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Review of Modern Methods for Seismic Retrofitting of Reinforced Concrete Structures

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Abstract

The present research aims to evaluate the urban renewal and rehabilitation plan for the Sirous neighborhood located in the dilapidated fabric of Tehran's District 12. It attempts to assess this neighborhood using the phenomenon of gentrification of natives. This research is applied and practical in nature based on its objectives, and it employs a descriptive-analytical evaluation method. Information was gathered using library-documentary methods and surveys. Given the dilapidation of the Sirous fabric and the proposed reconstruction and regeneration plans, and considering that it is one of the old and central neighborhoods in Tehran, there is a necessity to evaluate the maps and indicators of gentrification in the Sirous neighborhood, which indicates a high emergence of this phenomenon. The goal is to determine how this phenomenon will grow in the near future, especially considering the activities and operations that the neighborhood will face after its reconstruction in subsequent years. The phenomenon of gentrification was first introduced in the 1980s and is still being explored, requiring more research on this subject, particularly in countries like Iran with many valuable historical fabrics and dilapidated areas to test gentrification and its counter-phases. This research, by outlining primary, secondary, and guiding indicators in the Sirous neighborhood, evaluates three items: accessibility to work centers, high architectural value, and low housing value, which received the highest affirmative responses from interviewees. A high level of gentrification and gentrification of natives is expected in this neighborhood.

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Introduction

Iran is located on the seismically active Alpine-Himalayan belt, and consequently, it has always been exposed to earthquake-related hazards. The experience from devastating past earthquakes such as Bam, Rudbar, Manjil, Kermanshah, and others has shown that a significant portion of financial damages and human casualties is due to weaknesses in structural systems and non-compliance with engineering principles for seismic-resistant design and construction of buildings. Therefore, strengthening structures, especially concrete structures—which constitute the majority of constructions in the country—has been recognized as one of the most important priorities in civil engineering (Zarei, 2023). Concrete structures, due to advantages such as availability of materials, reasonable cost, and ductility, have been widely used in construction projects. However, if improperly designed or executed, they suffer serious damages under seismic forces. On the other hand, many existing concrete structures in the country have been designed according to outdated codes without considering seismic requirements, and thus are in need of reinforcement and rehabilitation. In this regard, the use of modern strengthening methods can play a decisive role in reducing the seismic vulnerability of these structures (Arabi & Nobahari, 2022).

In recent decades, with significant advances in earthquake engineering, construction materials, and execution techniques, new and efficient methods for seismic strengthening of concrete structures have been developed (Bahadri, 2021). These methods, relying on advanced engineering principles and using high-performance innovative materials, can remarkably improve the load capacity, ductility, and durability of concrete structures against dynamic seismic forces. Compared to traditional methods, modern strengthening techniques usually offer benefits including ease and speed of implementation, reduction in disruption to the structure’s use, lower weight of the strengthened structure, and extension of the structure’s service life (Pirhayati & Alfti, 2021). Therefore, adopting these methods not only enhances structural safety but also provides more attractive economic and practical options for engineers and contractors (Nouri, 2020). The urban expansion and growing population in earthquake-prone regions further emphasize the necessity of seismic strengthening of concrete structures.

In recent years, scientific and technological advancements have introduced new techniques and materials for strengthening structures, including the use of fiber-reinforced polymer (FRP) composites, energy dissipation systems (dampers), post-tensioning methods, local connection reinforcement, concrete and steel jacketing, and utilization of ultra-high-performance concrete. These approaches aim to increase load-bearing capacity, ductility, energy absorption, and displacement control caused by earthquakes. This article attempts to analytically and descriptively introduce and review the most important modern seismic strengthening methods for concrete structures. The research methodology involves a literature review and examination of credible domestic and international scientific sources. Alongside reviewing basic concepts, the advantages and disadvantages of each strengthening method are evaluated, and finally, solutions for optimizing the application of these techniques in national construction projects are proposed. It is hoped that the findings of this study will effectively contribute to enhancing structural safety, reducing earthquake damages, and promoting sustainable development in the country’s construction sector.

2. Importance and Necessity of the Research

The importance and necessity of seismic strengthening of concrete structures arise from multiple factors that can be examined from human, economic, social, and cultural perspectives. A detailed review of these dimensions highlights the urgent need for extensive research in this field. A deep understanding of this necessity has been the main motivation for conducting this comprehensive review.

2.1 Human Aspect: Preservation of Life and Vulnerability Reduction

The most important and undeniable reason for seismic strengthening of concrete structures is the preservation of human lives and reducing societies' vulnerability to earthquakes (Mohammadi & colleagues, 2020). Severe earthquakes, especially in densely populated urban areas, can lead to building collapses and the entrapment of inhabitants under rubble. Past earthquakes worldwide have demonstrated that insufficient structural resistance to seismic forces can cause massive human tragedies, resulting in thousands of deaths (Tavahidi Nia et al., 2017). Strengthening structures, aimed at improving building safety levels and reducing the likelihood of collapse, plays a direct and crucial role in saving human lives. In other words, structural strengthening is an investment in life and can prevent devastating human catastrophes caused by prevent earthquakes (Hejaziān and Lazegi Nazarghah, 2016). Statistics and figures related to casualties from major earthquakes in recent decades clearly indicate this harsh reality that ignoring structural strengthening can lead to irreparable consequences.

In addition to loss of lives, earthquakes can cause severe injuries and permanent disabilities among survivors (Pourabdollah Ghadam and Jalali, 2015). Injuries resulting from debris, falling objects, and damage to non-structural components of buildings can severely affect individuals' lives and impose heavy medical and rehabilitation costs on society. Strengthening structures, by reducing the extent of damage and improving structural and non-structural performance of buildings against earthquakes, can significantly decrease the number of injuries and earthquake-related harms, thereby enhancing public health and welfare (Doa’i and Shariatmadar, 2008). Seismically retrofitted hospitals and medical centers can continue to provide medical services to the injured during earthquakes and play a vital role in alleviating suffering and saving lives.

2-2 Economic Aspect: Reducing Financial Losses and Protecting National Assets

Earthquakes, aside from human losses, impose enormous economic damages on societies (Hadianfard and Alishir, 2007). Destruction of buildings, industrial units, vital infrastructure (such as transportation networks, water, electricity, and gas), and commercial centers leads to loss of national capital, halting economic activities, and causing widespread financial problems for individuals and governments.

Reconstruction of earthquake-affected areas requires very high costs and long time durations, which can severely slow down economic development (Yaghoubpour, 2024). Strengthening concrete structures, by reducing the vulnerability of buildings and infrastructure against earthquakes, can prevent widespread destruction and consequently minimize earthquake-induced economic damages. This is especially important for critical and essential buildings such as hospitals, fire stations, power plants, and bridges, which have a fundamental role in societal functioning and the national economy (Zarei, 2023). In other words, investing in structural strengthening is a preventive and economical measure that can, in the long run, prevent massive financial resource wastage caused by earthquakes. Economic calculations show that the cost of strengthening structures is negligible compared to the reconstruction expenses after earthquakes and damages caused by business closures and lost economic opportunities.

2-3 Social Aspect: Enhancing Community Resilience and Sustainability

Resilient communities are those capable of effectively coping with crises and natural disasters, including earthquakes, and can quickly return to normal conditions after events (Arabi & Nobahari, 2022). Structural strengthening, as a key component of urban resilience, plays an essential role in increasing community capacity to confront earthquakes. Earthquake-resistant buildings act as safe shelters for citizens during earthquake events and can prevent chaos and social unrest afterwards (Bahadri, 2021).

Moreover, reinforcing vital infrastructure enables the provision of essential services to affected people, such as rescue, medical care, temporary housing, and supplying basic needs after an earthquake, thereby accelerating recovery and rehabilitation of affected areas. Thus, strengthening concrete structures not only helps preserve life and property but also contributes to enhancing social resilience and community sustainability (Pirhayati & Alfti, 2021). The presence of strong buildings and sustainable infrastructure improves the public’s sense of security and confidence and supports social cohesion as well as a faster return to normal life following earthquakes.

2-4 Cultural and Historical Aspect: Preserving Cultural Heritage and National Identity

Many concrete structures, especially within historical and cultural urban fabrics, have high spiritual and cultural values and are considered part of a community’s cultural heritage and national identity (Nouri, 2020). Destruction of these structures due to earthquakes not only causes material damage but inflicts irreversible harm on the cultural and historical identity of societies and can erase the memories and cultural values of a generation.

Strengthening such structures, through specialized methods sensitive to historical and cultural values, helps preserve this priceless heritage for future generations and prevents the destruction of cultural and historical identity (Fathi, Farhang & Lāma’i, 2015). This requires high technical knowledge, precision in execution, and use of materials and methods compatible with the historic fabric. Attention to cultural and historical aspects in strengthening reflects a deep understanding of intangible values of human civilization and a commitment to safeguarding them against natural disasters.

2-5 Environmental Aspect: Sustainable Development and Reduction of Adverse Effects

Strengthening existing structures, compared to their demolition and complete reconstruction, is considered a more sustainable and environmentally compatible approach (Koupayizadeh, Dashti & Bazafkan, 2013). Demolition and reconstruction of buildings produce large amounts of construction waste, consume considerable energy, and emit greenhouse gases, which lead to significant negative environmental impacts.

Structural strengthening, by using modern and low-input methods, can help reduce the consumption of natural resources, minimize construction waste production, and decrease pollutant emissions, thereby contributing to sustainable development goals (Ghayamati, 2015). Additionally, selecting strengthening materials with an environmental focus, such as recycled materials and those with long lifespans, can further reduce the negative environmental impacts of the construction industry. In today's world, where attention to environmental issues and carbon footprint reduction is of special importance, adopting sustainable strengthening approaches is a responsible and forward-looking choice.

2-6 Compliance with National and International Laws and Regulations

In many countries, stringent laws and regulations exist concerning building safety against earthquakes. These regulations require owners and builders to comply with seismic strengthening standards and undertake necessary actions to improve the seismic safety of structures. Strengthening existing structures to comply with these laws and regulations and to avoid legal liabilities resulting from non-compliance is essential and unavoidable (Nastari, Dapis & Tudisco, 2025). Moreover, insurance for buildings located in seismic zones often requires seismic retrofitting as a condition for coverage. Compliance with these rules is not only a legal matter but also reflects attention to safety and responsibility toward citizens and society.

Given the broad dimensions of the importance and necessity of strengthening concrete structures against earthquakes, conducting scientific and applied research in this field has special significance (Lifshitz Scherzer et al., 2024). Such research can contribute to developing more efficient, economical, sustainable, and locally adapted strengthening methods, formulating more precise and up-to-date standards, raising public awareness about seismic retrofitting importance, and ultimately making communities safer and more resilient against earthquake hazards (Wu, 2024). Scientific studies play a fundamental role in advancing knowledge and technology in seismic strengthening and can provide solutions to current challenges and introduce innovative approaches.

3. Theoretical Foundations of the Research

Seismic strengthening of concrete structures is a multifaceted and complex area of structural engineering, requiring a deep understanding of structural behavior under dynamic loads, material properties, and modern execution techniques. The theoretical foundations of modern strengthening methods are based on earthquake engineering principles, material mechanics, and new construction technologies. This section describes the theoretical basics of some of the most important and widely used modern strengthening methods for concrete structures. Understanding these theoretical foundations is essential and unavoidable for the correct selection and proper design of strengthening methods.

3-1 Strengthening Using Fiber-Reinforced Polymers (FRP)

Fiber-Reinforced Polymers (FRP) are a family of advanced composite materials made by combining reinforcing fibers with a polymer matrix. The reinforcing fibers, typically carbon, glass, or aramid, play the primary role in bearing loads and increasing the composite’s strength and stiffness (Joshi & Patil, 2022). The polymer matrix, usually made of epoxy or polyester resin, transfers forces between fibers, protects the fibers from environmental damage, and provides integrity to the composite. Due to their unique mechanical properties—such as high strength-to-weight ratio, corrosion resistance, and ease of shaping—FRPs are recognized as a novel and highly effective method for seismic strengthening of concrete structures (Almujali & Alhaddad, 2024). The variety of fiber types and polymer resins allows producing FRP materials with diverse properties tailored to the specific needs of different projects.

FRP Mechanism in Concrete Strengthening: The performance of FRP systems in strengthening concrete structures is based on the principle of bracing and increasing tensile and shear resistance of the concrete member. Concrete, as a brittle material, has very good compressive strength but relatively low tensile and shear strength. Under seismic loads, concrete members experience significant tensile and shear stresses that can cause cracking and failure. FRP systems, by forming an external brace layer on the concrete surface, prevent crack propagation and significantly enhance the tensile and shear strength of the member (Ma & Fang, 2021). In other words, FRPs act as a protective “skin” over the concrete, shielding the concrete core against destructive seismic forces. This bracing function is similar to steel confinement bands used around concrete columns to increase confinement strength, but FRPs are much lighter and faster and easier to install.

Application Methods of FRP in Strengthening:

FRPs can be used in various ways to strengthen concrete structures. The two main and most common methods are:

Externally Bonded Reinforcement (EBR) Systems:

In this method, FRP strips or sheets are adhered to the external surface of the concrete member using special epoxy adhesives (Singh & Srivastava, 2022). The EBR method is very popular due to its ease and speed of execution, relatively low cost, and no need for extensive demolition of the existing structure. EBR systems can be used to increase flexural strength (by installing FRP longitudinally on the member), shear strength (by installing FRP vertically or diagonally on the member), and confinement strength (by wrapping FRP around columns). This method is especially suitable for strengthening existing residential, commercial, and office buildings, as well as bridges and other concrete infrastructures that require fast and economical strengthening.

Near Surface Mounted (NSM) Systems:

In this method, FRP bars or strips are placed into grooves pre-cut in the surface of the concrete member and then filled with special cement-based or epoxy resin mortars (Nastari, Dapis & Tudisco, 2025). Compared to the EBR method, NSM provides higher load capacity and better bonding between FRP and concrete. NSM systems are more suitable for strengthening members that require significant increases in strength and stiffness or are exposed to harsh environmental conditions (such as marine structures). Also, because the FRP fibers are protected by the mortar cover, NSM systems show greater resistance to fire and mechanical damage.

Figure 1. Strengthening of Columns and Beams with FRP

(Source: Pourabdollah Ghadam, 2024)

Types of FRP Fibers and Their Properties: The type of fibers used in producing FRP has a direct effect on its mechanical properties and performance in strengthening. The most common types of FRP fibers are:

Carbon Fibers (CFRP - Carbon Fiber Reinforced Polymer):
Carbon fibers, due to their very high tensile strength, high modulus of elasticity, and light weight, provide the best mechanical performance among FRP fibers (Lifshitz Scherzer et al., 2024). CFRPs are the most expensive type of FRP fibers, but because of their superior performance, they are widely used in seismic strengthening projects for important concrete structures. Applications of CFRP include strengthening of high-rise buildings, long-span bridges, and structures that require a high strength-to-weight ratio.

Glass Fibers (GFRP - Glass Fiber Reinforced Polymer):
Glass fibers are less expensive than carbon fibers and have relatively good tensile strength and modulus of elasticity (Wu, 2024). GFRPs, due to their affordable price, corrosion resistance, and electrical insulation properties, are widely used in general strengthening of concrete structures and marine structures. Applications of GFRP include strengthening of ordinary residential, commercial, and industrial buildings, as well as concrete structures in corrosive environments.

Aramid Fibers (AFRP - Aramid Fiber Reinforced Polymer):
Aramid fibers have high impact resistance, good fatigue resistance, and suitable ductility (Joshi & Patil, 2022). AFRPs are used less frequently than carbon and glass fibers, but in specific applications where high impact and fatigue resistance are required—such as strengthening military and industrial structures against explosive loads—they can be an appropriate option. Additionally, AFRPs have good abrasion resistance, making them useful for strengthening structures exposed to wear and impact.

3-2 Concrete Jacketing Strengthening

Concrete jacketing is a traditional yet highly effective strengthening method in which a new concrete layer is cast around the existing concrete member to increase the cross-sectional dimensions and consequently, the load-bearing capacity and stiffness (Almujali & Alhaddad, 2024). Concrete jacketing can be used to strengthen columns, beams, walls, and concrete slabs, and is effective in increasing compressive, flexural, and shear strength of the members. This method is especially suitable for strengthening structures that require a significant increase in strength and stiffness, or that have suffered severe damage. Besides increasing strength, concrete jacketing can also improve the durability of the structure and protect the existing concrete from environmental effects.

Mechanism of Concrete Jacketing in Strengthening:
The strengthening mechanism of concrete jacketing is based on increasing the cross-sectional area of the concrete member, thereby increasing its load-bearing capacity. With a larger cross section,

the compressive, flexural, and shear strengths of the member increase, and its stiffness improves as well (Ma & Fang, 2021). To ensure a proper bond between new and old concrete, the old concrete surface should be roughened thoroughly and cleaned from contaminants. Furthermore, the use of steel reinforcement bars, called "connection rebar," which link the new and old concretes together, is necessary to transfer forces effectively between the two concrete layers (Singh & Srivastava, 2022). In cases where increased confinement of the concrete core is needed, stirrups (hoops) can be used inside the concrete jacket. It should be noted that due to the increase in cross-sectional dimensions, concrete jacketing also increases the structural weight, which must be considered in the strengthening design.

Figure 2. Strengthening with Concrete Jacketing
(Source: Pourabdollah Ghadam, 2024)

Types of Concrete Jacketing Based on Materials and Execution Methods:
Concrete jacketing can be classified into various types depending on the kind of materials used and the method of execution:
Conventional Reinforced Concrete Jacket:
In this type of jacket, conventional concrete with a specified strength and common steel reinforcement bars are used (Nastari, Dapis & Tudisco, 2025). Due to its ease of execution and relatively low cost, the conventional reinforced concrete jacket is the most widely used type and is suitable for most strengthening projects. This type of jacket is commonly applied for strengthening low to medium-rise residential, commercial, and industrial buildings, as well as bridges and other ordinary concrete structures.

High-Strength Concrete Jacket:
This jacket type uses concrete with compressive strength higher than that of the main member (Lifshitz Scherzer et al., 2024). High-strength concrete jacketing is appropriate for strengthening structures that require a significant increase in strength or where there is limited space for increasing the cross-sectional dimensions. It is typically utilized in strengthening high-rise buildings, heavily loaded columns, and structures where minimal increase in cross-sectional size is desired.

Self-Consolidating Concrete Jacket:

Self-consolidating concrete (SCC) is a highly flowable concrete that can fill the formwork easily and completely without the need for vibration (Wu, 2024). The use of SCC in concrete jacketing is particularly advantageous in cases where access to the execution site is limited or when...

Concrete Jacketing (continued):

Self-Consolidating Concrete Jacket:

Self-consolidating concrete (SCC) is a type of highly flowable concrete that can easily flow into formwork and fill voids without the need for vibration (Wu, 2024). Using SCC for concrete jacketing is especially beneficial in situations where site access is limited and/or the need exists to obtain a smooth and uniform surface finish. This type of jacket is suitable for strengthening members with complex shapes, heavily reinforced sections, and structures demanding high-quality concrete surfaces.

Precast Concrete Jacket:

In this method, concrete jacketing elements are manufactured in a controlled factory environment and then transported to the project site, where they are installed around the existing concrete member (Joshi & Patil, 2022). Precast concrete jacketing significantly speeds up execution and improves the quality of the jacket. This method is appropriate for large and sensitive projects requiring rapid construction and high precision. Additionally, precast jacketing can be used for strengthening structures that must minimize operational disruptions, such as heavily trafficked bridges and occupied buildings.

3-3 Strengthening with Steel Bracing

Steel braces are structural members used to increase the lateral stiffness of structures and control their lateral displacement under seismic lateral loads (Almujali & Alhaddad, 2024). Using steel bracing, especially in concrete buildings that suffer from poor lateral stiffness and ductility, is a very effective and economical seismic strengthening method. Steel braces create parallel lateral load paths alongside the main frame and absorb earthquake forces, transferring them safely to the foundation, thereby preventing damage to the concrete frame. This method is particularly efficient for strengthening medium- and high-rise concrete buildings, as well as buildings with irregular floor plans or large openings.

Mechanism of Steel Bracing in Strengthening: Steel braces enhance structural performance primarily by increasing lateral stiffness and energy dissipation capacity of the structure. Due to the high stiffness and strength of steel, braces significantly increase lateral stiffness and reduce the natural vibration period of the structure (Ma & Fang, 2021). A shorter vibration period reduces seismic response and the imposed forces on the structure.

Besides stiffness increases, steel brace systems—especially Buckling Restrained Braces (BRB)—have high energy dissipation capacity by undergoing plastic deformations during earthquakes and dissipating seismic energy, thus improving structural damping (Singh & Srivastava, 2022). Increased damping results in reduced vibration amplitudes and lowered earthquake damage. Due to their light weight, rapid installation, and the possibility of external application, steel bracing systems are suitable options for seismic strengthening of existing concrete buildings.

Types of Steel Bracing Systems: Concentrically Braced Frames (CBF):
In a concentrically braced system, brace members connect to beams and columns at a single point (node) (Nastari, Dapis & Tudisco, 2025). Diagonal braces and cross braces are the most common types. CBFs are widely used due to simple design and construction, high efficiency, and relatively low cost. They are particularly suitable for short- and medium-height buildings. Diagonal braces provide more architectural openness with larger openings but less stiffness compared to cross braces, which offer higher stiffness and stability.

Eccentrically Braced Frames (EBF): In eccentrically braced systems, braces connect to beams at different points, leaving a “link beam” between them (Lifshitz Scherzer et al., 2024). The link beam serves as an energy dissipator during earthquakes, undergoing plastic deformations that dissipate seismic energy through hysteresis. Compared with CBFs, EBFs provide higher ductility and are better suited for medium- and high-rise buildings. Their superior ductility makes EBFs preferable for structures exposed to severe seismic events.

Buckling Restrained Braces (BRB): BRBs are an advanced type of steel brace designed to prevent buckling under high compressive forces (Wu, 2024). They consist of a steel core encased in a protective casing that prevents buckling, allowing the brace to effectively dissipate energy in both tension and compression. BRBs provide significantly higher energy dissipation capacity than conventional braces and dramatically improve seismic performance. They are ideal for tall buildings and critical structures requiring high ductility and damping. Although BRBs are more expensive than conventional braces, their superior seismic performance justifies the cost

Figure 3: Strengthening with Steel Bracing (Source: Pourabdollah Ghadam, 2024)

3-4 Seismic Isolation Strengthening

Seismic isolation is an advanced, performance-based method for strengthening structures against earthquakes, based on the principle of reducing the transmission of seismic forces to the structure (Joshi & Patil, 2022). In seismic isolation systems, the structure is separated from its foundation

and placed on a series of seismic isolation bearings. These bearings, typically made of elastomeric materials (natural or synthetic rubber) and steel, possess very high lateral flexibility and are able to concentrate lateral displacements caused by the earthquake at the isolation level, thereby preventing the transfer of destructive forces to the superstructure.
In other words, the seismic isolation system “traps” the earthquake forces and does not allow them to damage the building. This method is especially suitable for strengthening highly sensitive and important structures such as hospitals, data centers, museums, and governmental and military buildings that require very high seismic performance.

Figure 4. Strengthening with Steel Bracing
(Source: Pourabdollah Ghadam, 2024)

Mechanism of Seismic Isolation in Strengthening:
The seismic isolation mechanism is based on increasing the fundamental period of the structure and enhancing the effective damping of the system. By placing the structure on seismic isolation bearings, the natural vibration period of the structure significantly increases (typically about 2 to 3 times its original value) (Almujali & Alhaddad, 2024). This increase in period moves the structure's natural frequency away from the dominant frequency range of the earthquake spectrum, thereby drastically reducing the seismic response and forces imposed on the structure. Besides increasing the vibration period, seismic isolation bearings—especially elastomeric bearings—have substantial inherent damping that adds to the total system damping and reduces the amplitude of structural vibrations. Thus, seismic isolation significantly improves seismic performance both by reducing earthquake forces on the structure and by increasing damping (Ma & Fang, 2021). As a high-level strengthening method, seismic isolation can effectively protect both the structure and its contents against severe earthquakes.

Types of Seismic Isolation Systems:
Seismic isolation systems are classified based on the type of isolation bearings used:

Elastomeric Isolation Systems:
These systems use laminated rubber bearings (LRB), which consist of alternating layers of rubber and steel (Singh & Srivastava, 2022). LRBs offer both high lateral flexibility and high vertical stiffness, efficiently carrying the vertical loads of the structure. Due to their reliable performance, relatively low cost, and easy implementation, elastomeric isolation systems are the

most commonly used seismic isolation systems. LRBs are also highly resistant to environmental degradation and have a long service life, making them suitable for varying climatic conditions.

Friction Pendulum Systems (FPS):

FPS systems utilize bearings based on friction between sliding surfaces and pendulum motion (Nastari, Dapis & Tudisco, 2025). FPS bearings provide high damping capacity by dissipating seismic energy through friction. These systems are particularly suitable for structures that require high damping and precise control of lateral displacements. Due to their frequency-independent behavior, FPS are good choices for structures exposed to a wide range of earthquake frequencies.

Hybrid Isolation Systems:

Some seismic isolation systems combine elastomeric and friction pendulum bearings to leverage advantages of both types (Lifshitz Scherzer et al., 2024). Hybrid systems offer better seismic performance compared to single-type systems and are ideal for highly sensitive and important structures requiring maximum safety. By adjusting parameters of different types of bearings, hybrid systems can optimize structural performance for a wide range of earthquake motions.

4. Strengthening with Energy Dissipation Systems

Energy dissipation systems comprise a group of devices used to increase structural damping and reduce earthquake response (Wu, 2024). Dampers convert the seismic kinetic energy into other forms of energy, such as heat or plastic deformation energy, thereby reducing structural vibrations and internal forces. Using energy dissipation devices is especially effective in tall buildings or structures with low inherent damping. Dampers can be installed in various locations within the structure—such as between columns and beams, inside bays, or as diagonal braces. Energy dissipation systems, as active strengthening measures, can effectively control seismic response and reduce earthquake-induced damage.

4-1 Mechanism of Energy Dissipators in Strengthening

The functioning mechanism of energy dissipators is based on increasing the damping of the structural system. Damping reduces vibration amplitudes and dissipates earthquake energy (Joshi & Patil, 2022). Ordinary concrete structures typically have relatively low inherent damping (usually around 5% critical damping). Using energy dissipators can significantly increase effective system damping (often to 20% or more). This increase in damping results in reduced seismic response, decreased displacements, forces, and accelerations within the structure, consequently reducing earthquake damage (Almujali & Alhaddad, 2024). In other words, energy dissipators "absorb" and "consume" earthquake energy to prevent damage to the structure. They serve as complementary methods to other strengthening measures and can substantially improve seismic performance.

4-2 Types of Energy Dissipators

Energy dissipators are categorized based on their working mechanisms and materials:

Viscous Dampers: Viscous dampers operate based on the flow of viscous fluid (usually silicone oil) through an orifice or nozzle (Ma & Fang, 2021). The damper force is proportional to the relative velocity at its ends.

Viscous dampers, due to their linear behavior, frequency independence, and high reliability, are the most commonly used type of energy dissipators. They are especially effective in reducing lateral displacements and floor accelerations in tall buildings.

Steel Hysteretic Dampers:

Steel hysteretic dampers work based on the plastic deformation of steel under loading and unloading cycles (Singh & Srivastava, 2022). Earthquake energy is dissipated through hysteresis loops in the steel during each load cycle. These dampers are highly effective due to their speed-independent behavior, high stability, and the ability to be designed for various energy capacities. They are particularly useful to reduce internal forces on structural members and prevent damage.

Friction Dampers: Friction dampers dissipate kinetic energy by friction between solid surfaces during relative movement (Nastari, Dapis & Tudisco, 2025). The damping force is approximately constant and independent of velocity and displacement. Due to their simple construction, low cost, and adjustable friction force, friction dampers are an economical and efficient option for strengthening concrete structures. They are especially effective in limiting lateral displacements and preventing damage to non-structural components.

Tuned Mass Dampers (TMD): TMDs consist of an additional mass (damper mass) attached to the main structure along with a spring system and a viscous damper (Lifshitz Scherzer et al., 2024). The damper mass is tuned so that its natural vibration frequency equals the main structure's fundamental frequency. During an earthquake, the damper mass vibrates and absorbs and dissipates the structural vibrational energy. TMDs are particularly effective in reducing specific vibration modes and improving occupant comfort in tall buildings. They are specifically designed to mitigate oscillations caused by wind and mild to moderate earthquakes.

5. Execution Guidelines and Considerations

Successful implementation of advanced strengthening methods requires strict adherence to specific guidelines and execution considerations for each technique. Below are the most important practical points which play a key role in achieving the expected performance of the strengthening system:

Execution of FRP Systems: (Nouri, 1399)

Surface Preparation: Concrete surface must be completely clean, dry, and free from any contaminants or dust. The surface should be mechanically roughened (e.g., sandblasting or wire brushing) to improve adhesion of FRP to concrete. Adhesion tests on sample specimens must be carried out prior to final application.

Epoxy Adhesive Preparation: Epoxy should be prepared according to the manufacturer’s instructions with accurate mixing ratios. Ambient temperature and concrete surface temperature must be within the recommended range. Use high-quality epoxy adhesives with valid certifications.

FRP Application: FRP layers should be carefully applied with uniform pressure to avoid air voids. The fiber orientation must comply with design drawings. Specialized rollers are recommended to apply uniform pressure on the FRP.

Curing: After application, curing must be done for the specified time (per manufacturer's instructions) to allow full hardening of the epoxy. During curing, avoid applying loads or impacts to the FRP system.

Protection: The installed FRP system must be protected against mechanical damage, impacts, and UV radiation. Applying UV protective coatings prolongs system life. In corrosive environments, use corrosion-resistant FRP systems.

Execution of Concrete Jacketing: (Fathi, Farhang & Lamei, 1394)

Old Concrete Surface Preparation: Roughen the old concrete surface and remove all loose coatings, paint, and contaminants. Use bonding agents to improve bonding between new and old concrete.

Installation of Connection Reinforcements: Connection rebars must be embedded in the old concrete per design drawings and connected to jacket reinforcement. Use high-quality bonding adhesives for rebar anchorage.

Formwork: Formwork must be precise, sturdy, and watertight. For complex jacket shapes, use metal or prefabricated formwork.

Concrete Pouring: Use concrete of suitable quality with controlled slump and place in layers. For normal concrete, appropriate vibration is necessary to remove air voids and ensure compaction. Self-consolidating concrete requires no vibration. Concrete quality drastically affects strengthening performance and must meet project specifications.

Curing: Proper curing for at least 7 days is essential to achieve desired strength and prevent cracking. Special care is needed in hot and dry climates.

Execution of Steel Bracing Systems: (Koupai Zadeh, Dashti & Bazafkan, 1392)

Detailed Execution Drawings: Must include complete connection details, dimensions, and material specifications prepared by qualified structural engineers using design software.

Fabrication: Steel bracing components should be fabricated in factories under strict quality controls. Welding must be performed by certified welders per standards, with strict quality inspection.

Installation: Careful installation per drawings, with secure tightening and alignment. Use cranes and appropriate equipment as needed.

Corrosion Protection: Steel surfaces should be protected by coating or galvanization depending on site conditions. Periodic inspection and maintenance of protective coatings are necessary.

Execution of Seismic Isolation Systems: (Qiamati, 1394)

System Design: Must be developed by experienced engineers using advanced dynamic analysis software. Selection of bearing type, number, and location should consider structural and site conditions, seismic spectra.

Isolation Bearings Procurement: Bearings are to be sourced from reputable manufacturers with quality certificates and tests verified. Quality of bearings directly affects system performance.

Foundation Preparation: Bearing foundations must be flat, level, and sufficiently strong per executed drawing details. Proper foundation construction is critical.

Bearing Installation: Carried out by trained personnel with appropriate equipment, following manufacturer’s guidelines and supervision by expert engineers. Ensure correct placement and secure connections.

Periodic Inspection and Maintenance: After installation, regular inspections must be conducted, maintenance planned and executed by specialists. Replacement of bearings when needed should follow manufacturer instructions.

Execution of Energy Dissipation Systems: (Nastari, Dapis & Tudisco, 2025)

Damper Selection: Type and quantity must be chosen based on detailed dynamic analyses considering structural properties and seismic response spectrum. Optimal damper placement enhances strengthening effectiveness.

Procurement: Use high-quality dampers from trusted suppliers with certification and approved testing. Damper quality significantly impacts system performance.

Installation: Follow execution drawings and manufacturer instructions carefully. Connections to structure must be tight and damper function verified. Supervision by experienced engineers is essential.

Periodic Inspection and Maintenance: Regular performance checks and maintenance are required. For viscous dampers, fluid replacement; for steel hysteretic dampers, replacement of worn parts must be done per manufacturer guidelines.

Conclusion

This comprehensive review examined modern seismic strengthening methods for concrete structures. It highlighted the importance and necessity of retrofitting in earthquake-prone regions from multiple perspectives including human, economic, social, cultural, environmental, and legal aspects. The theoretical foundations and operational principles of five prevalent advanced strengthening techniques—FRP application, concrete jacketing, steel bracing, seismic isolation, and energy dissipation systems—were thoroughly explained.

Practical project examples applying these methods were presented along with detailed execution guidelines and considerations. The findings clearly show that modern retrofitting approaches are powerful tools to enhance the safety and resilience of concrete buildings against earthquakes.

Selecting an appropriate method involves thorough project-specific evaluation, in-depth engineering analyses, and strict conformity to relevant guidelines and standards. No single method universally fits all situations; designers need to weigh advantages, limitations, and project constraints to select the best individual or combined methods.

Designers must possess sufficient knowledge and experience in advanced strengthening techniques to analyze project conditions accurately and implement optimal solutions. Key takeaways include:

Retrofit choices should be value-engineering driven, balancing cost, performance, speed of execution, durability, environmental factors, and other relevant criteria to maximize benefits relative to cost.

Combining strengthening methods often yields better performance than using one method alone. For example, combining FRP and concrete jacketing can simultaneously improve strength and ductility; integrating buckling restrained braces with viscous dampers enhances stiffness, damping, and ductility.

Environmental sustainability principles should guide the selection of strengthening methods, emphasizing eco-friendly materials, energy-efficient processes, and waste reduction.

Continuous training of engineers and workers through specialized courses, workshops, and dissemination of execution standards is crucial to improve technical knowledge, workmanship quality, and reduce errors.

Ongoing research and development are essential to create more efficient, economical, sustainable, and reliable strengthening technologies. Important research fields include developing new FRP materials with better mechanical properties and durability, improving seismic isolation and damping system techniques, and tailoring methods for special structures (e.g., historic or marine buildings). Innovation and R&D will pave the way for better future seismic retrofit solutions.

Ultimately, retrofitting concrete buildings against earthquakes is a social and engineering responsibility requiring comprehensive collaboration among the engineering community, government, owners, and the public.

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