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Seismic Retrofitting of Reinforced Concrete Bridges: Global Methods and Local Applications in Duhok City, Iraq

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Abstract

Bridges built before the introduction of the modern seismic design codes are very prone to damage caused by earthquakes, especially in developing regions that do not have systematic retrofit programs. In Duhok City, Iraq, the rising seismic activity, in addition to the deterioration of reinforced concrete (RC) bridges, poses a high threat to the resilience of transportation and the safety of the population. The current research is focusing on reviewing the world methods of seismic retrofitting of RC bridge structures and on their suitability for the local area of Duhok. To fulfil these goals, a literature study of worldwide seismic retrofitting techniques has been performed, which includes steel jacketing, composite material wrapping (CFRP), reinforced concrete jacketing, foundation retrofitting, base isolation, smart materials, and viscous dampers. The methods were relatively evaluated in terms of performance in the form of cost, feasibility of application, strength improvement, and ductility improvement. Simultaneously, the field research processes were conducted using qualitative research methods, as on-site visits and consultations with local infrastructure officials were conducted to examine current practice in the retrofitting process and retrofit design in Duhok. The findings shown reveal that, although the global techniques that have been verified to strengthen, enhance the ductility, and the seismic performance of materials used in the constituents of RC bridges, there are no systematic seismic retrofit programs presently implemented in Duhok. There are no elaborate performance-based examinations of the seismic factor, but simply a simplified approach to the design practices. Comparative analysis indicates that the steel jacketing and CFRP wrapping offer the best balance between performance and feasibility of normal bridge elements in the area, whereas other advanced systems, including base isolation and shape memory alloys, are more appropriate to critical infrastructure that must be functional immediately after the earthquakes occur. The results show that there is a critical lack of connection between global developments in seismic retrofitting and local application. The creation of a national retrofit system and the incorporation of methodologies focusing on performance-based assessment will be necessary steps toward enhancing seismic resilience in Duhok and other areas.

Keywords

Retrofitting, Bridge, Seismic, Jacketing, CFRP

1. Introduction

Retrofitting, in general, involves integrating new technologies or features into existing systems to enhance their strength and long-term viability. Retrofitting strategies vary depending on the type of structure and the specific challenges it faces. Among these, seismic retrofitting is crucial (Pampanin, 2006), particularly in regions prone to earthquakes. This process focuses on reinforcing older structures to withstand seismic activity and minimize potential damage (Reitherman & Arch, 2012; Thakkar et al., 2001). The extensive damage observed in bridges during recent global earthquakes has spurred significant advancements in earthquake-resistant design and retrofitting techniques for these critical infrastructures (Arya et al., 1992; Dhefto, 2013). Bridges built before 1970 are especially vulnerable, as they were often designed without adequate seismic considerations due to the absence of ductility provisions in seismic codes at the time. Consequently, these older bridges may exhibit insufficient earthquake resistance and ductility, making them susceptible to damage even from moderate seismic events (S.K. Thakkar, 2008). Post-earthquake damage assessments have consistently supported this observation, further revealing that proactive seismic retrofitting could have prevented much of the damage observed in bridges and flyovers (Keady et al., 2000; Rossow, 2010). Engineers designing retrofitting solutions for existing bridge components must therefore prioritize maintaining operational functionality during moderate earthquakes and ensuring life safety in the event of a major earthquake (Furlanetto et al., 2008; Moehle & Eberhard, 2000).

More recent research has added to the knowledge base of confinement behavior and material efficiency in reinforced concrete strengthening work. In an experimental and analytical investigation on the confinement behavior of low-strength concrete under axial compression carried out by Ali et al. (2022a), it is proven that enhanced confinement behavior increases the load-carrying capacity and the deformation properties greatly. Their results demonstrate the need to use confinement efficiency in altering the disease modes and enhancing structural ductility as a strong foundation of seismic strengthening.

Likewise, a study conducted by Ali et al. (2021) to investigate the mechanical response and concrete member performance under strengthened reinforced concrete under complex loading conditions has found the importance of idealized material setups in enhancing performance both in strength and in lifecycles. These tests confirm the suitability of high-performance strengthening materials in the improvement of structural resilience, not compromising on constructability.

Moreover, performance-based investigation and other analytical studies on retrofitted structural components under seismic loading have been undertaken. As Ali et al. (2022b) showed, the retrofit strategies should no longer be evaluated by their strength uptake only but by the strength in relation to their displacement capacity or ductile demand and the alteration of the brittle failure mechanism. Their efforts support the shift in the performance-based seismic assessment systems in bridge rehabilitation.

Besides, the current advancement in composite and cement-based strengthening materials has presented optimized material systems that best help in structural efficiency and sustainability. Ali et al. (2023) emphasized the future of advanced composite materials in improving structural behavior at the cost of less material consumption and minimal environmental impact. These results add to the developing attitude according to which seismic retrofitting must combine not only the considerations of structural performance but also the considerations of material optimization.

These recent contributions indicate a clear shift toward performance-driven and material-efficient retrofit methodologies that integrate experimental validation with advanced analytical modelling to ensure seismic resilience of existing bridge systems.

In spite of these developments, the majority of modern literature is focused on experimental confirmation or computer simulation of certain strengthening methods under controlled conditions. Little research has been conducted on the systematic assessment and contextualization of globally validated retrofit measures in moderate seismic areas that lack full-scale retrofit schemes, including Northern Iraq. Localquently, the comparative evaluation of the applicability of retrofit and references to local building peculiarities, construction tradition, and seismic hazards of the region are still needed.

This review will provide an overview of damage patterns in common reinforced concrete (RC) bridges, which are the common retrofitting methods, and the latest developments in bridge retrofitting technologies. Section 2 describes the seismic retrofitting methodology, with the initial section of this methodology describing the philosophy of design that will guide retrofit strategies, and then the decision-making criteria, performance goals, and the procedures that need to be followed. Section 3 looks at structural shortcomings common in bridge components, which include superstructure, bearings, substructure, and foundations, according to post earthquake assessment worldwide. In section 4, several seismic retrofitting methods, including steel jacketing, composite material wrap, reinforced concrete jacketing, and innovative methods, including base isolation and smart materials, are thoroughly reviewed. Section 5 provides recent advances in retrofitting techniques. Section 6 puts these global approaches into context by exploring the seismic nature of Duhok City and existing practices through field visits to local infrastructure authorities. Section 7 offers a comparative analysis of retrofitting approaches, assessing their performance across various criteria. Lastly, the conclusions and specific suggestions that can be used to enhance bridge seismic resilience in Duhok and other concepts are presented in Section 8.

2. Methodology

2.1 Seismic Retrofitting Design Philosophy and Performance

The general aim of bridge seismic design is to ensure that inelastic action is localized to the readily accessible, inspectable, and repairable zones so that the amount of downtime following a seismic event is minimal (Calvi & Priestley, 1991; Hipley, 1997; Priestley et al., 1996). The capacity-design approach assumes that as the load placed on the non-yielding structural components exceeds the ability of the yielding components to sustain that load, these structural components will eventually deflect. Such columns have characteristics that ensure the prevention of non-ductile failure cases like shear or bond failure and support the anticipated displacement loads (Ballantyne et al., 2002).

In contrast to the construction of buildings, which entails the application of the weak beam/strong column philosophy, bridge design promotes plastic hinges in the columns. The reason is that it is simpler to inspect, retrofit, and repair columns rather than superstructure elements (M. Srbić et al., 2021). This philosophy also informs retrofitting strategies, directing reinforcement to potential plastic hinge regions and ensuring the overall system develops a predictable yield mechanism(Elwood & Eberhard, 2006).

Elements expected to undergo inelastic cyclic deformation are retrofitted for strength and ductility, suppressing brittle failure. All other members and connections are retrofitted to respond elastically to these induced forces (Holombo et al., 2000).

Seismic retrofitting design targets two performance levels namely, minimum performance (comparable to new bridge design) and High performance (ensures vital connectivity immediately after an earthquake).

Zhang and Alam (Zhang & Alam, 2018) define the minimum criteria as withstanding Design Basis Earthquakes (DBE) with only modest, repairable damage and withstanding Maximum Considered Earthquakes (MCE) without collapse, sustaining only limited repairable damage.

They emphasize that seismic load performance cannot be directly inferred from static load design. Yet, most design codes lack specific performance criteria for individual components, necessitating the use of defined damage states. Ghobarah (Ghobarah, 2001) proposed a drift-based classification, summarized in Table 1:

Table 1. Damage States and Drift Limits (Ghobarah, 2001)

Damage State	Drift (%)	Description
No Damage	< 0.2	Elastic behavior
Repairable Damage	< 0.5	Minor cracking, easily repairable
Irreparable Damage	< 1.5	Severe damage, major repairs needed
Near Collapse	< 2.5	Structural integrity endangered
Collapse	> 2.5	Complete failure

For higher performance objectives, such as ensuring operational routes immediately after an earthquake, more advanced retrofitting is required. This includes:

- Mitigating girder support loss
- Preventing substructure collapse
- Addressing liquefaction-induced foundation failures (American Association of State Highway Transportation Officials, 2014; Hwang et al., 2001)

The required performance level should be identified early in the retrofit planning phase. Table 2 links seismic performance levels with corresponding goals and retrofitting implications:

Table 2. Seismic Performance Levels and Retrofitting Implications

Performance Level	Seismic Goal	Retrofitting Implication
Operational	Immediate post-earthquake usability	Advanced techniques (e.g., base isolation, SMA)
Life Safety	Preventing collapse and ensure evacuation	Steel/CFRP jacketing, seismic restrainers
Collapse Prevention	Preventing structural failure	Minimal retrofit; focus on critical elements

2.2 Retrofitting Decision-making

It is required to make two simple decisions at the starting point of undertaking a retrofitting procedure for any bridge, which are:

1. Is it necessary to get a retrofit or not?
2. To what degree should the bridge be retrofitted.

Also, there are several factors that might be qualitative or quantitative that should be considered to prioritize the part of the bridge or the whole bridge structure to be retrofitted against the seismic action (Caterino et al., 2008). These basic factors, Structural Vulnerability (V), Seismic Hazard (H), and Importance Classification (I) are discussed in detail below (I. Buckle et al., 2006)

a. Structural Vulnerability (V): is defined as the function of bridge structural properties, which explains the conditions of the whole bridge (Viera et al., 2000). Visual inspection is used as a means of estimation for this function, where the lowest value of V is 1, and the highest is 10 (Blakelock et al., 1999).

b. Seismic Hazard (H): A probabilistic technique is used to determine a bridge site's seismic danger. The region's geology, geographical location, and seismology, along with previous documentation of past occurrences, are used to determine these seismic threats (Yashinsky & Karshenas., 2003). The acceleration coefficient (A), which shows the Peak Ground Acceleration (PGA) that is anticipated to happen as a result of an earthquake at some point during the next 475 years, reflects seismic danger. Within 50 years, there is a 10% chance that this acceleration will be exceeded. The site coefficient (S) is another element that modifies the PGA. Consequently, the definition of seismic hazard is provided in the following equation (Buckle Ian & Ian, 1995).

$$E = 12.5 \times A \times S \qquad (1)$$

Where A is the acceleration coefficient given in Table 3 from the relative earthquake hazard map (IISEE, 2012), and S is the site coefficient as given in Table 4.

Table 3. Seismic region and design base acceleration

Region	Description	Acceleration Coefficient
1	Very High seismic relative hazard	0.35
2	Intermediate seismic relative hazard	0.25
3	Low seismic relative hazard	0.20

Table 4. Site Coefficient

Soil Profile Type	Site Coefficient
I	1.0
II	1.2
III	1.5
IV	2.0

c. The Importance Classification (I): Which reflects the importance of the road network's bridge. The subjective assessment of a bridge's significance should consider its social, survival, financial, and defence needs (Valenzuela et al., 2010). Three important classifications are specified as:

   i. Strategic: bridges that are officially designated as strategic by a local plan or whose loss would have a significant economic impact (this category additionally involves bridges that span routes which are recognised as essential).
   ii. Critical: Bridges that are necessary to prevent secondary life safety and that must be operational right after an earthquake.
   iii. Standard: All other bridges are classified as standard.

Selecting a retrofit measure should be done in a way that lessens the likelihood of the bridge collapsing completely or suffering significant structural damage. Retrofitting bridges is necessary in two different situations: existing bridges that are vulnerable to damage but do not meet current codes, bridges that have not yet been subjected to even mild earthquakes, and existing bridges that have sustained damage from earthquakes.

Detailed seismic evaluation results and leveling of risk should be available to consider the first decision, while the process of reduction of the seismic risk is involved in the second decision, and that through involving measures of retrofitting such as seating width extension and/or providing of restrainers (Caterino et al., 2008). Providing some of the seismic devices can work as an additional reduction of the seismic risk, for instance, providing devices for energy dissipating/dampers, also using base isolation bearings between the bridge superstructure and substructure (G. C. Lee et al., 2007). Other kinds of retrofitting procedures can be used. such as the jacketing of the bridge substructure, which required a plastic hinge region to be available, this could be done to increase the strength and ductility of the retrofitted part.

2.3 Bridge Seismic Retrofitting Procedure

The seismic retrofitting procedure for bridges includes several steps, which are:

- Preliminary Screening: The bridges that are damaged by the seismic activity can be recognized through the preliminary screening. This procedure, as mentioned by Majid and Yousefi, is mainly based on (a) Seismicity (b) Vulnerability, and (c) Importance. According to these three factors, the process of rating and prioritization for the bridges to be retrofitted can be done (Majid & Yousefi, 2012). Needs based framework to develop an Integrated Bridge Index (IBI) has been utilized by Valenzuela et al. as an aid in bridge maintenance and rehabilitation prioritization and decision making. The index weighed the structural distress, hydraulic vulnerability, seismic risk, and strategic importance of the bridge (Valenzuela et al., 2010).
- Detailed Seismic Assessment: Bridge seismic capacity, weaker sections, and model of failure, all can be calculated through a detailed evaluation process of the existing bridges according to the expected performance during and after the seismic action.

  The assessment procedure is usually required to be more precise than the codes since it reflects the real situation of the structure. ATC and Kawashima had worked to develop a number of methods that are used for prioritization of the bridges to be retrofitted (ATC, 1983; Kawashima et al., 1991). In addition, Buckle, Friedland and et al. (I. Buckle et al., 2006)mentioned that there are two strategies possible to be pursued when structural deficiencies are being highlighted by seismic vulnerability assessment, those are: (1) strengthening some critical structural members to increase the bearing capacity namely, the resistance (R) and/or (2) reducing the earthquake-induced actions namely, the seismic demand (S).
- Selection and Design of Retrofit Measures: It is necessary to identify whether a single component of the bridge needed to be retrofitted such as increase the seating width, providing restrainer or major retrofitting process including the whole bridge component to be done, which might be (Bazaez & Dusicka, 2015): retrofitting of the foundation, jacketing of the piers and replacement of the bridge bearings.
- Re-analysis of Retrofitted Structure: In this step, the dynamic analysis method is used to repeat the analysis process. Current design codes should be used in the checking of the retrofitted structure, as considered by Maraveas and Miamis et al., while the techniques that are used in the retrofitting process can be checked through a model of a prototype component in labs under the impact of cyclic loading test (Maraveas et al., 2014).

This study employs a dual approach combining a global literature review with localized field investigation, providing a multidimensional perspective that distinguishes it from previous reviews.

To determine the techniques of retrofitting and to differentiate and compare the methods, a survey of international academic papers, technical reports, and seismic design codes was carefully conducted in the first place. These were measured against the key performance indicators: cost, ease of application, strength improvement in the structure, and the enhancement in ductility. Comparative matrices were constructed to assess the efficacy and practicality of each method in a systematic way**.**

Second, the qualitative fieldwork consisted of visits and consultations with the infrastructure agencies in Duhok, such as the Municipality of Duhok District, the Directorate of Roads and Bridges, and the General Directorate of Roads and Bridges. These interactions supported first-hand knowledge of practices, policy gaps, and technical preparedness, and offered a contextual background, which is generally lacking in the current literature**.**

Moreover, the paper incorporates the design philosophy of performance-based design to put and present the analysis of the retrofit solutions within the framework of the desired seismic outcomes. Such a methodological combination of literature-based synthesis and field-grounded knowledge provides a new participant in the literature regarding the seismic retrofitting of the RC bridges, especially in the low-studied areas such as Duhok.

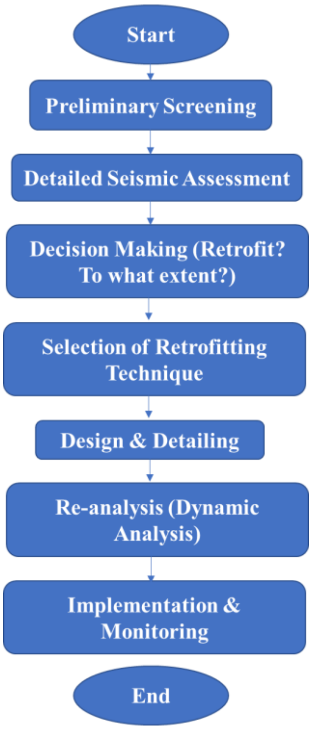

Fig.1 Systematic framework for seismic retrofitting of reinforced concrete bridges.

3. Bridge Structural Deficiencies

Several deficiencies in different parts of the bridge had been highlighted as a result of past earthquakes within the performance observation of bridges, such as:

3.1 Superstructure

The superstructure comprises all the components of a bridge above the supports, which provide the deck to support the roadway and the superstructure supporting system, which works to support the decking system and transfers the load into the bearings, as shown in Fig. 2.

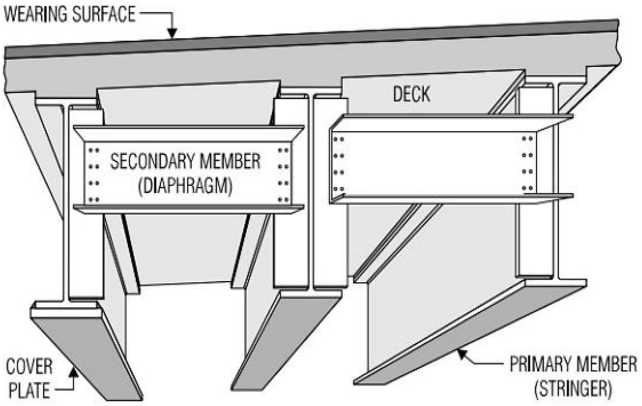

Fig. 2 Typical components of a reinforced concrete bridge system, including superstructure, bearings, substructure (piers and abutments), and foundations (Rossow, 2010)

Typically, when it comes to multi-span simply supported bridges, there are no connections or linkages between two adjacent spans; therefore, the spans are disconnected from the supports as a result of piers' motion of failure in bearings, as shown in Fig. 3. When the seismic forces are high, fixed bearings are unable to withstand then bearing failure occurs. In other cases, collapse of the bridge spans directly from their supports cause unfixable damage to the bridge (Keady et al., 2000). Another failure observed within the superstructure of the bridges at the expansion joints near the support or at the abutments, which is inadequate seat length resulting in span unseating (Furlanetto et al., 2008).

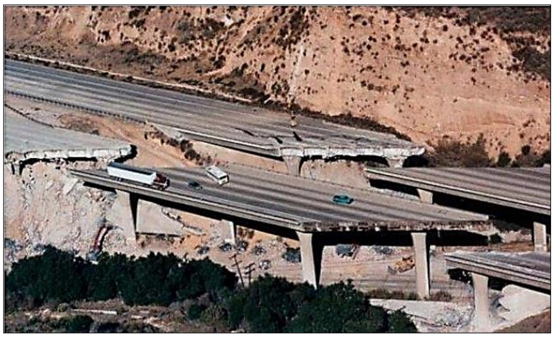

Fig. 3 Typical deck unseating failure in a multi-span simply supported bridge during seismic excitation, resulting from inadequate seat length and bearing displacement.(Keady et al., 2000)

3.2 Bearings

A bridge bearing is considered one of the bridge elements, shown in Fig. 4, which provides an interface between the superstructure system and the substructure**.**

The bridge bearings have mainly three primary functions, which are transmitting all the loads from the superstructure to the substructure, permitting longitudinal movement of the superstructure due to thermal expansion and contraction, and allowing rotation caused by dead and live load deflection (Rossow, 2010).

Several issues of jumping and inadequacy of bearing to accommodate the displacement occurred during the earthquakes, which shows dissatisfactory performance of the rocker and roller bearings (Dhefto, 2013).

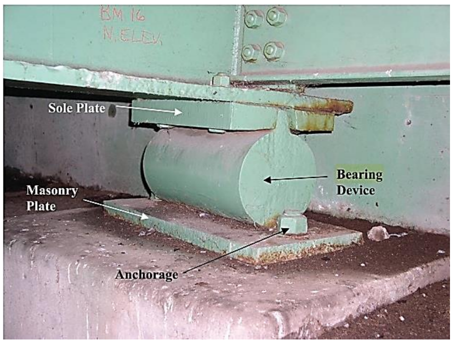

Fig. 4 Typical bridge bearing system illustrating its four essential components and their role in transferring vertical loads while accommodating thermal movements and seismic displacements

3.3 Substructure

Consists of all elements required to support the superstructure and overpass roadway and work to transmit the loads from the superstructure system through bearings into the foundation.

Columns and piers are considered to be most of the substructure parts that are subjected to damage and failure during earthquake occurrence. The RC columns and piers have observed to have several deficiencies such as (Moehle & Eberhard, 2000): (i) Insufficient of shear strength, (ii) Inadequate flexural strength, (iii) Poor confinement and transverse reinforcement (iv) Insufficient longitudinal steel lap splicing (v) Lack of ductile details in the column's plastic hinge area (vi) Premature longitudinal steel termination in piers (vii) Joints between pile cap beams have insufficient strength, see Fig. 5.

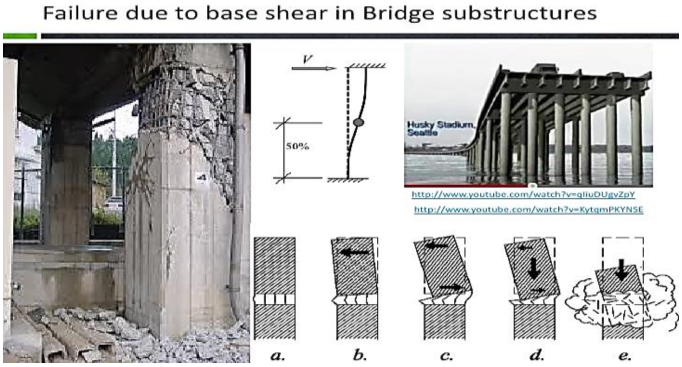

Fig. 5 Substructure damage in a reinforced concrete bridge pier due to inadequate confinement and shear capacity under seismic loading, emphasizing the need for column strengthening strategies (Moehle & Eberhard, 2000)

3.4 Inadequacy of foundation and Liquefaction of soil

Failure can occur as a result of unequal settlements, such as those shown in Fig. 6, and loss of span. Also, if an increase in earth pressure occurred, this would cause the abutments to fail. whereas abutment slumping usually happens in soft soils (Barbosa & Silva, 2007). Foundation failure can result from inadequate strength of piles, footings, and walls.

Fig. 6 Foundation instability resulting from soil liquefaction during seismic events, leading to excessive settlement and loss of lateral support for bridge substructures (Barbosa & Silva, 2007)

4. Seismic Retrofitting Techniques

All retrofitting methods are successful in reducing the vulnerability of the bridge parts to damage that results from subjecting the bridge to seismic activity. There are many techniques for bridge seismic retrofitting, and the following part will discuss the most common retrofitting techniques that are used widely to accommodate the damage in the bridge components:

4.1 Steel Jacketing

Steel jacketing is a well-established seismic retrofitting method used primarily to enhance the structural performance of reinforced concrete (RC) bridge columns. This technique involves encasing columns with steel jackets to improve confinement, increase shear and flexural strength, and prevent brittle failures. Compared to conventional hoops or spirals, steel jackets provide superior transverse confinement and are particularly effective in the plastic hinge regions of columns (H. A, 2016; Tsai & Lin, 2002).

The main benefits are the delay of shell concrete spalling and blocking longitudinal bars buckling, as stated by Tsai and Lin (Tsai & Lin, 2002). It was also noted by Sivarajan and Poornima that these characteristics of strength and ductility improved through passive confinement (Sivaraja & Poornima, 2012). A number of experiments conducted on different types of column geometry have always reported better seismic behavior in the presence of a steel jacketing; circular, rectangular, and square (Bsisu, 2002; Haroun & Elsanadedy, 2005; Memon & Sheikh, 2005).

The FHWA has described that steel jacketing can be considered as effective to enhance shear strength and flexural ductility, particularly as full-height jackets (Fig. 7). The jackets are usually made of A36 steel and have a 2-inch (51 mm) clearance at the ends of the columns to prevent touching the cap or footing and cause an increase in moment capacity (FHWA, 2006). The recommended jacket thickness is 0.375 inches (9.5mm -25mm) (FHWA, 2008).

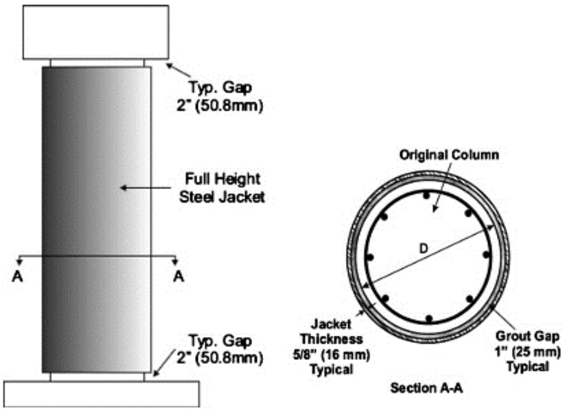

Fig. 7 Details of a typical full-column steel jacket (FHWA, 2006).

Circular columns benefit most due to uniform confinement, while rectangular sections require elliptic or rectangular jackets. Julio Garzón-Roca et al. found that specimens reinforced with steel cages (Type B) offered higher resistance and ductility than those with chemical anchors (Type A) (Julio et al., 2010). Bsisu (Bsisu. KhairulDeen Isam, 2009) confirmed that square columns retrofitted with steel jackets exhibited over double the original compressive strength.

Design details such as end stiffeners, anchor bolts, and grout or adhesive fillers significantly influence performance. Aboutaha et al. and Chai et al. highlighted that longer jackets with bolts enhance strength in plastic hinge zones (Figs. 8 and 9) (Aboutaha et al., 1996; Chai et al., 1991).

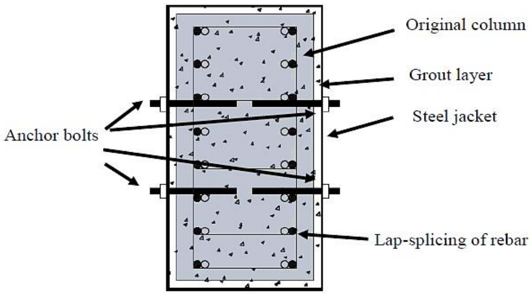

Fig. 8 Steel jacketing retrofit configuration for a reinforced concrete column with inadequate lap-splice detailing (Aboutaha et al., 1996).

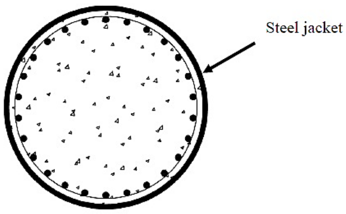

Fig. 9 Steel jacket retrofit on circular reinforced concrete columns (Chai et al., 1991).

Lin et al. demonstrated that octagonal jackets outperformed elliptical ones in mitigating lap-splice failures (Fig. 10) (Lin et al., 2010). Xiao et al. showed that angle stiffeners offer a balance of practicality and performance (Fig. 11)(Xiao & H., 2003).

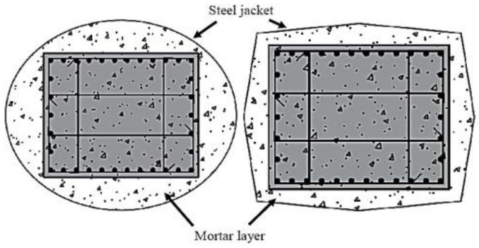

Fig. 10 Elliptical (a) and octagonal (b) steel jacket retrofit with concrete infill (Lin et al., 2010).

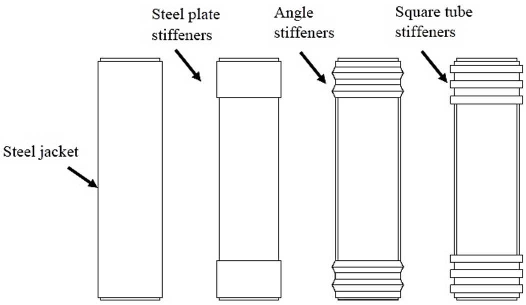

Fig. 11 Steel jackets with no stiffeners; plate, angle, and square tube stiffeners (Xiao & H., 2003).

Interface treatment is also crucial. Choi and Kim observed that adhesives could reduce compressive strength by weakening the confinement mechanism(Choi & Kim, 2008). Uy (Uy, 2002) showed that using both glue and bolts improved anchorage, particularly in slender columns (Fig. 12). Choi et al. and Li et al. confirmed that jacket thickness has a nearly linear relationship with peak strength; two-layer jackets performed comparably to single-layer jackets of the same total thickness (Fig. 13)(Choi & Kim, 2008; Li et al., 2005). Belal et al. found that steel cages with more battens performed better than thin steel plates (Fig. 14) (Belal et al., 2014).

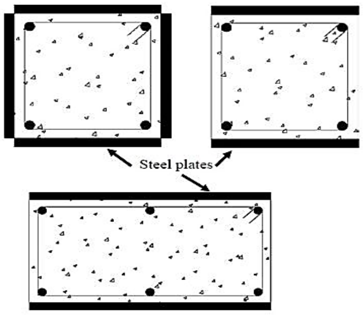

Fig. 12 Partial and complete steel jackets on square and rectangular columns (Uy, 2002).

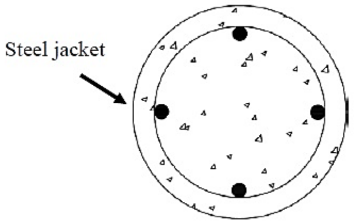

Fig. 13 Standard steel jacket on circular reinforced concrete columns (Li et al., 2005).

Steel jacketing remains a cost-effective and dependable retrofitting method, especially when detailed appropriately. Table 5 summarizes key configurations and outcomes for practical reference.

Table 5. Summary of Steel Jacketing Configurations and Outcomes

Configuration	Key Findings	Recommended Use
Full Steel Jacket with Anchor Bolts	Improves confinement and ductility, enhances strength in plastic hinge zones.	Bridge piers in high seismic zones
Steel Jacket with End Stiffeners	Delays local buckling, facilitates plastic hinge relocation	Columns with expected plastic hinge formation
Elliptical/Octagonal Jacket	Reduces lap-splice failure, improves ductility	Lap-splice deficient rectangular columns
Two-layer Jacket (Same Total Thickness)	Performs similarly to a one-layer of the same total thickness	Cost-sensitive retrofits needing equivalent performance
Jacket with Adhesive	Reduces confinement effect, not ideal for high seismic demand	Low seismic demand applications (use with caution)
Angle Stiffeners	Practical and effective; easy to fabricate and weld	Rapid retrofit scenarios with standard profiles
Welded Strip Bands	Improves confinement, avoids weld line failure	Supplemental confinement under lateral loading

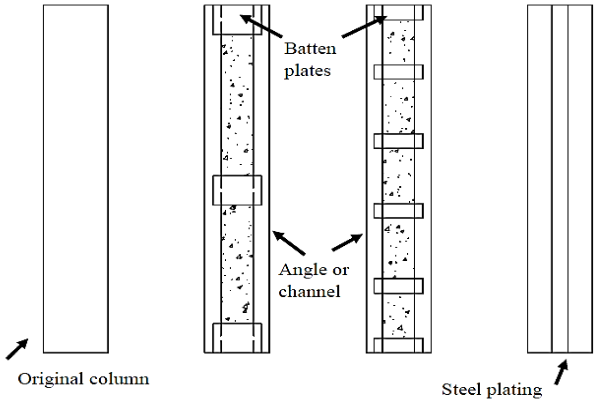

Fig. 14 Column with steel cages (3 and 6 battens) vs. steel plating (Belal et al., 2014).

Due to the close fault excitation, Liu, Sung, and Berry also demonstrated that steel jackets were sufficiently effective to be used for seismic repair of the damaged RC bridge columns. The repair technique was thought to be simple to use and economical because the steel plate was immediately fastened to the damaged RC bridge column (Liu et al., 2014). The steel jacket's confinement effect has the potential to significantly boost lateral load-carrying capacity and postpone the loss of such capacity brought on by buckling failure (Berry & Eberhard, 2005). Table 6 compares physical properties of jacketing materials used (e.g., steel, CFRP, RC).

Table 6. Comparison of Physical Properties of Jacketing Materials

Material	Density (kg/m^3)	Tensile Strength (MPa)	Durability	Weight Impact	Corrosion Resistance
Steel	~7850	250–600	High	High	Low
CFRP	~1600	1000–2000	High	Low	Excellent
Reinforced Concrete	~2400	20–50 (concrete), 400+ (steel)	Moderate	Moderate	Moderate

4.2 Composite Material Jacketing

Widely used in retrofitting is composite material jacketing, especially with Advanced Composites Materials (ACMs), which have been found to have great qualities, including high strength and weight ratio, corrosion resistance, and simple application. These ones, such as fiberglass and fiber-reinforced plastic (FRP), carbon fiber sheets, and aramid fiber sheets, are especially handy in those situations when access to construction is limited. Its common use is to wrap thin and flexible composite sheets around the columns, either in the plastic hinge regions or throughout the complete height, in an effort to increase strength and ductility (Kawashima, 2000; Priestley et al., 1996; Saadatmanesh et al., 1997).

Despite the effectiveness of the composite jackets, which have been proven by laboratories, design methodologies are yet to be established, and it is not clear how they will behave during large-scale seismic events (Haroun & Elsanadedy, 2005; Unjoh, 2000).

One of the composites that has been most studied regarding retrofitting employs CFRP (Carbon Fiber Reinforced Polymer). The example is that Oukaili & Merie revealed the increase in the shear capacity of hollow piers reinforced with CFRP sheets, despite having large openings (Oukaili & Merie, 2021). Saeed et al. compared the hysteretic behavior of piers that are retrofitted with one and two layers of CFRP. They determined that CFRP wrapping substantially enhanced the load capacity, lateral, and energy dissipation of the ductile character at the levels of driftage higher (Saeed et al., 2015).

These findings are supported by other studies. According to Craig and Soudki (Craig & Soudki, 2002), FRP composite is the best of the best in the rehabilitation of seismic structures. The advantages of this are that they are resistant to corrosion, weigh less, and can be installed faster. In their study, Sharaf and Soudki (Sharaf & Soudki, 2002) affirmed their success in enhancing flexural and shear capacity.

These systems have also been tested using the method of Finite element analysis. Obaidat et al. also studied CFRP-concrete interface behavior with validated FEA (Obaidat et al., 2010), and Moghaddam analyzed beam-column joint behavior with different types of FRP using ABAQUS, which demonstrated a good correlation with the lab results (Moghaddam, 2012). Hadi & Tran (Hadi & Tran, 2014) introduced a retrofitting method using a segmental concrete cover wrapped in CFRP, showing enhanced shear capacity and minimized debonding. Salahaldin A. et al. (Salahaldin et al., 2022) identified failure modes, including adhesive debonding and CFRP fracture, with performance improving as the strip spacing decreased.

Design guidance is also available. Waghmare (Waghmare, 2011) outlined important considerations like jacket width and reinforcement detailing for different structural elements. Eslami & Ronagh (Eslami & Ronagh, 2015) conducted nonlinear FEA on FRP-retrofitted connections and validated the results against cyclic load tests, confirming accurate predictive capabilities (Fig. 15).

4.3 Reinforced Concrete Jacketing

Reinforced Concrete Jacketing (RCJ) is a prevalent retrofitting technique whereby structural members that have already been built (e.g. columns or joints) are covered with a new concrete layer that is reinforced. The jacket in use usually has longitudinal reinforcements, circular bindings, hoops, and wire mesh that has been welded onto it. The methodology is meant to increase the capability of the component to facilitate the resistance of lateral loads via the capitalization of the shear strength, flexural strength, and ductility, see table 7 that provides a comprehensive comparison of different types of Jacketing techniques and their recommended uses

RCJ can also be quite appropriate for members who are damaged or deficient and require restoration. According to Vaghani et al. (Vaghani et al., 2014), RCJ is divided into three major types, namely beam jacketing, column jacketing, and beam-column joint jacketing. RCJ is commonly used all over the world due to its consistency and ease of construction. Experimentally, it could be proven to be useful by Karayannis et al. (Karayannis et al., 2008), who presented a new RC jacketing of beam-column joints under seismic load. The retrofitted specimens had much enhanced seismic performance, as depicted in Fig. 16, compared to the original ones.

Table 7. Summary of Composite Jacketing Techniques and Findings

Configuration	Key Findings	Recommended Use
Single-layer CFRP on Hollow Piers	Increases shear capacity despite structural openings	Hollow piers with moderate seismic demand
Multi-layer CFRP Jacketing	Enhances energy dissipation and ductility at high drift levels	High-seismic zones requiring ductility improvement
FRP Laminated Composites (Various Types)	Lightweight, corrosion-resistant, quick to apply	Remote or space-constrained bridge elements
Segmental Concrete Cover + CFRP Wrap	Improves shear strength, reduces debonding risk	Beam-column joints with cracking or geometry concerns
CFRP with Reduced Strip Spacing	Enhances shear capacity, mitigate fracture and debonding	Beams requiring a strength upgrade with precise control
FE-Validated Bonded FRP Models	Accurately predict cyclic and monotonic performance	Analytical design for joints and load path calibration

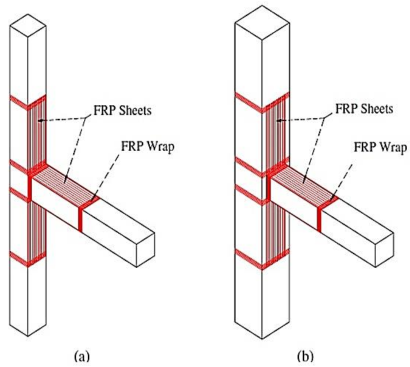

Fig. 15 Schematic illustration of the flange-bonded scheme in an exterior connection with beams and columns: (a) equal dimensions and (b) different dimensions (Eslami & Ronagh, 2015).

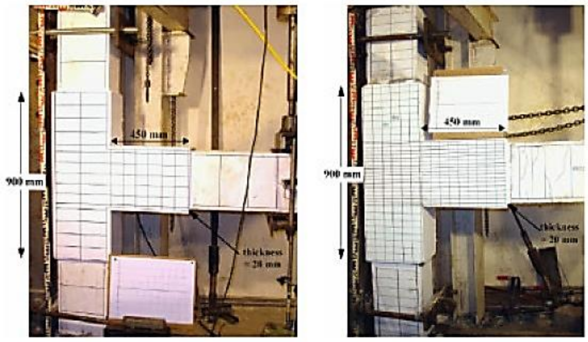

Fig. 16 Application of RC jacketing to beam-column joint (Karayannis et al., 2008).

Marlapalle, Salunke & Gore (Marlapalle et al., 2014) supported the benefits of RCJ in compliance with IS15988:2013, but also noted disadvantages: increased section size, added dead weight, and longer implementation time. Minafò (Minafò, 2015) proposed a stress-block-based analytical method for strength prediction in jacketed columns, concluding that it is valid if all parameters are well calibrated.

RCJ substantially increases the column's flexural and shear capacity. Proper anchorage of longitudinal reinforcement into the footing is critical to ensure plastic hinge formation occurs in the column rather than the foundation (Priestley et al., 1996; Unjoh, 2000). For circular columns, closely spaced spiral ties provide effective confinement, while in rectangular columns, elliptical or circular jacketing is more efficient in preventing buckling in the central region, as noted by Priestley (Priestley et al., 1996).

RC jacketing is also economical and widely accessible, although it increases section thickness by approximately 0.5 m. Beschi et al. (O. Montes et al., 2015) showed that high-performance fiber-reinforced concrete (HPFRC) jackets improved both bearing capacity and ductility of joints. Notably, they also reported that using thin jackets preserved the structure's original stiffness, a crucial factor when dynamic properties must remain unchanged (Beschi et al., 2011).

Table 8. Summary of Reinforced Concrete Jacketing Applications and Insights

Application Type	Key Findings	Recommended Use
Beam-Column Joint Jacketing	Improves ductility and seismic performance	Seismically deficient joints in RC frames
Column Jacketing with Dowels	Increases flexural strength; hinges form above the footing	Columns requiring energy dissipation under lateral load
Circular Jacket with Spiral Ties	Enhances confinement and shear strength	Circular piers or slender columns
Elliptical Jacket for Rectangular Sections	Prevents mid-height buckling of longitudinal bars	Rectangular columns with poor detailing
Thin HPFRC Jackets	Boosts strength while preserving structural stiffness	Retrofitting where stiffness uniformity is critical

Reinforced Concrete Jacketing continues to offer a dependable, cost-effective solution for strengthening existing bridge and building components, especially when tailored with adequate detailing and structural considerations, a comparison of the applications of Reinforced Concrete Jacketing are illustrated in Table 8.

4.4 Foundation Retrofitting

Modena et al. stated that earthquake-resistant rules for bridge design were only recently adopted by the Italian code (but more in general also in the European earthquake-prone areas). Consequently, many existing bridges demonstrate insufficient resistance to lateral seismic forces in their peers and abutments, particularly concerning shear reinforcement, detailing for sectional ductility, and the capacity of their foundations. Furthermore, bearings and support often lack the necessary capabilities for effectively transferring inertial forces to the substructure (Modena et al., 2004).

While foundation retrofitting can be expensive, it is often avoided. Although generally undesirable, foundation rocking and uplift are sometimes viewed as a form of seismic isolation, potentially reducing seismic forces in the bridge's superstructure and substructure. Doshi et al., within their research, conclude that the effect of seismic forces along with axial load on bridge foundation can be retrofitted by micro piles with different diameters in layered soil. The study was based on considering the bending moment pattern in the middle of a group of nine piles (Doshi et al., 2017).

Malhotra concluded that technologies like tie-down anchors, micro piles, and post-grouted piles effectively address the need for high-capacity foundations installable in confined spaces with limited clearance and minimal disruption. Technologies such as compaction grouting, stone columns, jet grouting, and deep soil mixing effectively mitigate geotechnical seismic hazards like liquefaction, lateral spreading, and seismic settlement (Malhotra, 2007). Table 9 shows which retrofitting techniques are most applicable for different structural components.

Table 9. Recommended seismic retrofitting techniques for different bridge components

Bridge Component	Suitable Retrofitting Techniques	Notes/Advantages
Columns	Steel Jacketing, CFRP Wrapping, RC Jacketing	Enhances shear/flexural strength & ductility
Beams	CFRP Wrapping, RC Jacketing	CFRP preferred in confined spaces
Joints	RC Jacketing, CFRP Wrapping, SMAs	Critical for force transfer, benefits from ductility
Foundations	Micro Piles, Jet Grouting, Base Isolation	Expensive but vital for stability
Bearings	Elastomeric Bearings, Viscous Dampers	Allows energy dissipation and motion control
Deck/Expansion Gaps	SMA Restrainers, Viscoelastic Dampers	Prevents unseating during seismic events

5. Recent Advances in Retrofitting Techniques

There have been developments in retrofitting using newer materials and innovative technology. Some of these developments include seismic base isolation, structural control, smart materials, and viscous dampers.

5.1 Seismic Base Isolation

Although there may not be any structural damage, the people and contents of the building are harmed and damaged by the intensified accelerations of the earthquake ground motion throughout the structure. To lessen these effects, a relatively recent and economical method is to utilize base isolators placed between the structure's base and foundation to separate the structure from seismic ground motions (Kelly, 1986). A design concept called seismic isolation suggests separating a structure, a portion of it, or even equipment installed within it from the destructive power of earthquakes. Shifting the structure's fundamental frequency away from the main frequencies of the earthquake ground motion and the fixed-base superstructure's fundamental frequency is one of the objectives of seismic isolation (I. G. Buckle & Mayes, 1990). A further objective of an isolation system is to reduce the delivered acceleration into the superstructure by offering an extra channel for energy dissipation. By isolating a structure from the supporting ground, usually in a horizontal direction, this creative design method seeks to lessen the transmission of seismic motion to the structure (Jangid & Datta, 1995). As stated by Humar and Saatcioglu, throughout the past twenty years, a number of existing structures, especially in the USA, New Zealand, and Japan, have undergone seismic retrofits employing base isolation. It is anticipated that enhanced design techniques and criteria will lower the damage in modern buildings to acceptable levels in the case of a moderate to major earthquake as a result of the building code's increasingly strict seismic design requirements (Saatcioglu & Humar, 2003).

The most effective and widely used method of preserving a building from destructive earthquakes is seismic isolation. The effectiveness of base isolation systems is being investigated by numerous researchers worldwide. The seismic base isolation (SBI) retrofitting method includes a number of solutions that are based on the isolation principle. The isolation system options include high-damping rubber bearings and elastomeric bearings with external dampers, shown in Figs. 17-19, a lead rubber bearing, and a friction pendulum system (FPS) (*Seismic Isolation Bridges*, 2016).

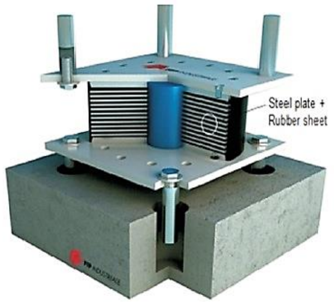

Fig. 17 Elastomeric base isolator used in seismic retrofit applications (Seismic Isolation Bridges, 2016)

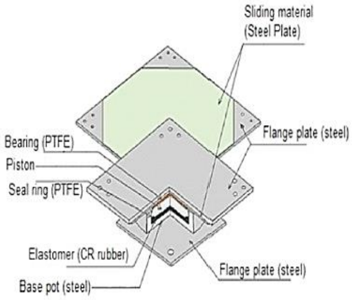

Fig. 18 Slider Isolator (Seismic Isolation Bridges, 2016)

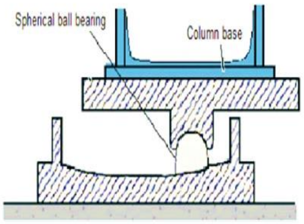

Fig. 19 Rotational ball bearing (Seismic Isolation Bridges, 2016)

An analytical model for a seismically isolated viaduct near Osaka, Japan the site of the 1995 Kobe earthquake—was created by Feng et al. When compared to the non-isolated bridge, they found that the installation of those isolators substantially reduced the response acceleration of the bridge superstructure and pier deformation (Feng et al., 1996).

According to Kawamura et al., two mid-rise RC constructions in Japan were retrofitted using the seismic isolation technique. The two retrofitted buildings were situated in an area where an earthquake with a Richter magnitude of 7-8 was predicted to happen soon. Their research led them to the conclusion that this is the best retrofitting technique because it allows for work to be done outside the structure and has beneficial seismic performance. Additionally, they stated that due to the significant deformation and the need for room for plumbing, staircases, elevators, and escalators to follow the significant displacement of the isolation story, the clearance to other structures should be greater than 40 cm (Kawamura et al., 2000).

5.2 Structural Control

Structural control aims to minimize vibrations through passive or active techniques(Dyke et al., 1997; K & S., 1994). Passive methods involve seismic base isolation (SBI) to decouple the structure from ground motion and/or passive energy dissipation (PED) devices to reduce dynamic response (Abe & Y. Fujino, 1998). Active methods are used by actuators to apply external forces based on system feedback. While more complex, active control offers superior control and adaptability compared to passive systems, holding significant potential for bridge engineering (Wu. Ziaguang, 2000).

Passive control systems can enhance a structure's energy dissipation capacity using localized devices, either within a seismic isolation system or distributed throughout the structure. These supplemental energy dissipation systems have been reviewed by Soong et al.(Constantinou & MD. Symans, 1993; Soong & MC. Constantinou, 1994)

These systems aim to absorb a substantial portion of seismic energy, lessening the stress on the primary structure. Depending on their design, they can also enhance the stiffness and strength of the structure(ATC (Applied Technology Council), 1993). Passive control systems operate without external power; structural motion drives relative movement within the devices, which then dissipates energy. These devices come in various forms, dissipating energy through mechanisms like yielding steel, viscoelastic behavior in rubber, viscous fluid shearing, fluid orificing, and sliding friction (ATC (Applied Technology Council), 1994). Seismic isolation systems are another type of passive control, inserting a flexible layer between the foundation and superstructure to lengthen the system's natural period. This increased flexibility typically deflects much of the earthquake energy, reducing accelerations in the superstructure while increasing displacement at the isolation level. Kelly (JM. Kelly, 1993) and Skinner et al. (Skinner et al., 1993) provide descriptions of seismic isolation systems.

5.3 Smart Materials

In recent years, a variety of applications have made use of shape memory alloys, a group of metallic alloys with special thermo-mechanical properties (Otsuka & Wayman, 1998). Heating the alloy to a temperature higher than the austenite finish temperature (Af) can recover the residual strain created upon unloading when it is loaded below a particular temperature known as the martensite finish temperature (Mf). Shape Memory Effect (SME) is the term used to describe this phenomenon. In contrast, the material recovers all of its residual strain after an unloading plateau that is degraded from the loading plateau if it was loaded at a temperature higher than Af. Stated differently, the material exhibits considerable elastic strain (6%-8%). Fig. 20 shows super elastic behavior in SMAs.

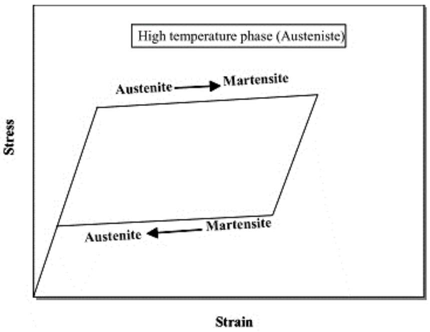

Fig. 20 Super-elastic phenomenon in shape memory alloys (Otsuka & Wayman, 1998)

Wilde et al. explored an adaptable base isolation system designed for elevated highway bridges, integrating laminated rubber bearings with shape memory alloy (SMA) bars. The system's behavior was simulated mathematically and assessed analytically under earthquake scenarios featuring accelerations of 0.20g, 0.40g, and 0.60g. In the event of a minor earthquake (0.20g), the system functioned as a firm link connecting the pier and the deck. When subjected to a moderate earthquake (0.40g), the SMA bars augmented the system's capacity to dampen vibrations, attributed to the stress-driven martensite transformation within the alloy. During a major earthquake (0.60g), the SMA bars delivered hysteretic damping and served as a mechanism for controlling displacement, stemming from the alloy's increased rigidity following the completion of the phase transformation (Wilde et al., 2000).

DesRoches and Delemont expanded on the study of SMAs within bridge applications. Their work detailed an initial assessment regarding the effectiveness of employing shape memory alloy connectors to lessen the impact of seismic activity on bridges with simple spans, as depicted in Fig. 21. The research included practical tests to define the properties of SMA wires and bars. This was followed by analytical investigations into how SMAs influence the seismic behavior of a multi-span, simply supported bridge. The findings revealed that SMA connectors, when positioned at the central hinges, demonstrate a superior capability to decrease the extent of relative hinge movement when compared to traditional steel cable connectors (DesRoches & Delemont, 2001).

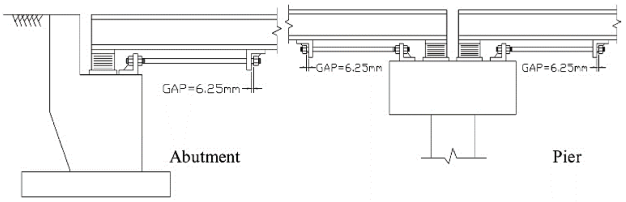

Fig. 21 Application of shape memory alloys to bridge retrofit, SMA restrainers used at abutment and intermediate hinge (DesRoches & Delemont, 2001)

The shape memory and super elastic properties of SMAs are temperature dependent. At lower temperatures, they exhibit the shape memory effect, while at temperatures 20 to 300 °C above their transformation temperature, they display super elasticity. The transformation temperature is determined by the alloy's composition. SMAs can function as both restrainers and dampers, and their shape memory effect allows them to dissipate considerable energy (Andrawes & Desroche, 2004). One application of SMAs is in restrainers, which are installed between adjacent spans to limit excessive relative movement. Steel cables have historically been used for this purpose, but they lack re-centering capability and increase the ductility demand on the structure. SMA-based restrainers overcome these drawbacks (Castellano et al., 2001).

5.4 Viscous Dampers

Viscous dampers are energy-dissipating devices fitted between superstructures and substructures. They incorporate a piston inside a silicone or oil-filled chamber that produces damping forces that are related to the velocity of the piston (Boroschek et al., 2003). The dampers have been proven to be efficient, simple to install, and viable in field applications (Sarrazin et al., 2005).

Feng and Kim et al. (M. Q. Feng et al., 2000) conducted a linear and nonlinear finite element analysis of viscoelastic dampers in bridge expansion joints. Findings indicated that the viscous elements had a significant effect on reducing relative displacements without adding column bending moments and ductility requirements.

Table 10 provides a comprehensive summary of the most recent applications and innovations in retrofitting techniques.

Table 10. Summary of Recent Retrofitting Innovations and Applications

Technology	Mechanism / Benefit	Recommended Use
Seismic Base Isolation	Reduces seismic force transmission via base decoupling	Bridges and buildings in high seismic zones
Structural Control	Passive/active systems to reduce vibrations and displacements	Tall or flexible structures prone to resonance
Shape Memory Alloys	Self-centering and energy dissipation through SME behavior	Span restrainers, joints, and displacement-sensitive areas
Viscous Dampers	Dissipate seismic energy via velocity-dependent resistance	Expansion joints and connections in bridges

6. Local Context: Duhok City

Despite recent earthquakes, no retrofitting programs have been implemented in Duhok. Design practices only include a seismic factor of 0.2, considering the region as Zone II, contrary to the Iraqi seismic code, which places it in Zone III.

Duhok city, located in Duhok governorate within the Kurdistan Region of Iraq, and as one of the Iraqi cities, has witnessed many minor, unnoticeable earthquakes over the decades. In the last few years, the earthquakes that affect this area, and Iraq in general, have increased in their severity and started to be more noticeable, with an increase in the number of minor earthquakes. More damage had been noticed in the structures located in this area of study, such as cracks and deformations of the building. Bridges are considered one of the efficient structures in Duhok city as a part of the transportation system, shown in Fig. 22. Most of the bridges in Duhok city are pre-stressed RC bridges, and their locations are distributed along the city due to its geographical location in a valley between two mountains.

Fig. 22 Duhok city roadway network

6.1 Earthquakes: reasons and effects

Seismic events are a severe danger to human lives and conditions, as it is sudden and destructive. These effects are not just limited to the initial shaking on the ground, most of them tend to cause secondary effects in the form of ground rupture, crustal shift, landslides, tsunamis, overflows, conflagration, and explosion (Gubin I.E., 1950).

Although earthquake forecasting is elusive, the only way to reduce the devastating effects of these catastrophes and lower casualties is to take proactive actions. These are the production of correct seismic zoning maps, maintenance of earthquake-resistant construction measures, and long-term public education initiatives to prepare the community for possible dangers and create resilience. Additionally, it is essential to increase the ability of the governmental services and emergency departments to successfully react to these natural disasters (Dzhurik et al., 2004; Dzhurik V.I. Serebrennikov S.P. et al., 2012).

Earthquake risk is not constant but grows along with the rising seismic activity of the Earth and human activities that affect the crust of the Earth. Unrestrained resource extraction, such as oil and gas exploitation, massive mine activities, high hydraulic projects, and improper disposal of industrial wastes, are contributory factors to increased seismic vulnerability (Papadopoulos et al., 2003). Subsequently, the risk increases with the existence of nuclear installations and other environmentally prone installations within the regions prone to seismic activities, whereby even small earthquakes or other events, such as landslides, may interfere with the operational aspect of these installations.

The specification of seismic zones is an important, but complex process in modern seismology. As an example, the United States has a five-year requirement to revise its seismic hazard assessments, whereas Russia has a requirement of 10-15 years to revise the same. Even though seismic zoning maps are continually updated through additional earthquakes and more seismological knowledge, overall, globally, there is a scarcity of complete maps, and the best that can be done is to update areas that have known earthquake activity (Ambraseys et al., 1994). Seismic zoning is based on two basic methods analysis of historical earthquake events (Historical methods) and geodynamic interpretations of seismicity and source zones (Deductive methods).

Verma et al. and Silva et al. characterize earthquakes as destructive natural events. The impact of earthquakes on the environment is termed Earthquake Environmental Effects (EEE), categorized as either primary (direct consequences of the earthquake) or secondary (resulting from the primary effects). Earthquake intensity scales utilize EEE and other environmental impacts to quantify the magnitude of seismic events.

6.2 Available Retrofitting Techniques in Duhok City

The researcher had visited the concerned governmental offices to search and identify the retrofitting procedures, techniques, and methods applied as precautions in Duhok city bridges to sustain any future earthquakes that might happen after the occurrence of several noticeable earthquakes in the last few years. The offices visited were the municipality of Duhok district, the Directorate of Roads and Bridges, and the general directorate of roads and bridges in Duhok governorate. All the offices visited stated that there are no techniques, nor procedures are followed as precautions against earthquakes and the damage that might occur in Duhok district or in Duhok government as a whole. Since there were no damage or observed deformations in the city bridges after the earthquakes that occurred in the last few years, for clarity, a summary of the gathered information provided by the aforementioned governmental offices are listed in table 11

The only input for earthquakes that is taken into consideration during the design of new bridges in Duhok city is the seismic factor that is used in the calculation of the design loads, which will be applied to the designed bridges in Duhok city. The seismic factor taken by the designing company (0.2), considering that Duhok is located within zone 2, which is the seismic zone affecting the whole of Iraq.

On the other hand, the Iraqi seismic zoning, which is shown in Fig. 23, is still following the code 2/ 97 of Iraqi seismic code requirements for buildings, in which Duhok governorate is located within zone III.

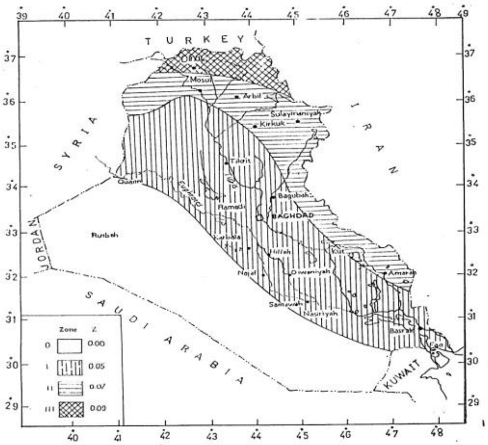

Fig. 23 Iraq seismic zoning map

Table 11. Consolidate information from the field visits to governmental offices

Institution Visited	Seismic Retrofit Actions Identified	Observations
Municipality of Duhok	None	Acknowledges design uses a 0.2 seismic factor only
Directorate of Roads and Bridges	None	No retrofit policy or implementation
General Directorate of Roads and Bridges	None	Confirms absence of retrofit practices city-wide

7. Comparative Analysis of Retrofitting Techniques

This section offers a comparative evaluation of seismic retrofitting techniques for reinforced concrete (RC) bridges, based on five key performance indicators: cost (material, labor, and implementation expenses), application ease (complexity and labor intensity), strength gain (increase in axial, flexural, and shear strength), ductility improvement (enhanced deformation capacity before failure), and structural suitability (compatibility with specific bridge elements like columns, joints, and foundations). This multi-criteria analysis allows the engineers and policymakers to use the most suitable technique according to the needs of the project, economic factors, and typologies of bridges. A conventional and common technique, steel jacketing will offer excellent confinement and substantially enhance both shear and flexure, especially to circular columns, especially when combined with end stiffeners and anchor bolts, but needs to be carefully installed on-site through welding, which may affect labor expenses. CFRP wrapping is characterized by high strength-to-weight ratios and corrosion resistance; it is easier to apply and has a lower weight compared to other materials and studies have found it to be more effective at high drift rates since it is dissipated better, making it highly desirable in tight spaces or using a product where aesthetics is paramount; initial material costs are high but it has been found that CFRP wrapping performs better at higher drift levels because it is dissipated more effectively. Reinforced concrete jacketing (RCJ) is very efficient in enhancing the structural integrity but also increases the mass and can necessitate foundation retrofitting, thus more costly in places with limited access and necessitating more time, but due to its cost and compatibility with local contractors, it remains an option in low-resource facilities. Base isolation systems separate the superstructure from ground shaking and minimize the seismic impact on the superstructure but are costly and technically challenging; the most secure level of protection is provided, especially in the case of vital infrastructure, where being available after the earthquake is a requirement. Shape memory alloys (SMAs) are another new solution, and their capacity to dissipate energy and re-center properties make them perfect in bridge restrainers and joints; although expensive, their reusability and high seismic behavior make them worth being used in strategic retrofitting. A comparison has been made between these techniques in Table 12.

Table 12. Comparative evaluation of seismic retrofitting techniques for different bridge components.

Technique	Cost	Application Ease	Strength Gain	Ductility Gain	Suitability
Steel Jacketing	Moderate	Moderate	High	High	RC Columns
CFRP Wrapping	High	Easy	Moderate	High	Hollow/Slim Piers
RC Jacketing	Low	Difficult	High	Moderate	Joints & Beam-Columns
Base Isolation	High	Complex	High	High	Superstructures
SMAs (Smart Alloys)	High	Moderate	Moderate	High	Expansion Joints

Steel and CFRP jacketing offer an optimal balance between cost and performance for typical bridge components in Duhok. RC jacketing remains a pragmatic solution for broader applications where cost constraints exist. For high-priority structures, integrating base isolation and SMAs should be considered, especially where uninterrupted post-earthquake operation is required.

8. Conclusions and Recommendations

This review has synthesized findings regarding the seismic retrofitting of bridges. The study concluded that bridge retrofitting is crucial due to outdated designs and insufficient ductility in existing structures, a fact underscored by recent earthquakes. Many bridges can be effectively retrofitted using straightforward techniques. Key considerations include retrofit philosophy, assessment, procedures, validation, and the use of advanced materials.

Effective retrofitting techniques include using longer steel jackets with anchor bolts for columns, continuous reinforcement in plastic hinge regions, and octagonal jackets for improved ductility. Whole jackets perform better than split jackets, and jacket thickness relates linearly to peak strength.

Ultimately, retrofitting success depends on enhanced strength and ductility, validated by performance during seismic events and laboratory testing. Advanced solutions like seismic base isolation and shape memory alloys (SMAs) offer further potential, with SMAs showing promise in restrainer applications due to their recentering capabilities.

In a practical approach, the results of this research provide a systematic foundation on which the infrastructure authorities and decision-makers should consider priorities in terms of retrofit measures based on the seismic needs of regions, the structural setup, and the economic viability. The comparative appraisal approach that is advanced in this paper has the potential to aid engineers in choosing the right strengthening methods that strike a balance between the increase in performance and the constructability and cost of the structure. Moreover, the results of this study could become an initial source of localized seismic retrofit guidelines for bridge infrastructure in moderate seismic areas like Northern Iraq.

Based on these conclusions, the following recommendations are put forth for future work and coordination:

1. Establishment of a National Bridge Retrofit Program: A comprehensive bridge retrofit program is imperative for the nation and should be implemented for vulnerable bridges that have not yet been subjected to seismic events. The retrofitting of existing bridges is directly relevant to mitigating potential disasters caused by earthquakes and should be prioritized accordingly.
2. Enhancement of Collaboration between Governmental Agencies and Universities: Enhanced coordination between governmental agencies and universities is essential to continuously update and refine the information and techniques used in developing the transportation system, including bridges, highways, and traffic data management. This can be achieved through the sharing and discussion of recent research findings generated by academic staff, facilitating the practical application of cutting-edge knowledge.
3. Prioritization of Research on Unresolved Issues in Bridge Seismic Retrofitting: While bridge seismic retrofitting has made substantial progress, several issues require further investigation to ensure effective solutions. These include:
   - Development of Standardized Seismic Assessment Methodologies: The establishment of a standardized methodology for the seismic assessment of existing bridges, particularly those that have sustained damage or have a high probability of damage in future earthquakes, is critical.
   - Validation of Retrofit Techniques through Analytical and Experimental Methods: Rigorous validation of retrofit techniques through both analytical and experimental methods is necessary. Experimental methods should include shake table testing, pseudo-dynamic testing, quasi-static cyclic load testing, and performance monitoring during earthquakes.
   - Exploration of Structural Control Techniques: The application of structural control techniques in bridge retrofitting warrants further investigation. This includes active methods, passive energy dissipation devices such as dampers, and passive approaches like base isolation.
   - Continued Research on Smart Materials: Further research should be conducted on the use of smart materials, such as SMAs, for retrofitting as dampers and restrainers. Given their direct benefits to maintenance and retrofitting, research into monitoring structural health and detecting damage in buried sections of foundations and superstructures is essential.
   - Development of Design Techniques for Modern Composite Materials: It is necessary to establish comprehensive design techniques for retrofitting using modern composite materials, ensuring their effective and reliable application.
4. Adoption of Proactive Governmental Policies: Governmental policies should include strategic investments in global observations to advance the science of observation and measurement, which is fundamental to progress in this field. Furthermore, efforts should be made to enhance the scientific rigor of prediction methodologies and the reliability of forecasts, as and when they become feasible. Large-scale mapping of earthquake hazards using up-to-date seismic zoning codes and linking these maps to development planning processes is also essential, including micro-zonation of urban areas at risk of earthquakes.
5. Promotion of Partnerships and Public Awareness: The government should foster closer partnerships with financial and legal institutions, insurance companies, community-based organizations, and industry stakeholders. Increased investment in public awareness campaigns, education, training, and human resource development in the area of disaster mitigation is also vital for building community resilience.

Further studies should be done on the numerical and experimental analysis of locally representative bridge systems in the future so that the improvement in performance of various retrofit methods under region-specific seismic conditions can be measured. Specifically, the performance-based assessment frameworks (nonlinear time-history analysis) could be utilized to optimize the retrofit choice in terms of displacement demand, ductility capacity, and cost efficiency. Also, enhancing studies could be done concerning the development of the regionally calibrated seismic retrofit guidelines and prioritization model to guide the infrastructure authorities to introduce systematic and economically viable retrofit programs.

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