structure from the lateral mechanisms of the earthquake ground motion [103].

For this function, rubber bearings are most frequently utilized; Figure 14a depicts a typical laminated rubber bearing made by Wellington-based Robinson Seismic Limited. In order to give both horizontal flexibility and vertical rigidity, a rubber bearing is usually made up of alternating laminations of steel plates (shims) and thin rubber layers. Bridges are frequently supported by these bearings. The bearing has steel plates installed on both the top and bottom that are used to fasten it to the base and building. In the vertical direction, the bearing is extremely powerful and rigid, while in the horizontal direction, it is flexible. Horizontal flexibility transforms damaging horizontal shaking into soothing movement, while vertical rigidity guarantees the isolator will sustain the weight of the structure. As seen in Figure 14b, a lead-rubber bearing is a slightly modified design with a solid lead "plug" in the middle to absorb energy and increase damping. Lead-rubber bearings are frequently used in seismic isolation of structures [102,104,105].

The sliding system is an example of the second fundamental kind of base isolation system. Limiting the shear transfer across the isolation interface is how this operates. Numerous sliding methods have been put forth, and some have even been put into practice. Figure 14c depicts a popular sliding system known as a "spherical sliding bearing." Bearing pads with a curved surface and low friction support the building in this system. The building is free to slide on the bearings in the event of an earthquake. The building slides both vertically and horizontally because to the curved surface of the bearings. The horizontal or lateral forces are limited by the forces required to shift the building a little upward [102,106].

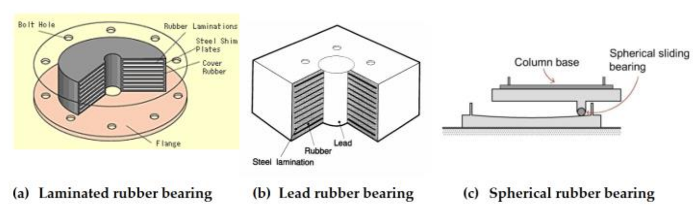

Figure 14: Base isolation devices [107].

4.1.2 Sliding Isolation with Adaptive Behavior

A sliding contact with a low coefficient of friction is what makes up sliding bearings. Sliders in friction pendulum bearings are held up by a spherically concave surface made of PTFE or stainless steel [101,108]. According to recent research, when the event period is near the isolation system period, a near-field earthquake's large long-term component could result in an excessive reaction [109-111]. Engineers were forced to expand the size of the isolators at a higher expense in order to accommodate huge displacements [112,113]. The shortcomings of conventional friction pendulum bearings prompted the creation of novel techniques that integrate sliding isolators with flexibility. The following categories apply to adaptive sliding isolators: sliding bearings with many spheres [114-116], sliding isolators with variable friction [117,118], and sliding isolators with variable curvature [119]. Figure 15 displays a three-story residential building constructed on a base-isolated ground-floor slab as part of the 2009 L'Aquila earthquake rehabilitation in Italy [120] that friction pendulum devices were used.

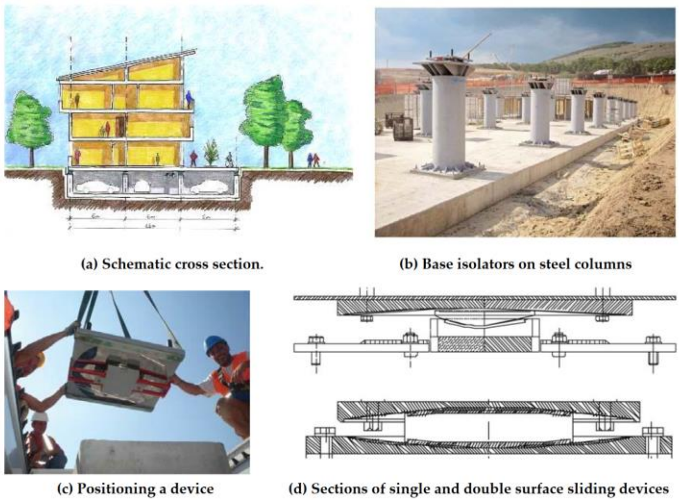

Figure 15: Photographic representation of a three-story residential structure built with base-isolated foundations [120].

4.2 Energy Dissipation Devices

Energy dissipation devices have become increasingly sophisticated in recent years. In order to prevent buildings and facilities from collapsing during earthquakes, dampers are used, and these buildings are seismically equipped by dissipating energy through seismic isolation and dampers. Semi-active, active, and passive control devices are the three main groups into which they can be separated [121]. Figure 16 illustrates common uses for several of these dampers. A seismic damper's primary function is to lessen the impact of vibrations and seismic forces in a structure throughout an earthquake or other seismic activity. In order to lessen displacement and stress on the structure, seismic dampers absorb or dissipate seismic force energy and transform it into heat. This enhances the structure's overall seismic performance and guards against damage [122]. Xu, et al. [123] suggested that hybrid passive control tools, which mix friction and viscoelastic dampers, can successfully reduce seismic impacts, especially in high-rise structures.

A common passive control method for separating a building's superstructure from the foundation is base isolation. Set up isolation mechanisms, like dampers or bearings, between the base and the superstructure accomplishes this. In the event of an earthquake, these technologies lessen the relocate of seismic powers to the structure by enabling the base to move independently of the superstructure. Because it can lessen the chance of structural deterioration or collapse throughout an earthquake, base isolation is a common technique for enhancing the seismic performance of structures [124]. Figure 17 illustrates the division of passive device and Table 15 lists energy dissipation device classification and applications.

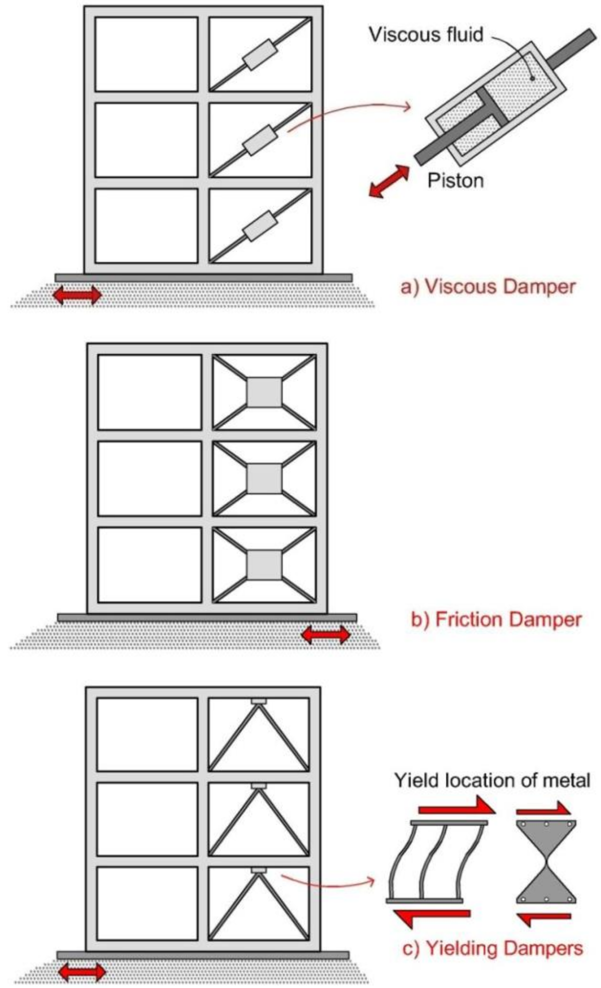

Figure 16: Dissipation devices [102].

Figure 17: Passive device division [122].

Table 15: Classification and applications of energy dissipation devices.

Device type	Operating principle	Energy dissipation mechanism	Notable applications
Metallic dampers	Yielding of metals	Hysteretic	Torre Mayor, Mexico City
Friction dampers	Surface friction	Coulomb friction	Canadian Space Agency Building
Viscoelastic dampers	Material deformation	Combined viscous and elastic	World Trade Center (pre-2001)
Fluid viscous dampers	Fluid orifice	Viscous	Taipei 101

5. Performance Assessment Methods

5.1 Numerical Analysis

An advanced method for simulating RC structures is nonlinear finite element analysis (NFEA), which is especially important for retrofit evaluation. This approach allows engineers to capture intricate behavioral features like as geometry effects, material non-linearity, and the interplay between existing and retrofit elements [125]. The ability of contemporary NFEA software to model progressive damage, fracture propagation, and ultimate failure modes offers crucial information for optimizing retrofit design. Performance-based design approaches have revolutionized retrofit strategies by focusing on achieving specific performance objectives rather than merely meeting code requirements. Table 16 outlines the comparison between different numerical analysis approaches.

Table 16: Comparison of nonlinear finite element analysis (NFEA), performance-based design, and real-time simulation techniques.

Method	Primary applications	Key advantages	Limitations
NFEA	Detailed structural analysis, Complex geometries	High accuracy, Comprehensive results	Computationally intensive, Requires expertise
Performance-based design	System-level assessment, Risk analysis	Risk-informed decisions, Economic optimization	Complex implementation, Data requirements
Real-time simulation	Dynamic response analysis, Control system design	Immediate feedback, Rate-dependent effects	Hardware limitations, Scaling issues

Performance-based design in seismic retrofitting differs from traditional design by focusing on achieving specific performance objectives rather than simply meeting prescriptive code requirements. Traditional seismic design methods follow a code-based approach, where structures are designed to withstand predefined loads and forces, often using conservative safety factors. This approach does not explicitly account for varying levels of seismic intensity or the expected behavior of a structure during different earthquake scenarios.

In contrast, Performance-based design evaluates how a structure will perform under realistic seismic conditions, allowing engineers to tailor retrofitting strategies based on performance objectives such as immediate occupancy, life safety, or collapse prevention. This method involves advanced nonlinear analyses, including time-history and pushover simulations, to predict the actual response of retrofitted structures under earthquake loading.

The benefits of Performance-based design in seismic retrofitting include greater flexibility in selecting retrofit solutions, optimized cost-effectiveness by targeting critical structural weaknesses, and improved resilience by ensuring that retrofitted buildings perform as intended during seismic events. By integrating Performance-based design, engineers can prioritize retrofitting efforts based on risk levels, structural deficiencies, and intended post-earthquake functionality, ultimately leading to safer, more reliable, and economically efficient retrofitting strategies.

5.2 Experimental Validation

Hybrid simulation combines physical testing with numerical modeling, offering a cost-effective approach to validating retrofit designs. McCrum and Williams [126] emphasizes that this method is particularly valuable for large structures where full-scale testing would be impractical. By physically testing critical components while numerically simulating the remainder, engineers can obtain comprehensive performance data while managing resource constraints [127].

Real-time substructure testing represents an advanced experimental technique that enables detailed investigation of critical structural components. Shake table testing remains the gold standard for seismic performance validation. According to Martinelli and Filippou [125], these tests provide the most realistic assessment of retrofit performance under seismic loading, allowing observation of actual dynamic behavior and failure modes. While resource-intensive, shake table tests offer irreplaceable validation data for retrofit designs. Table 17 shows the comparison between several experimental validation methods.

Yang, et al. [128] introduced a modern sort of Nonlinear Energy Sink (NES), a structural passive control technology aimed at reducing seismic responses in buildings. The NES involves of a horizontal trajectory and an added mass block, which acts as a damper by absorbing and dissipating energy through a horizontal nonlinear restoring force. Hypothetical evaluation of the NES is provided, including the formulation of its returning force and the system's equation of motion. The findings specify that the NES successfully dissipates energy and decreases the seismic response of the structure, especially in terms of top-story displacement and acceleration. The effectiveness of the NES is influenced by the natural frequency of the frame and the spectral properties of the seismic waves, offering broadband control over a range of frequencies.

Table 17: Assessment of hybrid simulation, real-time substructure testing, and shake table testing [125,126].

Method	Scale	Cost level	Data quality	Primary applications
Hybrid simulation	Medium to large	Moderate	High	System response, component interaction
Real-time substructure	Component to medium	Moderate	Very high	Local behavior, interface effects
Shake table	Small to full	Very high	Excellent	Seismic performance, dynamic effects

Moreover, Sunca, et al. [129] considered the results of pounding between adjacent RC buildings on their seismic responses, addressing a gap in experimental research that has largely focused on steel structures. Three half-scale, two-story RC models were constructed and tested under three conditions: (i) without pounding, (ii) pounding between a taller and shorter building (slab-to-slab interaction at one floor), and (iii) pounding between buildings of equal height (slab-to-slab interaction at two floors). The results revealed that different types of pounding significantly influenced structural responses, including floor accelerations, displacements, hysteretic behavior, and dynamic characteristics. Each pounding scenario triggered distinct damage mechanisms, highlighting the critical impact of pounding on RC buildings during earthquakes. Figure 18 shows the general dimensions of the test setup.

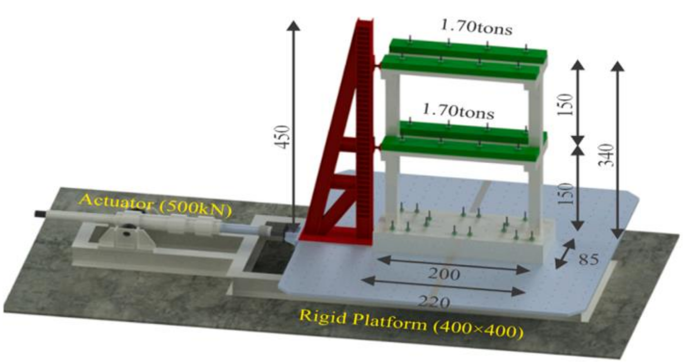

Figure 18: Dimensions of the test setup (dimensions in cm) [129].

6 Future Trends and Challenges

6.1 Emerging Technologies

An important development in seismic retrofitting technology is the combination of adaptive systems and smart materials. The combination of insulating materials and textile-based composites is transforming conventional retrofit techniques by providing gains in both seismic and energy performance [130]. Advanced modeling of FRP strengthening in RC frames can greatly improve seismic performance, especially in beam-column connections where conventional retrofit techniques are limited, as Del Vecchio, et al. [131] show. The smart materials and systems used in seismic retrofitting of RC structures are tabulated in Table 18.

Table 18: Evaluation of innovative materials such as textile-based composites, FRP, smart sensors, and adaptive dampers [130,131].

Material/system	Primary function	Benefits	Implementation challenges
Textile-based composites	Structural strengthening	Dual seismic-energy benefits	Installation complexity
FRP systems	Joint reinforcement	High strength-to-weight ratio	Cost considerations
Smart sensors	Performance monitoring	Real-time data collection	System integration
Adaptive dampers	Dynamic response control	Adjustable properties	Maintenance requirements

In seismic retrofitting, sustainability has grown in significance recently. The increasing emphasis on environmentally friendly retrofit materials and methods that reduce environmental effect while preserving structural integrity is highlighted by Pohoryles, et al. [132]. This includes creating novel composite materials and integrated solutions that meet energy efficiency and structural needs. Experiences with post-earthquake rehabilitation have brought to light the significance of effective and sustainable retrofit techniques, especially in residential buildings [2]. The sustainability aspects used in retrofit solutions are summarized in Table 19.

The convergence of advanced monitoring technologies with structural health assessment represents a paradigm shift in seismic retrofit evaluation. McCrum and Williams [126] describe how hybrid testing methods and advanced monitoring systems enable better understanding of structural performance, allowing for more effective retrofit designs. Güneyisi [133] demonstrates that reliability-based assessment approaches, supported by monitoring data, can significantly improve the effectiveness of retrofit solutions.

Sustainability metrics are rigorously quantified through lifecycle assessments (LCAs) aligned with ISO 14040 [134] standards, which evaluate embodied carbon, energy consumption, and material efficiency. For instance, FRP systems demonstrate a 30-40% reduction in embodied carbon compared to steel jacketing, attributable to lower material mass (1.5-2.5 kg/m² vs. 10-15 kg/m² for steel) and reduced transportation emissions due to lightweight properties [49]. Similarly, SMA-based retrofitting exhibits a 25% decrease in lifecycle energy consumption over 50 years, owing to minimal maintenance needs and high durability [69]. Case studies further validate these claims: the 2017 Swiss retrofit of RC slabs using Fe-SMA strips achieved a 15% reduction in material waste and 20% lower CO_2 emissions compared to conventional CFRP-strengthened slabs, as quantified through post-installation LCAs [99]. In the L'Aquila earthquake reconstruction, base-isolated buildings equipped with elastomeric bearings reduced operational energy demand by 35-50% over 30 years by minimizing post-earthquake repair cycles [102]. A comparative LCA table (Table 20) synthesizes these findings, contrasting embodied carbon, energy intensity, and waste generation across methods:

Table 19: Analysis of green composites, integrated solutions, resource-efficient materials, and life-cycle cost considerations [132].

Aspect	Current practice	Future direction	Environmental impact
Materials	Traditional concrete	Green composites	Reduced CO_2 emissions
Energy efficiency	Single-purpose retrofits	Integrated solutions	Enhanced building performance
Resource use	New materials focus	Recycled content integration	Lower resource depletion
Life-cycle cost	Initial cost focus	Whole-life consideration	Improved sustainability

Table 20: Comparative LCA of retrofitting methods: Quantitative environmental impact metrics.

Retrofitting method	Embodied carbon (kg CO_2/m^2)	Energy consumption (GJ/m^2)	Material waste (%)	Case study reference
Concrete jacketing	120-150	1.8-2.2	12-18	Campione, et al. [5]
Steel jacketing	200-250	2.5-3.0	8-10	Wu, et al. [15]
FRP (CFRP)	80-100	1.2-1.5	5-8	Swiss Fe-SMA Project, 2017
SMA (Ni-Ti)	150-180	1.5-1.8	3-5	L'Aquila Base Isolation, 2009

6.2 Research Needs

Despite significant advances in retrofit technologies, there remains a critical need for standardized design procedures. According to Di Ludovico, et al. [2], post-earthquake reconstruction experiences have highlighted variations in retrofit implementation quality and effectiveness. Table 21 lists the research priorities in retrofit standardization. Moreover, the challenges and opportunities of Building Information Modeling (BIM) integration are summarized in Table 22.

Table 21: Identification of gaps in design guidelines, performance metrics, and testing standards [2].

Research area	Current status	Priority level	Expected impact
Design guidelines	Fragmented	High	Improved consistency
Performance metrics	Variable	Critical	Better assessment
Implementation protocols	Limited	High	Quality assurance
Testing standards	Developing	Medium	Validated solutions

Table 22: BIM integration challenges and opportunities [126].

Aspect	Current challenge	Opportunity	Implementation timeline
3D modeling	Limited retrofit templates	Enhanced visualization	Short-term
Data integration	Fragmented information	Unified platform	Medium-term
Collaboration	Communication gaps	Improved coordination	Short-term
Performance analysis	Limited tools	Advanced simulation	Long-term

One of the biggest challenges engineers face when implementing retrofitting methods in real-world applications is the cost constraint associated with advanced materials like FRP and SMA, which often require significant upfront investment. This financial barrier can be particularly problematic in resource-constrained regions. Additionally, technical complexity arises due to the need for specialized installation techniques, such as base isolation systems or SMA components, which demand highly skilled labor that may not be readily available. Engineers must also contend with constructability challenges, especially when using conventional methods like concrete or steel jacketing, which can increase the dimensions of structural elements and create conflicts with architectural or spatial requirements. Durability concerns further complicate retrofitting efforts, as environmental exposure (e.g., UV degradation of FRP or corrosion in steel jackets) necessitates ongoing maintenance, often overlooked in long-term planning. Moreover, regulatory gaps present another challenge, as existing building codes may not fully accommodate emerging retrofit technologies, leading to delays in approval and implementation. To overcome these obstacles, hybrid strategies—combining cost-effective traditional methods with targeted use of advanced solutions—can optimize both performance and affordability. Workforce training, standardization of guidelines, and the integration of digital tools like BIM can further facilitate smoother implementation. Policymakers can also play a crucial role by updating regulations and offering incentives to encourage sustainable retrofitting solutions.

Future research in seismic retrofitting should focus on several key areas to enhance structural resilience, sustainability, and cost-effectiveness. One critical area is the development of advanced materials, such as next-generation FRP and SMA, which offer superior strength, durability, and self-healing capabilities but require further optimization for large-scale application. Research should aim to improve material performance under extreme conditions, reduce costs, and enhance long-term sustainability. Another important focus is refining performance-based design frameworks, integrating real-time structural health monitoring and artificial intelligence to create adaptive retrofitting strategies that respond dynamically to seismic activity. Additionally, life-cycle cost analysis and environmental impact assessment should be prioritized to promote the adoption of low-carbon, resource-efficient retrofitting solutions. Addressing constructability challenges is also crucial, particularly for retrofitting methods that require specialized labor or complex installation procedures; research should explore prefabricated or modular retrofitting techniques to streamline implementation. Furthermore, updating seismic design codes and standardization is essential to ensure regulatory frameworks align with emerging technologies and facilitate wider adoption. The expected outcomes of this research include the development of more cost-effective, durable, and scalable retrofitting solutions, improved predictive models for seismic resilience, and greater integration of smart materials and monitoring systems for proactive infrastructure management. Table 23 shows a comparative analysis of old and innovative retrofitting techniques based on their cost, durability, and seismic performance.

While advanced materials such as SMA and FRP entail higher initial costs, their long-term economic advantages are substantial. A lifecycle cost analysis (LCCA) spanning 50 years reveals that SMA-based retrofitting achieves 30-40% lower total costs compared to steel jacketing due to reduced maintenance, minimal downtime, and near-zero residual deformation, which eliminates post-earthquake repair expenses [64,72]. For instance, in a 10-story hospital retrofit in California, SMA dampers reduced annual maintenance costs by 60% and extended service life by 25 years, offsetting their upfront premium within 15 years [68]. Similarly, FRP systems demonstrate 20-30% lifecycle cost savings in corrosive environments (e.g., coastal regions), as their non-corrosive nature eliminates steel replacement cycles [49].

Table 23: Comparative analysis of conventional and advanced retrofitting methods: cost, durability, and seismic performance metrics.

Retrofitting method	**Cost**	**Durability**	**Seismic performance**	**Key limitations**
Conventional methods				
Concrete jacketing	Moderate	Excellent	- Strength: +40-100% - Ductility: +100-200%	Increased member size, labor-intensive
Steel jacketing	High	Good (with protection)	- Axial capacity: +30–80% - Shear strength: +40–100% - Confinement: significant	Corrosion risk, maintenance required
Advanced methods				
FRP systems (CFRP/GFRP)	High	Excellent	- Lateral load capacity: +40% - Seismic behavior factor: +100%	Debonding risk, surface preparation needed
SMA (Ni-Ti)	Very high	Very good	- Strain recovery: ≤8% - Energy dissipation: +30–40%	Temperature sensitivity, specialized labor
Base isolation (elastomeric)	Very high	Good	- Inter-story drift: –50-75% - Acceleration: –65-85%	Complex installation, high upfront cost
Hybrid dampers (SMA-FRP)	High	Excellent	- Energy dissipation: +40-50% - Self-centering: 85-95%	Integration complexity, cost-effectiveness

Conclusions

In order to address the issues of aging infrastructure and the requirement for increased earthquake resilience, seismic retrofitting of RC structures has undergone significant change. This review provides insights into the efficacy, sustainability, and applicability of both conventional and sophisticated retrofitting procedures, highlighting their advantages and disadvantages. It is possible to make the following important conclusions:

1- Concrete jacketing increases strength (40-100%) and ductility (100-200%) but adds structural weight and labor.
2- Steel jacketing enhances axial capacity (30-80%) and shear strength (40-100%) but requires corrosion protection and maintenance.
3- FRP composites improve lateral load capacity (40%), ductility (100-200%), and reduce weight (50-75%) but face debonding risks.
4- SMAs enable 8% strain recovery, 30-40% energy dissipation gains, and 70% residual deformation reduction for self-centering systems.
5- Base isolation reduces inter-story drift (50-75%), accelerations (65-85%), and damage (40-60%) but incurs high initial costs (20-50% of project costs).
6- Hybrid systems (e.g., SMA-FRP) achieve 50-60% energy absorption improvement and 90% deformation recovery.
7- FRP/SMA reduce embodied carbon (20-40%) and lifecycle maintenance costs (30-50%) compared to traditional methods.
8- SMA retrofitting offers 30-40% lifecycle cost savings over 50 years due to minimal repairs and extended service life.

This review underscores a paradigm shift from strength-based to resilience-driven retrofitting. Advanced materials like FRP and SMA, combined with system-level innovations (e.g., base isolation, hybrid dampers), offer transformative potential to enhance seismic performance while aligning with sustainability goals. However, widespread adoption hinges on overcoming cost barriers, improving durability, and establishing standardized protocols. The proposed future work can be summarized as follows:

1- Material Optimization: Developing low-cost, high-performance SMA/FRP hybrids with self-healing capabilities.
2- Standardization: Creating unified design codes and testing protocols for emerging technologies.
3- Smart Integration: Exploring AI/ML-driven retrofitting frameworks paired with IoT-enabled structural health monitoring.
4- Policy Advocacy: Advocating for regulatory updates to incentivize sustainable retrofitting in seismic-risk zones.
5- Environmental Impact: Conducting lifecycle assessments (LCAs) to quantify long-term carbon savings of advanced systems.

Funding

This research received no external funding.

Authors contribution

Diyar Nasih Qader conceptualized the study, supervised the overall research, and contributed significantly to the manuscript's structure and technical content. **Hind Mahmood Khudhur** carried out the initial literature review and data curation, and contributed to the writing and editing of the manuscript. **Pshtiwan Shakor** provided critical insights into seismic retrofitting technologies and supported the comparative analysis of conventional and advanced methods. **Ghazi Bahroz Jumaa** contributed to the sections on experimental validation and base isolation systems, and participated in proofreading. **Sarwar Hasan** led the review of advanced materials, particularly FRP and SMA systems, and assisted with the compilation of tables and figures. **Sathvik Sharath Chandra** focused on sustainability analysis, lifecycle assessment, and helped refine the performance-based framework. All authors reviewed and approved the final manuscript.

Conflict of interests

The authors declare no conflicts of interest.

References

[1] Sugano, S. Seismic rehabilitation of existing concrete buildings in Japan. *12th WCEE, Auckland, New Zealand* (2000).
[2] Di Ludovico, M., Prota, A., Moroni, C., Manfredi, G. & Dolce, M. Reconstruction process of damaged residential buildings outside historical centres after the L'Aquila earthquake: part I—" light damage" reconstruction. *Bull. Earthq. Eng.* **15**, 667-692 (2017).
[3] Calvi, G. Choices and criteria for seismic strengthening. *J. Earthq. Eng.* **17**, 769-802 (2013).
[4] Julio, E., Branco, F. & Silva, V. Structural rehabilitation of columns with reinforced concrete jacketing. *Prog. Struct. Eng. Mater.* **5**, 29-37 (2003).
[5] Campione, G., Fossetti, M., Giacchino, C. & Minafò, G. RC columns externally strengthened with RC jackets. *Mater. Struct.* **47**, 1715-1728 (2014).
[6] Dubey, R. & Kumar, P. Experimental study of the effectiveness of retrofitting RC cylindrical columns using self-compacting concrete jackets. *Constr. Build. Mater.* **124**, 104-117 (2016).
[7] Jara, J., Montes, O., Olmos, B. & Martínez, G. Parametric study of medium span bridges retrofitted with reinforced concrete jacketing. *Can. J. Civ. Eng.* **46**, 567-580 (2019).
[8] Bouvier, C. A. *Techniques of seismic retrofitting for concrete structures*, Massachusetts Institute of Technology, (2003).
[9] Priestley, M. *Seismic design and retrofit of bridges*. (John Wiley & Sons, 1996).
[10] Xiao, Y. & Wu, H. Retrofit of reinforced concrete columns using partially stiffened steel jackets. *J. Struct. Eng.* **129**, 725-732 (2003).
[11] Chong, X. *et al.* Experimental investigation of retrofitting seismically damaged reinforced-concrete frames using steel jacketing. *Structures* **62**, 106243 (2024).
[12] Hung, C.-C., Hsiao, H.-J., Shao, Y. & Yen, C.-H. A comparative study on the seismic performance of RC beam-column joints retrofitted by ECC, FRP, and concrete jacketing methods. *J. Build. Eng.* **64**, 105691 (2023).

[13] Standard, B. Eurocode 3—Design of steel structures—. *BS EN* **1**, 2005 (1993).
[14] Standard, B. International standards. *INTERNATIONAL ORGANIZATION* **1988**, 12-15 (1988).
[15] Wu, Y.-F., Liu, T. & Oehlers, D. J. Fundamental principles that govern retrofitting of reinforced concrete columns by steel and FRP jacketing. *Adv. Struct. Eng.* **9**, 507-533 (2006).
[16] ChaiI, Y. H., Priestley, M. N. & Seible, F. Seismic retrofit of circular bridge columns for enhanced flexural performance. *Structural Journal* **88**, 572-584 (1991).
[17] Altalabani, D. & Hejazi, F. Development of Rectangular Vibration Isolators with Double Core Systems for Structures. *Int. J. Civ. Eng.* **21**, 763-787 (2023).
[18] Altalabani, D., Hejazi, F., Rashid, R. S. B. M. & Abd Aziz, F. N. A. Development of new rectangular rubber isolators for a tunnel-form structure subjected to seismic excitations. *Structures* **32**, 1522-1542 (2021).
[19] Yue, C. *et al.* Utilization finite element and machine learning methods to investigation the axial compressive behavior of elliptical FRP-confined concrete columns. *Structures* **70**, 107681 (2024).
[20] Ferraioli, M., Concilio, A. & Molitierno, C. Seismic performance of a reinforced concrete building retrofitted with self-centering shape memory alloy braces. *Earthq. Eng. Eng. Vib.* **21**, 785-809 (2022).
[21] Varkani, M. M., Bidgoli, M. R. & Mazaheri, H. Mathematical modeling and dynamic response of concrete frames containing shape memory alloys under seismic loads. *Appl. Math. Model.* **111**, 590-609 (2022).
[22] Qian, H., Li, Z., Pei, J., Kang, L. & Li, H. Seismic performance of self-centering beam-column joints reinforced with superelastic shape memory alloy bars and engineering cementitious composites materials. *Compos. Struct.* **294**, 115782 (2022).
[23] Tavakol, M., HajiKazemi, H., Rajabzadeh-Safaei, N. & Masoodi, A. R. Influence of shape memory alloy on seismic behaviour of hollow-section concrete columns. *Proc. Inst. Civ. Eng. Struct. Build.* **176**, 815-832 (2021).
[24] Eslami, A. & Ronagh, H. R. Effect of FRP wrapping in seismic performance of RC buildings with and without special detailing–A case study. *Compos. Part B Eng.* **45**, 1265-1274 (2013).
[25] Saadatmanesh, H. Extending service life of concrete and masonry structures with fiber composites. *Constr. Build. Mater.* **11**, 327-335 (1997).
[26] Shahawy, M., Arockiasamy, M., Beitelman, T. & Sowrirajan, R. Reinforced concrete rectangular beams strengthened with CFRP laminates. *Compos. Part B Eng.* **27**, 225-233 (1996).
[27] Rabinovitch, O. & Frostig, Y. Experiments and analytical comparison of RC beams strengthened with CFRP composites. *Compos. Part B Eng.* **34**, 663-677 (2003).
[28] Saadatmanesh, H., Ehsani, M. R. & Jin, L. Repair of earthquake-damaged RC columns with FRP wraps. *Structural Journal* **94**, 206-215 (1997).
[29] Chaallal, O. & Shahawy, M. Performance of fiber-reinforced polymer-wrapped reinforced concrete column under combined axial-flexural loading. *Structural Journal* **97**, 659-668 (2000).
[30] Harajli, M. H. & Rteil, A. A. Effect of confinement using fiber-reinforced polymer or fiber-reinforced concrete on seismic performance of gravity load-designed columns. *Structural Journal* **101**, 47-56 (2004).
[31] Toutanji, H., Han, M., Gilbert, J. & Matthys, S. Behavior of large-scale rectangular columns confined with FRP composites. *J. Compos. Constr.* **14**, 62-71 (2010).
[32] De Luca, A. *et al.* Structural evaluation of full-scale FRP-confined reinforced concrete columns. *J. Compos. Constr.* **15**, 112-123 (2011).
[33] Mostoufinezhad, D. & Talaeitaba, S. Finite element modeling of RC connections strengthened with FRP laminates. (2006).
[34] Granata, P. J. & Parvin, A. An experimental study on Kevlar strengthening of beam–column connections. *Compos. Struct.* **53**, 163-171 (2001).
[35] Attari, N., Amziane, S. & Chemrouk, M. Efficiency of beam–column joint strengthened by FRP laminates. *Adv. Compos. Mater.* **19**, 171-183 (2010).
[36] Mahini, S. S. & Ronagh, H. R. Web-bonded FRPs for relocation of plastic hinges away from the column face in exterior RC joints. *Compos. Struct.* **93**, 2460-2472 (2011).
[37] Mukherjee, A. & Joshi, M. FRPC reinforced concrete beam-column joints under cyclic excitation. *Compos. Struct.* **70**, 185-199 (2005).
[38] Al-Sulayvani, B. J. & Al-Talabani, D. N. Strengthening and repair of circular RC slabs with openings using CFRP strips under repeated loading. *Constr. Build. Mater.* **84**, 73-83 (2015).
[39] Antonopoulos, C. P. & Triantafillou, T. C. Analysis of FRP-strengthened RC beam-column joints. *J. Compos. Constr.* **6**, 41-51 (2002).
[40] Mosallam, A. S. & Banerjee, S. Shear enhancement of reinforced concrete beams strengthened with FRP composite laminates. *Compos. Part B Eng.* **38**, 781-793 (2007).
[41] Ascione, L., Berardi, V. P., Feo, L. & Mancusi, G. A numerical evaluation of the interlaminar stress state in externally FRP plated RC beams. *Compos. Part B Eng.* **36**, 83-90 (2005).
[42] Qader, D. N., Sirwan, R. & Ali, M. K. Impact of composite and aluminium face sheets on the properties of the 3D-printed cores under quasi-static three-point bending. *Electron. J. Struct. Eng.* **24**, 12-15 (2024).
[43] Balsamo, A., Colombo, A., Manfredi, G., Negro, P. & Prota, A. Seismic behavior of a full-scale RC frame repaired using CFRP laminates. *Eng. Struct.* **27**, 769-780 (2005).
[44] Di Ludovico, M., Prota, A., Manfredi, G. & Cosenza, E. Seismic strengthening of an under-designed RC structure with FRP. *Earthq. Eng. Struct. Dyn.* **37**, 141-162 (2008).
[45] Garcia, R., Hajirasouliha, I. & Pilakoutas, K. Seismic behaviour of deficient RC frames strengthened with CFRP composites. *Eng. Struct.* **32**, 3075-3085 (2010).
[46] Niroomandi, A., Maheri, A., Maheri, M. R. & Mahini, S. S. Seismic performance of ordinary RC frames retrofitted at joints by FRP sheets. *Eng. Struct.* **32**, 2326-2336 (2010).
[47] Bachman, R. E., & Bonneville, D. R. The seismic provisions of the 1997 Uniform Building Code. *Earthq. Spectra* **16**, 85-100 (2000).
[48] IBC. *International building code*. (2006).
[49] Gkournelos, P., Triantafillou, T. & Bournas, D. Seismic upgrading of existing reinforced concrete buildings: A state-of-the-art review. *Eng. Struct.* **240**, 112273 (2021).
[50] Saeed, I. A., Kalfat, R., Al-Mahaidi, R., Al-Attar, T. S. & Al-Shather, B. S. Performance of RC beams strengthened using NSM FRP and cement based adhesives after exposure to elevated temperatures. *Structures* **69**, 107557 (2024).
[51] Winkler, P. Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair. *Internation Concrete Repair Institute* (2013).
[52] 440, A. C. I. C. (CSA S806–12 (reaffirmed 2017), Mississauga, Ontario, Canada, 2017).
[53] CNR-DT-200-R1. *Guide for the design and construction of externally bonded frp systems for strengthening existing structures*. (Italian National Research Council, 2013).
[54] Ibrahim Mohammed, I., Shakor, P., N Qader, D. & S Al-Luhybi, A. A comprehensive review of recent experimental and numerical investigations on the impact of openings in steel plate shear walls (SPSWs). *Passer J. Basic Appl. Sci.* **6** (2024).
[55] Kaptan, K. Effectiveness of externally bonded FRP systems in strengthening of RC structures in seismic areas. *Proc. Inst. Civ. Eng. Struct. Build.* **170**, 362-375 (2017).
[56] Bilotta, A. *et al.* Bond efficiency of EBR and NSM FRP systems for strengthening concrete members. *J. Compos. Constr.* **15**, 757-772 (2011).
[57] Janke, L., Czaderski, C., Motavalli, M. & Ruth, J. Applications of shape memory alloys in civil engineering structures—Overview, limits and new ideas. *Mater. Struct.* **38**, 578-592 (2005).
[58] DesRoches, R., McCormick, J. & Delemont, M. Cyclic properties of superelastic shape memory alloy wires and bars. *J. Struct. Eng.* **130**, 38-46 (2004).
[59] Xu, G. *et al.* Review on self-centering damper for seismic resilient building structures. *Structures* **54**, 58-77 (2023).
[60] Krumme, R., Hayes, J. & Sweeney, S. Structural damping with shape-memory alloys: one class of devices. *Smart Struct. Mater.: Passive Damp.* **2445**, 225-240 (1995).
[61] Li, H., Mao, C. X. & Ou, J. P. Experimental and theoretical study on two types of shape memory alloy devices. *Earthq. Eng. Struct. Dyn.* **37**, 407-426 (2008).
[62] Parulekar, Y. *et al.* Seismic response attenuation of structures using shape memory alloy dampers. *Struct. Control Health Monit.* **19**, 102-119 (2012).
[63] Clark, P. W., Aiken, I. D., Kelly, J. M., Higashino, M. & Krumme, R. Experimental and analytical studies of shape-memory alloy dampers for structural control. *Smart structures and materials 1995: Passive damping* **2445**, 241-251 (1995).

[64] Dolce, M., Cardone, D. & Marnetto, R. Implementation and testing of passive control devices based on shape memory alloys. *Earthq. Eng. Struct. Dyn.* **29**, 945-968 (2000).
[65] Miller, D. J., Fahnestock, L. A. & Eatherton, M. R. Self-centering buckling-restrained braces for advanced seismic performance. *Structures Congress*, 960-970 (2011).
[66] Zhao, X., Liu, Z., Wang, S., Yang, T. & Zhan, M. Design and analysis of an innovative hybrid shape memory alloys viscous damper. *Earthq. Eng. Eng. Vib* **36**, 72-78 (2016).
[67] Hui, Q., Hongnan, L., Wenjie, R. & Huai, C. Experimental investigation of an innovative hybrid shape memory alloys friction damper. *J. Build. Struct.* **32**, 58 (2011).
[68] Qian, H. *et al.* Development and investigation of an innovative shape memory alloy cable-controlled self-centering viscoelastic coupling beam damper for seismic mitigation in coupled shear wall structures. *Earthq. Eng. Struct. Dyn.* **52**, 370-393 (2023).
[69] Tabrizikahou, A. *et al*. Application and modelling of Shape-Memory Alloys for structural vibration control: State-of-the-art review. *Constr. Build. Mater*. **342**, 127975 (2022).
[70] Casciati, F. & Faravelli, L. Experimental characterisation of a Cu-based shape memory alloy toward its exploitation in passive control devices. *Journal de Physique IV* **115**, 299-306 (2004).
[71] Eggeler, G., Hornbogen, E., Yawny, A., Heckmann, A. & Wagner, M. Structural and functional fatigue of NiTi shape memory alloys. *Mater. Sci. Eng. A* **378**, 24-33 (2004).
[72] Alam, M. S., Nehdi, M. & Youssef, M. A. Seismic performance of concrete frame structures reinforced with superelastic shape memory alloys. *Smart Struct Syst* **5**, 565-585 (2009).
[73] Xu, L., Zhu, M., Zhao, J., Chen, M. & Shi, M. The Utilization of Shape Memory Alloy as a Reinforcing Material in Building Structures: A Review. *Materials* **17**, 2634 (2024).
[74] Youssef, M., Alam, M. & Nehdi, M. Experimental investigation on the seismic behavior of beam-column joints reinforced with superelastic shape memory alloys. *J. Earthq. Eng.* **12**, 1205-1222 (2008).
[75] Alam, M. S., Youssef, M. & Nehdi, M. Analytical prediction of the seismic behaviour of superelastic shape memory alloy reinforced concrete elements. *Eng. Struct.* **30**, 3399-3411 (2008).
[76] Nahar, M., Billah, A. M., Kamal, H. R. & Islam, K. Numerical seismic performance evaluation of concrete beam-column joint reinforced with different super elastic shape memory alloy rebars. *Eng. Struct.* **194**, 161-172 (2019).
[77] Oudah, F. & El-Hacha, R. Joint performance in concrete beam-column connections reinforced using SMA smart material. *Eng. Struct.* **151**, 745-760 (2017).
[78] Oudah, F. & El-Hacha, R. Innovative Self-Centering Concrete Beam-Column Connection Reinforced Using Shape Memory Alloy. *ACI Struct. J.* **115** (2018).
[79] Pei, Q., Wu, C., Cheng, Z., Ding, Y. & Guo, H. The seismic performance of new self-centering beam-column joints of conventional island main buildings in nuclear power plants. *Materials* **15**, 1704 (2022).
[80] Zafar, A. & Andrawes, B. Seismic behavior of SMA–FRP reinforced concrete frames under sequential seismic hazard. *Eng. Struct.* **98**, 163-173 (2015).
[81] Navarro-Gómez, A. & Bonet, J. L. Improving the seismic behaviour of reinforced concrete moment resisting frames by means of SMA bars and ultra-high performance concrete. *Eng. Struct.* **197**, 109409 (2019).
[82] Qian, H. *et al.* Experimental study on the seismic performance of self-centering bridge piers incorporating ECC and superelastic SMA bars in the plastic hinge regions. *Structures* **46**, 1955-1967 (2022).
[83] Qian, H., Wang, X., Li, Z. & Zhang, Y. Experimental study on re-centering behavior and energy dissipation capacity of prefabricated concrete frame joints with shape memory alloy bars and engineered cementitious composites. *Eng. Struct.* **277**, 115394 (2023).
[84] Wang, B. & Zhu, S. Seismic behavior of self-centering reinforced concrete wall enabled by superelastic shape memory alloy bars. *Bull. Earthq. Eng.* **16**, 479-502 (2018).
[85] Thomsen IV, J. H. & Wallace, J. W. Displacement-based design of slender reinforced concrete structural walls—experimental verification. *J. Struct. Eng.* **130**, 618-630 (2004).
[86] Ghassemieh, M., Bahaari, M. R., Ghodratian, S. M. & Nojoumi, S. A. Improvement of concrete shear wall structures by smart materials. *Open J. Civ. Eng.* **2**, 87 (2012).
[87] Ghassemieh, M., Rezapour, M. & Sadeghi, V. Effectiveness of the shape memory alloy reinforcement in concrete coupled shear walls. *J. Intell. Mater. Syst. Struct.* **28**, 640-652 (2017).
[88] Abraik, E. & Youssef, M. A. Seismic fragility assessment of superelastic shape memory alloy reinforced concrete shear walls. *J. Build. Eng.* **19**, 142-153 (2018).
[89] Cortés-Puentes, W. L. & Palermo, D. Seismic retrofit of concrete shear walls with SMA tension braces. *J. Struct. Eng.* **144**, 04017200 (2018).
[90] Cortés-Puentes, W. & Palermo, D. Modeling of concrete shear walls retrofitted with SMA tension braces. *J. Earthq. Eng.* **24**, 555-578 (2020).
[91] Cortés-Puentes, W. L. & Palermo, D. SMA tension brace for retrofitting concrete shear walls. *Eng. Struct.* **140**, 177-188 (2017).
[92] Abdulridha, A. & Palermo, D. Behaviour and modelling of hybrid SMA-steel reinforced concrete slender shear wall. *Eng. Struct.* **147**, 77-89 (2017).
[93] Cortés-Puentes, L., Zaidi, M., Palermo, D. & Dragomirescu, E. Cyclic loading testing of repaired SMA and steel reinforced concrete shear walls. *Eng. Struct.* **168**, 128-141 (2018).
[94] Soares, M. M., Palermo, D. & Cortés-Puentes, W. L. Modelling of mid-rise concrete shear walls reinforced with superelastic shape memory alloys: Nonlinear analysis. *Eng. Struct.* **247**, 113049 (2021).
[95] Tolou Kian, M. J. & Cruz-Noguez, C. Reinforced concrete shear walls detailed with innovative materials: seismic performance. *J. Compos. Constr.* **22**, 04018052 (2018).
[96] Abraik, E. & Assaf, J. Impact of ground motion duration on concrete shear walls reinforced with different types of shape memory alloy rebars. *Structures* **33**, 2739-2754 (2021).
[97] Abraik, E. & Asteetah, A. Parametric analysis of slotted concrete shear walls reinforced with shape memory alloy bars. *Case Stud. Constr. Mater.* **16**, e00806 (2022).
[98] Tabrizikahou, A., Kuczma, M., Łasecka-Plura, M. & Noroozinejad Farsangi, E. Cyclic behavior of masonry shear walls retrofitted with engineered cementitious composite and pseudoelastic shape memory alloy. *Sensors* **22**, 511 (2022).
[99] Schranz, B., Michels, J., Shahverdi, M. & Czaderski, C. Strengthening of concrete structures with iron-based shape memory alloy elements: Case studies. *5th SMAR Conference*, 1-8 (2019).
[100] Fritsch, E., Izadi, M. & Ghafoori, E. Development of nail-anchor strengthening system with iron-based shape memory alloy (Fe-SMA) strips. *Constr. Build. Mater*. **229**, 117042 (2019).
[101] Warn, G. P. & Ryan, K. L. A review of seismic isolation for buildings: historical development and research needs. *Buildings* **2**, 300-325 (2012).
[102] Buchanan, A. H. *et al.* Base isolation and damage-resistant technologies for improved seismic performance of buildings. (2011).
[103] Christopoulos, C. Principles of Passive Supplemental Damping and Seismic Isolation. *IUSS Press google schola* **2**, 325-336 (2006).
[104] Yang, T., Konstantinidis, D. & Kelly, J. M. The influence of isolator hysteresis on equipment performance in seismic isolated buildings. *Earthq. Spectra* **26**, 275-293 (2010).
[105] Kelly, J. M. Seismic isolation systems for developing countries. *Earthq. Spectra* **18**, 385-406 (2002).
[106] Toopchi-Nezhad, H., Tait, M. J. & Drysdale, R. G. Lateral response evaluation of fiber-reinforced neoprene seismic isolators utilized in an unbonded application. *J. Struct. Eng.* **134**, 1627-1637 (2008).
[107] Yuan, Y., Wang, S., Tan, P. & Zhu, H. Mechanical performance and shear constitutive model study of a new high-capacity polyurethane elastomeric bearing. *Constr. Build. Mater.* **232**, 117227 (2020).
[108] Morgan, T. A. & Mahin, S. A. *The use of base isolation systems to achieve complex seismic performance objectives*. (Pacific Earthquake Engineering Research Center, 2011).
[109] Lu, L.-Y., Lin, C.-C. & Lin, G.-L. Experimental evaluation of supplemental viscous damping for a sliding isolation system under pulse-like base excitations. *J. Sound Vib.* **332**, 1982-1999 (2013).
[110] Jangid, R. & Kelly, J. Base isolation for near-fault motions. *Earthq. Eng. Struct. Dyn.* **30**, 691-707 (2001).
[111] Bao, Y., Becker, T. C. & Hamaguchi, H. Failure of double friction pendulum bearings under pulse-type motions. *Earthq. Eng. Struct. Dyn.* **46**, 715-732 (2017).

[112] Lu, L.-Y., Huang, H.-W., Wu, Y. & Wang, S.-J. Theory and experimental verification of a double sliding isolator with variable curvature. *Eng. Struct.* **238**, 112265 (2021).
[113] Calvi, P. M. & Ruggiero, D. M. Numerical modelling of variable friction sliding base isolators. *Bull. Earthq. Eng.* **14**, 549-568 (2016).
[114] Becker, T. C. & Mahin, S. A. Experimental and analytical study of the bi-directional behavior of the triple friction pendulum isolator. *Earthq. Eng. Struct. Dyn.* **41**, 355-373 (2012).
[115] Fenz, D. M. & Constantinou, M. C. Spherical sliding isolation bearings with adaptive behavior: Experimental verification. *Earthq. Eng. Struct. Dyn.* **37**, 185-205 (2008).
[116] Fenz, D. M. & Constantinou, M. C. Behaviour of the double concave friction pendulum bearing. *Earthq. Eng. Struct. Dyn.* **35**, 1403-1424 (2006).
[117] Panchal, V. & Jangid, R. Seismic response of structures with variable friction pendulum system. *J. Earthq. Eng.* **13**, 193-216 (2009).
[118] Calvi, P. M., Moratti, M. & Calvi, G. M. Seismic isolation devices based on sliding between surfaces with variable friction coefficient. *Earthq. Spectra* **32**, 2291-2315 (2016).
[119] Murnal, P. & Sinha, R. Earthquake resistant design of structures using the variable frequency pendulum isolator. *J. Struct. Eng.* **128**, 870-880 (2002).
[120] Calvi, G. M. L 'Aquila earthquake 2009: reconstruction between temporary and definitive. *NZSEE Conference* (2010).
[121] Almajhali, K. Y. M., He, M. & Alhaddad, W. Enhancing seismic performance of structures: A comprehensive review of hybrid passive energy dissipation devices. *Structures* **69**, 107223 (2024).
[122] Maghareh, A., Dyke, S., Rabieniaharatbar, S. & Prakash, A. Predictive stability indicator: a novel approach to configuring a real-time hybrid simulation. *Earthq. Eng. Struct. Dyn.* **46**, 95-116 (2017).
[123] Xu, G. *et al.* Seismic resilience enhancement for building structures: a comprehensive review and outlook. *Structures* **59**, 105738 (2024).
[124] Dai Nguyen, X. & Guizani, L. Analytical and numerical investigation of natural rubber bearings incorporating U-shaped dampers behaviour for seismic isolation. *Eng. Struct.* **243**, 112647 (2021).
[125] Martinelli, P. & Filippou, F. C. Simulation of the shaking table test of a seven-story shear wall building. *Earthq. Eng. Struct. Dyn.* **38**, 587-607 (2009).
[126] McCrum, D. & Williams, M. An overview of seismic hybrid testing of engineering structures. *Eng. Struct.* **118**, 240-261 (2016).
[127] Salahaldin, A. I., Jomaa'h, M. M., Oukaili, N. A. & Ghaidan, D. J. Rehabilitation of hybrid RC-I beams with openings using CFRP sheets. *Civ. Eng. J.* **8**, 155-166 (2022).
[128] Yang, H., Li, Z., Wang, H., Zhang, M. & Ni, S. Shaking table test study on seismic performance of RC frame structure with NES. *Structures* **47**, 153-164 (2023).
[129] Sunca, F. *et al.* Shake table tests on story-to-story pounding between adjacent RC buildings. *Structures* **69**, 107544 (2024).
[130] Bournas, D. A. Concurrent seismic and energy retrofitting of RC and masonry building envelopes using inorganic textile-based composites combined with insulation materials: A new concept. *Compos. Part B Eng.* **148**, 166-179 (2018).
[131] Del Vecchio, C., Di Ludovico, M., Prota, A. & Manfredi, G. Modelling beam-column joints and FRP strengthening in the seismic performance assessment of RC existing frames. *Compos. Struct.* **142**, 107-116 (2016).
[132] Pohoryles, D. *et al.* Integrated seismic and energy retrofitting of existing buildings: A state-of-the-art review. *J. Build. Eng.* **61**, 105274 (2022).
[133] Güneyisi, E. M. Seismic reliability of steel moment resisting framed buildings retrofitted with buckling restrained braces. *Earthq. Eng. Struct. Dyn.* **41**, 853-874 (2012).
[134] ISO-14040. *Environmental management, Life cycle assessment, Principles and framework*. (2006).