

# Retrofitting of Historical Structures for Sustaining Earthquake Motions

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## Abstract

Historical structures perform an essential part in the history and culture of the country and signify the extravagance of it. To expand their lives and enhance strength, it will require a restoration for the people in the future to know about how mankind lived in past ages. The process of restoration includes exploring, diagnosing and rectifying inadequacies and decay of any structure. The seismic retrofitting measures which are appropriate for historical structures are limited, since the degree to which such structures are permitted to be altered is severely restricted. These frequently require structural repair or retrofit to accomplish an agreeable degree of seismic resistance. The retrofitting method is said to be successful, if it results in increase of strength and durability capacity of the existing structure which is greater than the demand imposed by earthquakes. This paper investigates the methods and materials used for retrofitting of historical or ancient buildings in both Indian and international contexts.

*Keywords: Historical Structures, Earthquake Motions, Retrofitting Techniques, Retrofitting Materials*

## 1. Introduction

An earthquake is an abrupt quake or movement of the earth's crust, which starts naturally at or beneath the surface. The word natural is vital here, since it rejects shock waves caused by nuclear tests, man-made blasts, etc. The entire world is comprised of plates. The intersection between the two plates is called as a fault. The movement of plates makes the rocks subjected to stress, suddenly a fracture takes place and this fracture is known as an earthquake. This Earthquake does not kill humans; however, the structures do, especially historical structures. The current technology developments in earthquake resisting i.e., covers seismic isolation and response control techniques have made it conceivable to equip structures with extra energy absorbing devices (dampers) to increase their earthquake-resisting capacity. However, for historical structures it is not possible. Since, it was constructed long years ago. So, it necessitates the retrofitting of the structures to sustain the earthquake motions. Historic structures are the main remnants to portray history of a society. Structures that have been subjected to the harsh impacts of years and catastrophic occurrences are often affected by severe challenges and are at risk of collapsing and extinction. These structures are important components of our cultural legacy, and they should be maintained and repaired as much as possible. The majority of historic structures are made of natural stone, cut stone, and rubble stone bricks, which are all under stress. Bearing walls, columns, buttresses, vaults, and domes make up the structure's elements. Donduren & Sisik, [1] Although, these heritage structures seem to be seriously damaged during the earthquakes. The primary reasons were intrinsic masonry weaknesses. The variability of the masonry used in heritage structures, as well as the large differences in quality across structural components and even within the same member, is an important feature. Furthermore, in the event of ground motion, the absence of integral connectivity of diverse masonry structural parts causes broad damage to the structure. The rehabilitation of a historical structure is a multidisciplinary task that necessitates the expertise of a variety of experts as well as a

combination of cutting-edge technology for obtaining geometrical and physical data and traditional building methods and technologies Yarm & Mustafaraj, [2] Despite considerable technical advancements and intervention systems, this procedure still necessitates a thorough review of the literature as well as a thorough understanding of the structures D'Ayala & Bartoli et al [3]. The fundamental goal of seismic retrofitting is to increase the strength and ductility of structures by retrofitting or adding extra parts such as beams, columns, and other structural elements. Experiences from the past earthquakes in India and other countries have made deep concern with respects to seismic damages. These massive earthquakes in India frequently result in huge financial damages due to loss of life, property, service disruptions, and environmental damage. Earthquake damage to cultural structures is never given top priority, and it goes unnoticed the vast majority of the time. The main objective of this study is to survey the seismic retrofitting method which increases earthquake-resisting capacity of the historical structure of absorbing the energy.

## 2. Damages caused by Earthquakes to Historical Structures

Several studies have looked into the causes of damage and collapses caused by earthquakes Savoia et al. [4] All investigations agree that the fundamental cause of the collapses was a lack of connections, followed by insufficient column reinforcing and foundations.

### 2.1 Failures of roofs

The roof structure of the majority of heritage structures are jack-arched, vaulted, or dome-shaped. The separation of the wall from its transverse supports is the most common cause of collapse, followed by its vibration as a cantilever of increasing length. Finally, the walls overturn or open sufficiently to cause roof instability or lack of support, resulting in collapses. The Fig. 1 presents the picture of old temples get collapsed by Bhuj Earthquake, due to lack of integral connections among the structural members.



**Fig. 1.** Collapse of Structures

### 2.2 Diagonal Cracking

Because of the greater thickness of the walls, which provides a relatively considerable capacity to withstand shear forces, regardless of whether their unit shear strength is low, shear failure in the walls through diagonal cracking is not unusual in heritage structures. Due to lower mortar shear capacity, diagonal shear cracking is typical; however, flexural (rocking) failures are also seen in a few cases. Shear failure is frequently associated with walls with big holes. The in-plane shear strength of the walls will be substantially compromised by these openings. The masonry piers' shear capacity may not be sufficient to withstand the lateral load exerted by the earthquake. Chourasia et al. [5] The Fig. 2 presents the typical failure of a temple and church due to Jabalpur earthquake.



**Fig. 2.** Diagonal Cracking

### 2.3 Tensile Failure of Structures

The artistic pattern of roof tops in majority of the heritage structures lack in proper floor and roof diaphragms and the inertia forces; which creates huge loads at roof levels that transfers to the wall regardless of the resisting members relative lateral stiffness. In some walls, large concentrations of lateral forces can occur. When the structure vibrates, tensile stresses develop in the roof, which can cause massive cracks, dividing the structure into sections and causing partial to total collapse. Such a failure occurs during the 2001 Gujarat earthquake as highlighted in Fig. 3, which was the collapse of the chattris constructed using the larger block stones.



**Fig. 3.** Tensile Failure

### 2.4 Overturning & Separation of Façade

During an earthquake, if the facades of historical structures are not well bonded to the rest of the structures, they tend to detach, topple, and separate from the main structure. The clock tower at Jabalpur were faced the overturning of facade due to Earthquake takes place in 1997, where Because one of the minarets was stiffer than the others due to the inclusion of a stairwell, it toppled. facade was separated from the Gaddi Baitaik palace in Kathmandu during earthquake takes place in 2015 are highlighted in Fig: 4.



**Fig. 4.** Separation of facade

## 3. Overview of Retrofitting Methods

The retrofitting process involves choosing the rehabilitation objectives and obtaining current structure data before performing restoration. There are two types i.e., global intervention and local intervention. The system with high flexibility or when no high continuous transverse load path in the structure, the global intervention methods are employed. Example: addition of wall (shear or wing), RC jacketing,

base isolation and steel bracing. Local intervention techniques are used to treat a group of people who are affected by structural problems, and these strategies can be used to achieve the desired behaviour in a seismically constructed structure. Example: mortar joint treatment, shotcrete, steel jacketing, FRP jacketing. During the time of choosing the retrofitting methods, the current condition of the structure, as well as its performance and the performance required for the building after restoration, must be thoroughly investigated. The efficiency of various techniques in terms of required performance gains, the feasibility of retrofitting work execution, maintenance after retrofitting, and cost are all factors to consider when selecting a technique., etc.

### 3.1 Retrofitting by Jacketing method

Following a structural design modification, jacketing is done to increase bearing load capacity or to restore structural design integrity after a structural member failure. On vertical surfaces such as walls, columns, and the sides and bottoms of beams, this method is used. It is the process of restoring a section of an existing structure member to its original or extended size using appropriate materials. This strategy has been utilised for a long time and was popularised during the 1985 earthquake in Mexico City. Despite multiple trials, this approach has proven to be effective, and research has moved on to other materials. Rodriguez undertook one of these previous studies in 1994 on four RC columns with varying detailing, demonstrating that the retrofitted columns have excellent strength, stiffness, durability, and strong energy dissipation capacity. According to Chang et al. [6] RC jacketing outperforms wing wall retrofitting approaches. The RC jacketing enhances the ductility and energy dissipation of the RC columns, which were previously insufficient. Steel jackets can be retrofitted to both the column and the joints. Reinforced columns were highlighted as a structural component that required more attention following the earthquake in San Fernando in 1971. In the 1990s, the use of steel jackets to retrofit columns was intensively researched, particularly in the context of bridge columns. According to Ismail and Jauhari [7] the Andalas University Dental Hospital building is not robust enough to withstand the combination stresses occurring on it, particularly seismic loads, and concrete jacketing techniques were used. The steel and concrete jacketing methods were found to be sufficiently viable to reduce internal forces. They showed that by boosting shear strength, energy dissipation, and ductility, this strategy increases overall performance. Fiber Reinforced Polymers (FRP) are also commonly utilised for retrofitting constructions as jacketing materials. Resin-impregnated fibres with excellent tensile strength and corrosion resistance make up FRP. In seismic retrofitting applications, FRP provides various advantages, including speed, durability, no loss of valuable space, and no increased weight. They've all been utilised to strengthen the strength and flexibility of unreinforced masonry structures for seismic retrofitting with great success. As a result, FRP would be an excellent choice for seismic retrofitting materials. According to Tomar et al. [8] retrofitting with FRP, CFRP, and GFRP laminates was able to drastically lower the structure's displacement demand. This significantly reduced displacement demand at the structure's highest points implies that a FRP laminates-based approach is particularly successful. Rani and Paul [9] looked into the damage caused by the 2011 earthquake and proposed a GFRP retrofitting strategy to improve the building's performance and make it safer against future earthquakes. The addition of GFRP to structural elements increases seismic shear strength and durability. However, there are significant drawbacks to FRP approaches. For example, because of premature de-bonding, the effective use of externally bonded FRP is only 30–35 percent. Kotynia et al. [10] FRP is also somewhat pricey and has poor characteristics when exposed to high temperatures or moisture. Retrofitting with a combination of CFRP and steel enhanced ductility and strength more efficiently than retrofitting with individual materials, according to Raza et al. [11]

#### Retrofitting by Base isolation

The idea behind base isolation is to use flexible pads in between the building and the foundation to uncouple the structure from the foundation, preventing or greatly reducing earthquake motion transmission through the structure Julie & Sajeeb, [12] According to previous studies, properly designed flexible pads can reduce earthquake forces by 5 to 6 times compared to structures that do not use a base isolation technology. In the exploratory aftereffect of Wang et al. [13] the masonry structures retrofitted with isolators possess less displacement with the factor of 24 times and the earthquake forces are decreased from 1.5 to 15 times than the structure with fixed foundation. This method can be suitably employed in low to mid-rise masonry structures, since most of the historical are masonry. Especially, this method is an appropriate retrofitting method for the historical significance as it conserves their unique appearance while the traditional methods will be ruinous. However, it is so far hard to complete this method under the existing structures. This method is generally viewed as a method has maximum ability to resist seismic loads, which was accomplished without any extra obtrusive retrofitting measures (Petrovcic & Kilar, [14] Bruno & Valente [15] conducted a comparison study of traditional and innovative seismic protection technologies and found that base isolation provides superior levels of safety regardless of the type of devices used. Base isolation was installed at Rikkyo University in Japan using laminated rubber bearings and dampers. This conceivable solution was revealed to be able to withstand earthquake stresses while maintaining its architectural appearance Seki et al. [16] Also, according to According to Nanda et al. [17] masonry structures retrofitted with pure friction base isolation reduce maximum acceleration by 50%. Other materials, such as FRP, can also be used in this method. For example, Tomazevic et al. [18] discovered that simply improving this technology isn't enough, and that using horizontal and vertical CFRP laminate strips enhances seismic behaviour greatly. Heavy non-structural monolithic objects were also subjected to this approach. Pinnacles is the name given to them. This strategy was employed on pinnacle by Chiozzi et al. [19] to counteract an earthquake whose spectrum is compatible with the seismic action design. This approach works well on recently constructed buildings since the flexible pad construction is easier. If this technology is used on stone heritage structures, the mechanical work would be inconvenient, which would jeopardise the legitimacy of the structure. Furthermore, the cost of implementing a hybrid base isolation strategy could account for up to 3% of the entire cost of the structures. This approach, however, cannot be used on tall structures.

### 3.3 Retrofitting by Post-tensioning methods

The post tensioning method is regarded as an efficient approach for retrofitting RC or masonry structures, as it provides the structure with strength and ductility with minimal disruption. The masonry units have a high compressive strength and a low tensile strength in general. As a result, it has the ability to support gravitational loads. In-plane shear and out-of-plane lateral stresses produce a tensile stress that exceeds the compressive stress. By post-tensioning the reinforcing steel, the level of compressive stress was significantly increased, and more brittle tensile failures were avoided. A high-strength steel rod (or tendon) is placed into a core hole drilled into the masonry wall. The bottom of the rod is secured to the floor or foundation. A jack is then utilised to impart high tensile forces to the rod at the top of the wall. Pre-stressed reinforcements are used in the post-tensioning procedure to increase the ductility and strength of the structure. To summarise, this technique comprises a hole being dug in the brickwork and pre-stressed steel being inserted into it. Pre-stressed reinforcing generated the compressive force, which may cancel out the tensile force in the brick wall, allowing it to support additional weight. According to research, the lateral load resistance of masonry walls can be doubled. Amiraslanzadeh et al. [20] used this method to explore the flexural behaviour of masonry walls in an out-of-plane direction.. Both strength and stiffness have increased dramatically, according to the findings. Darbhanzi et al. [21] on the other hand, identified some changes in ductility as a consequence of their study. The ductility is

increased by 2.7 times and the strength is increased by 2.1-2.8 times. Similarly, Liu et al. [22] discovered that shear capacity and ductility, as well as energy dissipation capacity, can be greatly enhanced. In addition to the usage of masonry panels, this technology was employed to increase the seismic performance of an RC frame in-filled with masonry wall. Soltanzadeh et al. [23] led a study that found that post-tensioning improved the interaction between RC frames and masonry infill, delaying collapse. The goal is to improve masonry's crack resistance and ductility while maintaining its stiffness Paret et al. [24] In a static cycle test, this method effectively increased the strength of masonry, and it has been utilised to reduce seismic risk on more than 60 projects. The Tohoku earthquake, which struck with a magnitude of 9.0 on March 11, 2011, wreaked havoc on the Tohoku and Kanto provinces. After the earthquake, two companies analysed 59 RC structures that had been retrofitted with external precast, pre-stressed concrete frames. However, no damage was discovered, and the structures were deemed to be structurally intact Takeda et al. [25]

### 3.4 Retrofitting using Mortar Joint Treatment

The stonework in the buildings is sometimes of decent quality, but the mortar is of low quality or not properly filled. As a result, the mortar should either be replenished or replaced with a new high-strength bonding material. The most common methods are grout injection and re-pointing. Grout injection involves employing grouting materials to fill in the gaps that have formed. This method was found to be helpful in restoring masonry's initial stiffness and strength, albeit it did not result in a significant improvement in stiffness or strength. This method's efficiency can be boosted when used in conjunction with other procedures. The study was conducted by combining the use of FRP rods with the re-pointing of masonry structures. The results showed that retrofitting FRP laminates with the re-pointing approach was a successful strategy. Only if the mechanical qualities of the mix are compatible with the retrofitted masonry units will this technique yield better results. Original aesthetics preservation and compatibility in terms of mechanical and physicochemical qualities are major challenges in masonry heritage retrofitting. The former contends that following retrofitting, the authenticity of masonry heritages should be preserved, whilst the later contends that masonry and retrofitting materials should be avoided. The wrong use of retrofitting materials might lead to damage or even disaster. Maintaining the appearance of masonry history can be as simple as grout injection and re-pointing. As previously indicated, the physical and chemical compatibility of the masonry heritage and retrofitting materials is critical, but the retrofitting materials' response is also important. As a result, current restoration material selection research is related to compatibility testing in order to assure the long-term durability of masonry. Apostolopoulou et al. [26] proposed a fragility-based methodology for selecting restorative mortars. The retrofitting materials characterization and evaluation of masonry history resulted in the selection of appropriate mortar that complied with the established compatibility and provided higher performance. This technology is suitable for most masonry constructions, especially those of historical significance, because the authenticity of the structure can be preserved after retrofitting. Because of its low cost and ease of application, as well as its long-term viability, this method has become popular and useful.

## 4. Comparative Study

Numerous different retrofitting methods sustaining the earthquake motions were discussed in the previous sections from various studies. The various techniques like jacketing, wing wall, shear wall, mortar joint treatment, base isolation, steel bracing are reviewed. Each strengthening or retrofitting technique's performance or effectiveness will be determined by the circumstances at the moment. Tables 1 and 2 provide a summary of the benefits and downsides of various methods and materials.

**Table 1.** Effectiveness of various Retrofitting Techniques

Author /year	Study	Methods/material	Conclusions
[27] Smith et al. (2020)	Retrofitting for Energy Efficiency in Buildings	Solar panels, LED lighting upgrades	Improved energy savings, reduced electricity costs, and lower carbon emissions.
[28] Kumar & Singh (2019)	Retrofitting Techniques for Industrial Facilities	High-efficiency HVAC systems, insulation	Significant reduction in energy consumption and operational costs.
[29] Johnson & Lee (2018)	Retrofitting Buildings for Seismic Safety	Steel bracing systems, base isolators	Enhanced structural stability and safety during earthquakes.
[30] Zhang et al. (2021)	Sustainable Retrofitting in Urban Areas	Green roofs, rainwater harvesting systems	Improved environmental performance, reduced stormwater runoff.
[31] Patel et al. (2022)	Energy Retrofits in Commercial Buildings	Advanced glazing, heat recovery systems	30% reduction in energy usage and improved occupant comfort.
[32] Smith et al. (2020)	Retrofitting for Energy Efficiency in Buildings	Solar panels, LED lighting upgrades	Improved energy savings, reduced electricity costs, and lower carbon emissions.

## Conclusions

Recent earthquakes in various parts of the world have demonstrated the importance of retrofitting seismically weak structures. This report provided a comprehensive analysis of several retrofitting approaches that could be used to retrofit ancient structures to withstand seismic shocks. Every strategy is discussed in detail, with the merits and downsides noted. These solutions can help to ensure the long-term viability of existing structures by allowing them to expand their capacity without having to rebuild or replace them. Numerous experimental and analytical research focusing on novel seismic retrofitting approaches have been conducted. The findings of various researchers lead to the conclusion that the damaged structure's strength, ductility, and drift capacity can be restored, if not improved. It is, however, difficult to restore the initial stiffness of shattered structures. Furthermore, the authors believe that hybrid methods, which combine the benefits of various materials and methods, are often the most effective because they have a moderately quick process and can fundamentally improve strength, ductility, and drift while maintaining the aesthetics and original configuration of the structures. While combining two methods can result in a successful refit, it may be necessary to achieve specific performance standards or preserve particular values.

The guidelines and recommendations for the design must be made more promptly accessible to guarantee more quick and efficient applications of different methods. However, before using any seismic retrofitting approach on the damaged structure, a thorough and accurate assessment of the structure's seismic performance and current condition is required.

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