

Advanced Retrofitting Techniques for Reinforced Concrete Structures: A State of an Art Technical Review

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ABSTRACT: Any technology or material has its limitations and to meet the new requirements, new technologies have been invented and used over the ages. A large number of reinforced concrete structures located at seismic prone areas are not capable of withstanding earthquakes according to the current code provisions. Furthermore the seismic behaviors of the existing buildings are affected due to design deficiency, construction deficiency, additional loads, additional performance demand, etc. Recent earthquakes have clearly demonstrated an urgent need to upgrade and strengthen these seismically deficient structures. The retrofitting is one of the best options to make an existing inadequate building safe against future probable earthquake or other environmental forces. Retrofitting reduces the vulnerability of damage of an existing structure during a near future seismic activity. It aims to strengthen a structure to satisfy the requirements of the current codes for seismic design. A significant amount of research work has been carried out in recent years to develop various strengthening and rehabilitation techniques to improve the seismic performance of structures. This paper aims to present an overview on different innovative and cost effective techniques of retrofitting for strengthening the damaged structures.

Seismic protection of buildings is a need-based concept aimed to improve the performance of any structure under future earthquakes. Earthquakes of varying magnitude have occurred in the recent past in India, causing extensive damage to life and property. Some recently developed materials and techniques can play vital role in structural repairs, seismic strengthening and retrofitting of existing buildings, whether damaged or undamaged. The primary concern of a structural engineer is to successfully restore the structures as quickly as possible. Selection of right materials, techniques and procedures to be employed for the repair of a given structures have been a major challenges. Innovative techniques of the structural repairs have many advantages over the conventional techniques. Some guidelines regarding selection of materials for repair work such as steel, fiber reinforced polymer, has been discussed in the present paper. The selection of materials and techniques to be used depend on many aspects that may be viewed from different perspective. i.e. requirement and availability of financial resources, applicability and suitability of materials for the repair of damaged structures. Use of standard and innovative repair materials, appropriate technology, workmanship, and quality control during implementation are the key factors for successful repair, strengthening and restoration of damaged structures.

The retrofit process is a general term that may consist of a variety of treatments, including: preservation, rehabilitation, restoration and reconstruction. Selecting the appropriate treatment strategy is a great challenge involved in the retrofit process and must be determined individually for each project. Depending on project objectives, preservation and renovation of buildings may involve an array of diverse technical considerations, such as fire life safety, geotechnical hazards and remedies, weathering and water infiltration, structural performance under earthquake and wind loads.

KEYWORDS: Retrofitting, Treatments, jacketing, Rehabilitation, Cracks, Corrosion, Preventive Measures, Epoxy, Grout, confinement, jacketing, fibre reinforced polymer jacketing, steel jacketing, beam jacketing, Retrofitting, Base Isolation, Retrofitting Techniques, Jacketing, Earthquake Resistance.

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I. INTRODUCTION

Preservation is defined as the process of applying measures to sustain the existing form, integrity, and materials of a historic property. Rehabilitation refers to the process of creating new application for a property through repair, alterations and additions while preserving those features which convey it's historical, cultural, or architectural values. Restoration is the process of accurately restoring a property as it existed at a particular period of time. Reconstruction is described as the act of replicating a property at a specific period of time.

Rehabilitation provisions require selecting the rehabilitation objectives and acquiring current building information prior to performing rehabilitation design. At the stage of selecting the retrofitting method, the current status of the existing structure and its performance are known, and the performance required for the structure after retrofitting. Factors that should be considered in selecting the method include the effectiveness of the various retrofitting methods with respect to the required performance improvements, the viability of execution of the retrofitting work, the impact of the retrofitting work on the surrounding environment, the ease of maintenance after retrofitting, economy and other factors.

Retrofit in structures is done to increase the survivability functionality. The applications include different types of bridges, buildings, and industrial structures, transport structures in urban areas, earth retaining structures and marine structures.

II. TYPES OF RETROFITTING OF CONCRETE MEMEBRS

Various retrofitting techniques namely global and local retrofitting techniques are adopted to achieve desired solution for an existing structure. Parametric analysis has been carried out to obtain most feasible solution by considering various parameters such as nodal displacement, storey drift and base shear. Classification of Retrofitting Techniques:

- Adding New Shear Walls:
 - Adding Steel Bracings.
 - Jacketing (Local Retrofitting Technique):
 - Base Isolation (or Seismic Isolation):
 - Mass Reduction Technique of Retrofitting:
 - Wall Thickening Technique of Retrofitting:
-
- Continuous fiber reinforced plate bonding construction method: Bonding continuous fiber reinforced plates to the surface of the existing structure to restore or improve load-carrying capacity
 - Continuous fiber reinforced plate jacketing construction method: Jacketing with continuous fiber reinforced plates around the periphery of the existing structure to restore or improve load-carrying capacity and deformation characteristics
 - Prestressed concrete jacketing construction method: Placing prestressing wires and prestressing stranded steel wires in place of lateral ties around the periphery of existing member sections and using mortar and concrete to bond them in order to reinforce the structure.
 - Prestressing introduction construction method: Using internal cables for the existing concrete members to provide prestressing and restore or improve the load carrying capacity of the members.
 - Repaving method: Replacing some or all of the existing concrete members with new members through the use of precast members or concreting on site to restore or improve load-carrying capacity

III. PRINCIPLES OF RETROFITTING DESIGNS

The principles of retrofitting design for buildings are:

- Strengthening of members versus strengthening of structural system. The members that do not meet safety requirements must be strengthened; however there is often an underlying mistake that the strengthening of whole

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structural system is neglected. Strengthening of connection between members is quite influential to structural integrity.

- Local strengthening versus global strengthening. Local strengthening of an individual member can be carried out only if the strengthening does not affect the structural performance of the whole system.
- Temporary strengthening versus permanent strengthening. The standards and requirements for temporary strengthening may be lower than those for permanent strengthening.
- Special considerations for earthquake resistant strengthening.
- To use new seismic technologies.

IV. SELECTION OF THE PROPER RETROFITTING MEASURE

Proper studies of the existing structure using various analytical tools need to be carried out to identify the weak zones within the structure prior to carrying out retrofitting works. It also helps in the selection of proper retrofitting measure that should be adopted in terms of economic and safety aspects.

Buildings structures lying in acceleration sensitive region and velocity sensitive region of the spectrum may require different retrofitting measures. Retrofitting option suitable for one structure may prove to be inefficient for another structure with different dynamic behaviour.

Also, after retrofitting, stiffness of an abuilding structure may increase significantly, thereby increasing a load demand on the structure than before retrofitting. Increase in stiffness also depends on the type of the retrofitting measure carried out. Conventional retrofitting measures as steel/concrete jacketing and inclusion of new walls are likely to increase the stiffness of the structure significantly; thereby altering its dynamic behaviour. In such re-analysis of the retrofitted structure shall be carried out. Modern jacketing technique such as fibre reinforced polymer (FRP) wrapping could be the best way to strengthen the capacity of structures without altering stiffness.

Besides the increment in stiffness of the structure, major repercussion in the conventional method of retrofitting could be the development of new load paths that may lead to concentration of loads at the foundation level. This happens in reinforced concrete (RC) frame structures, where inclusion of concrete shear walls in between the columns is carried out as a retrofitting measure. In such, existing foundation of the adjoining columns is likely to get overstressed.

Selection of the proper retrofitting technique shall be done by carrying out the detail analysis of the existing structure. Re-analysis including Re-design of the structure may be required after the introduction of retrofitting measures, so that the objectives of seismic retrofitting is me

V. RETROFITTING OF DESIGN PRINCIPLES

Design principles, even in case of retrofitting, as in case of new construction shall follow several factors. For instance in order to have a full advantage of the potential ductility of retrofitted RC members; it is desirable to ensure that flexure rather than shear govern ultimate strength. Shear failure is catastrophic and occurs with no advance warning of distress. Most of the existing RC columns and beams have been found deficient in shear strength and in need of strengthening. Shear deficiencies occur due to several reasons such as insufficient shear reinforcement or reduction in steel area due to corrosion, increased service load, Design principles in older codes and construction defects.

As far as possible design principle in case of retrofitting shall be to improve Shear, Bending, Axial and Ductile capacity of structural members and the structure as a whole. Most of the existing practices seem to provide increased confinement of the structural members-mainly increasing axial, shear and ductile behaviour. Increase in bending capacity could also be achieved if proper detailing and design principle is followed

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VI. GENERAL DEFICIENCIES IN REINFORCED CONCRETE (RC) STRUCTURES

There are three basic types of structural deficiency encountered in reinforced concrete constructions. These are Design, Detailing and Construction deficiencies:

✚ Design Deficiencies Include

- Inadequate provisioning of lateral load resisting members (e.g.; lack of shear walls or special moment-resisting frames)
- Lack of redundancy (alternative load paths) in the structural system (i.e; the beams and columns are sparse, or improperly located, such that a total structural collapse is triggered in the event of damage to only a few members)
- Irregularities in plan or elevation (e.g.; L or T – shaped plan, or vertical setbacks)
- Presence of soft or weak storeys, especially at the ground floor, as in the case of tall first storeys with large openings for doors and windows
- Presence of short columns, which usual fail in a specific pattern that is catastrophic
- Presence of overhangs
- Strong-beam weak-column joints, that is, cases where the beams are stronger than the columns they connect to. The problems is that damage at such connections tends to occur in the columns rather than the beams, and since the floors above the column rely on the column more than on the beam; and column damage can be more catastrophic than beam damage.

✚ Key Detailing Deficiencies Include

▪ Inadequate Transverse Reinforcing Bars

These are the smaller steel reinforcing bars running perpendicular to the axis of the beams and columns. Transverse reinforcement provides resistance against shear forces and imparts confinements to concrete within. This confinement increases the ultimate strength of concrete, and enables a beam or column to accommodate more damage without failing catastrophically. It is especially important to avoid wide spacing of transverse bars near beam-column joints. Modern design codes provide specific provisions for narrower transverse reinforcement spacing.

▪ Short overlap length at spliced joints

These are locations where one of the reinforcing bars that run longitudinally along, say a column ends and overlaps with another that continues farther along the column, as in the bottom portion of the column. If the overlap is too short, the force in one bar cannot be adequately transferred to the next one, which produces a generally unanticipated weak point in the column.

▪ Construction Deficiencies Include

Adverse conditions such as those listed above may be further aggravated by construction deficiencies, such as low – quality workmanship, use of inferior materials, and deviations from structural drawings and specifications during the construction phase.

VII. SPECIAL CONSIDERATIONS FOR EARTHQUAKE SAFETY

During earthquakes, acceleration would be higher at the upper storeys of the load bearing wall structured buildings. Due to this, wall panels at the top level are highly vulnerable, both in out - of plane and in – plane.

Also, at upper floors, the compressive stress in brick masonry due to dead load from upper storeys would be minimum than in lower storeys, hence lower shear strength of such masonry walls at upper storeys. In earthquakes, upper storey failures are more likely to occur in a load bearing wall system, so retrofitting measures shall be carried out in upper floors in much more details manner.

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Masonry walls with large window/door openings, without lintel/sill bands are the weaker ones stress concentrations at such window/door openings corners may take place and failure is more likely to initiate through these locations. Also, out – of – plane loading can severally damage and even cause collapse due to lack of rigidity in such walls? To strengthen such wall panels, window/door openings could be replaced by the solid walls or steel bands, channels could be provided from both sides of the wall running throughout the openings periphery.

Likewise, horizontal bands of steel wire mesh at the sill and lintel levels could be provided from both sides depending upon the wall's thickness. These actions would significantly enhance performance of brick masonry walls and overall structure's performance too besides, in masonry structures, masonry walls should also be checked for the development of in – plane shear stresses that could occur during an in –plane earthquake loading and suitable jacketing measures shall be employed to strengthen it as per the requirement.

VIII. RETROFITTING OF CONCRETE MEMBERS

- Continuous fiber reinforced plate bonding construction method: Bonding continuous fiber reinforced plates to the surface of the existing structure to restore or improve load-carrying capacity
- reinforced plate jacketing construction method: Jacketing with continuous fiber reinforced plates around the periphery of the existing structure to restore or improve load-carrying capacity and deformation characteristics
- Pre-stressed concrete jacketing construction method: Placing pre-stressing wires and pre-stressing stranded steel wires in place of lateral ties around the periphery of existing member sections and using mortar and concrete to bond them in order to reinforce the structure.
- Pre-stressing introduction construction method: Using internal cables for the existing concrete members to provide pre-stressing and restore or improve the load carrying capacity of the members.
- Repaving method: Replacing some or all of the existing concrete members with new members through the use of precast members or concreting on site to restore or improve load-carrying capacity.

IX. RETROFITTING AS STRUCTURAL BODY TO INCREASING THE CAPACITY OF CONCRETE MEMBERS

- **Beam addition method:** Adding beams between the main girders of the existing reinforced concrete deck to reduce the deck span and restore or improve the load carrying capacity of the reinforced concrete deck.
- **Seismic wall addition method:** Placing new reinforced concrete walls between existing reinforced concrete rigid-frame bridge piers and bonding them to form a continuous unit in order to restore or improve the load carrying capacity as a structural body.
- **Support point addition method:** Supporting the intermediate sections of the beams and other existing concrete members with new members to reduce the span of the members in order to restore or improve the load carrying capacity as a structure.

Seismic Isolation method: Using seismic isolation bearings and the like to reduce the seismic energy applied to the structure in order to improve its various performance values during an earthquake.

X. RETROFITTINGS FOR FOUNDATIONS

- Underground wall (beam) addition method: Connecting the foundations with cast-in-site diaphragm walls and underground connecting beams to distribute stress and ensure the stability of the entire system.
- Pile/footing addition construction method: When pile foundations are damaged or there is residual displacement, adding piles or footings to increase the load-carrying capacity of the foundation.

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- Foundation improvement method: Improving the ground around the foundation with cement improvement materials to improve the ground bearing capacity and horizontal foundation resistance. Also prevents excessive pore water pressure and liquefaction.
- Steel sheet-pile coffering construction method: Placing sheet-piles around the periphery of the footings and bonding them to the footings to improve bearing capacity and horizontal resistance.
- Foundation compacting method: When insufficient foundation bearing capacity is a concern due to scouring or the like, using concrete or the like to compact the ground around the foundation in order to restore bearing capacity.
- Ground anchor method: When bridge abutments or the like move or tilt laterally as a result of an earthquake, etc., using ground anchors to stabilize the bridge abutments.

XI. REPAIRS OF CRACKS

- Crack fills method: Forcing low viscosity resin and ultra-fine cement into the cracks in existing concrete members to seal the cracks.
- Fill method: Filling cracks, rock pockets, cavities, peeling and other small-scale missing sections in existing concrete members with resin and mortar to repair sections.
- Section repair method: Removing deteriorated or damaged portions of existing concrete.

XII. HISTORICAL BUILDING

Buildings with historic value are regional cultural assets worth preserving. Minimizing noise, disturbance, and damage to the surrounding buildings and providing temporary shoring and support are typical challenges involved in most retrofit projects. Depending on the extends of retrofitting, assessed risk, technical limitations, structural historic value, and economical constraints, the preferred retrofit strategies are studied to preserve the authenticity of historic fabrication and minimize removal of architectural material:

No penetration of Building Envelope

The process does not require any destructive procedure so the historic fabrication remains untouched. This approach is only applicable to very limited cases since structural components are mostly either embedded in or covered by the finishing.

Penetration without Breakage

The structural component subjected to retrofitting is accessible, and the retrofit process only requires drilling holes.

Breakage with Repair

In many cases, some destructive procedures are required to access the structural component or to perform retrofit process.

Replace

In cases structural components cannot be improved to meet retrofitting objectives or the damage or deterioration could not be repaired, components are replaced.

Rebuild

In cases a feasible retrofitting solution cannot be found, the historic building is reconstructed, partially or as a whole.

XIII. INNOVATIVE TECHNOLOGIES FOR HISTORIC PRESERVATIONS

The preservation of heritage architecture is a cultural objective rigorously pursued by communities and nations wishing to promote their history, civilization and aesthetic achievements. Structures built in the remote past by traditional methods have suffered the consequences of extreme loading events, such as earthquakes, over long time

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periods. Retrofitting is an approach based on recent technological developments and scientific knowledge, whereby modern construction methods and materials are applied to the repair and strengthening of historical structures. The use of reinforced concrete is proposed in the form of cast-in-place walls, jackets or tie-beams; that of carbon fibre reinforced laminates for strengthening walls and slabs. Innovative use of materials, such as shape memory alloys, self-compacting concrete or thin lead layers is also suggested. Particular attention is given to methods for moderating the consequences of destructive earthquakes. Seismic energy absorbing devices and base isolation systems are two effective means of providing protection against future seismic events although their application is often met with many technical challenges in practice.

Modern materials and equipment provide many retrofit options to improve the behavior of structural system, global strength, and stiffness or mitigate the seismic hazards. Some of the commonly used techniques in retrofitting are listed below:

✚ Post Tensioning

Post tensioning (fig1) is considered one of the potentially efficient retrofit options for reinforced concrete or masonry buildings. Masonry has a relatively large compressive strength but only a low tensile strength. Hence, it is most effective in carrying gravity loads. Commonly, induced tensile stresses exceed the compressive stresses and reinforcing must be added to provide the necessary strength and ductility.



Figure No. 1 External Post Tensioning



Figure No. 2 External Post Tensioning to restore
Or increase capacity

✚ Composite Wraps

Composite wraps or carbon fiber jackets are used to strengthen and add ductility to reinforced concrete and masonry components without requiring any penetration. Composite wraps are most effective on reinforced concrete columns by providing additional confinement.



Figure No. 3 Carbon FRP fibre installation and Composite Strengthening services



Figure No. 4 FRP composite Strengthening with Concrete solutions

✚ Micro-piles

Micro-piles are utilized in foundation rehabilitation and seismic retrofitting projects to enhance the foundation ultimate Capacity and reduce foundation deflection.

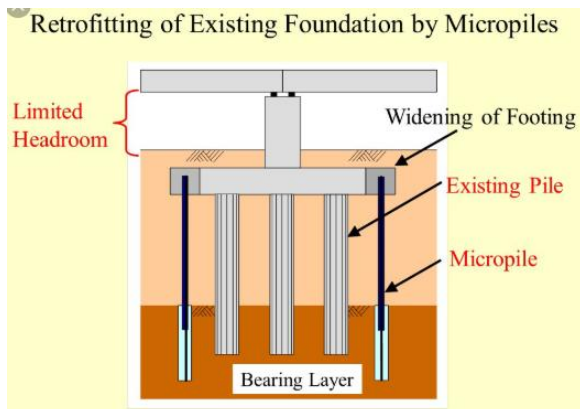


Figure No. 5 Model Foundations Retrofitted

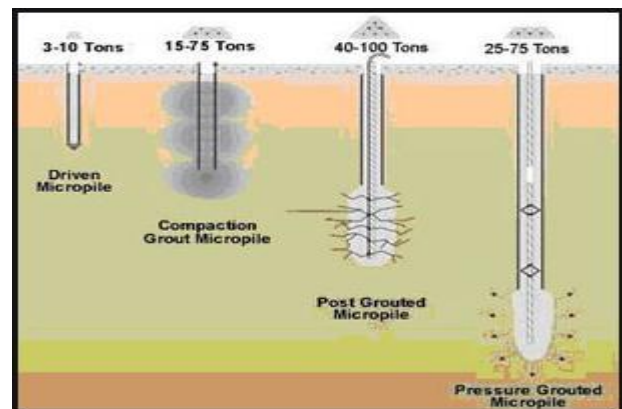


Figure No. 6 Micro Pile Foundations With Micro Piles

✚ Epoxy

Epoxy is one of the most versatile materials used in structural repair and retrofitting and it is used as a sealant, adhesive or mortar.

XIV. SEISMIC RETROFITTING TECHNIQUE

Seismic retrofitting is the modification of existing structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes. With better understanding of seismic demand on structures. Retrofitting of existing structures with insufficient seismic resistance accounts for a major portion of the total cost of hazard mitigation.

Thus, it is of critical importance that the structures that need seismic retrofitting are identified correctly, and an optimal retrofitting is conducted in a cost effective fashion. Once the decision is made, seismic retrofitting can be performed

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through several methods with various objectives such as increasing the load, deformation, and/or energy dissipation capacity of the structure. Conventional as well as emerging retrofit methods are briefly presented in the following subsections.

Seismic Retrofitting Techniques are required for concrete constructions which are vulnerable to damage and failures by seismic forces. In the past thirty years, moderate to severe earthquakes occur around the world every year. Such events lead to damage to the concrete structures as well as failures. Thus the aim is to focus on a few specific procedures which may improve the practice for the evaluation of seismic vulnerability of existing reinforced concrete buildings of more importance and for their seismic retrofitting by means of various innovative techniques such as base isolation and mass reduction. So Seismic Retrofitting is a collection of mitigation techniques for Earthquake engineering. It is of utmost importance for historic monuments, areas prone to severe earthquakes and tall or expensive structures.

- Earthquake creates great devastation in terms of life, money and failures of structures.
- Upgrading of certain building systems (existing structures) to make them more resistant to seismic activity (earthquake resistance) is really of more importance.
- Structures can be (a) Earthquake damaged, (b) Earthquake vulnerable
- Retrofitting proves to be a better economic consideration and immediate shelter to problems rather than replacement of building.

✚ Need for Seismic Retrofitting

- To ensure the safety and security of a building, employees, structure functionality, machinery and inventory
- Essential to reduce hazard and losses from non-structural elements.
- Predominantly concerned with structural improvement to reduce seismic hazard.
- Important buildings must be strengthened whose services are assumed to be essential just after an earthquake like hospitals.

✚ Problems faced by Structural Engineers are

Lack of standards for retrofitting methods – Effectiveness of each method varies a lot depending upon parameters like type of structures, material condition, amount of damage etc.,

✚ Basic Concept of Retrofitting

- Upgradation of lateral strength of the structure
- Increase in the ductility of the structure
- Increase in strength and ductility

✚ Classification of Retrofitting Techniques

Retrofitting Techniques		
Global Methods	Local Methods	Latest Innovative Techniques
Adding Shear Wall	Jacketing of Beams	Epoxy Resins
Adding Infill Wall	Jacketing of Columns	FRP (Fibre Reinforced Polymers) Coatings
Adding Bracing	Jacketing of Beam - Columns Joints	Composite Retrofitting System
Adding wing wall	Strengthening of Individual Footings	
Wall Thickening		
Mass Reduction		
Base isolation System		
Mass Dampers		
Steel Braces		

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XV. RETROFIT OF STRUCTURES USING MODERN MATERIALS

Current research on advanced materials in civil engineering is mainly concentrated on high performance concrete and steel, and fibre reinforced plastic (FRP) composites. FRP composite materials have experienced a continuous increase of use in structural strengthening and repair applications around the world in the last fifteen years. High specific stiffness and specific weight combined with superior environmental durability of these materials have made them a competing alternative to the conventional strengthening methods. It was shown through experimental and analytical studies that externally bonded FRP composites can be applied to various structural members including columns, beams, slabs, and walls to improve their structural performance such as stiffness, load carrying capacity, and ductility. FRP composites have enjoyed varying degrees of success in different types of applications.

In general, applications that allow complete wrapping of the member with FRP have proven to be effective. Wrapping of columns to increase their load and deformation capacity is the most effective and most commonly used method of retrofitting with composites. However, certain performance and failure mode issues regarding different wrapping configuration and fibre orientations, still need to be well understood. When wrapping is difficult or not allowed, such as when strengthening beams, slabs, or walls, success of the method is sometimes hindered by premature de-bonding failures. The performance of beams strengthened using pultruded FRP plates in various configurations.

Limited research and applications regarding seismic retrofitting of building systems with FRP composites have shown that a composite retrofitting does not significantly alter the stiffness and dynamic properties of the building. The main benefit of retrofitting with composites is the increase in deformation capacity of the building, and in its load capacity to an extent. This may achieve the retrofit objectives for buildings with lightly insufficient seismic resistance. For buildings with large seismic deficiencies, a combination of conventional and FRP strengthening techniques may prove to be an effective retrofitting solution.

As a practical and economical solution, the retrofit design involved replacement of the existing window frames with structural steel frames constructed from steel C-sections. A verification analysis of the retrofitted building showed that installation of steel window frames largely decreased the stress concentrations, but did not suffice to reduce all stresses to acceptable levels. For this reason, additional retrofitting was designed using externally bonded FRP composites around the openings in the walls to prevent or delay concrete crack propagation by bridging the stresses at crack locations. Thus, by combining conventional and innovative materials, an effective and economical retrofit design was achieved that did not significantly interfere with the function or historical and architectural character of the building. FRP composites are widely recognized for their potential use in seismic retrofitting applications. To achieve wide-range use of these materials, however, there is need for further research into a number of issues related to mechanics, design, and durability of FRP retrofitted concrete and steel systems. Despite considerable progress in these areas since early last decade further improvements are necessary to meet the needs of the retrofit industry. Failure mechanisms, with emphasis on brittle shear and de bonding failures, must be thoroughly understood and associated design procedures must be incorporated in design codes.

Influence of cyclic and fatigue loading on the FRP strengthened member performance must be characterized and accounted for in the design process. Although FRP composites are known for their favourable durability characteristics, only limited information is available on long-term durability and performance of FRP bonded concrete and steel systems. These issues need to be investigated through accelerated test studies and related design, application and protection requirements must be included in the design codes.

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XVI. SAMPLE CASE STUDIES FOR VARIOUS TYPES OF RETROFITTING TECHNIQUES

Case Study 1: Adding Infill walls (Shear Walls):

Adding concrete walls by infilling certain frame bays with reinforced concrete is popular for seismic retrofitting, but is covered by codes only if the connection of the old concrete to the new ensures monolithic behaviour. To avoid penalizing the foundation of the new wall with a very high moment resistance, the new concrete should not be thicker than, or surround, the old frame members. A cost-effective connection of these members to a thin new web was proposed by *Fardis et al, 2013*, alongside a design procedure and detailing that conform to current codes. Owing to practical difficulties, footings of added walls are often small and weakly connected to the other footings; hence they uplift and rock during the earthquake. Added concrete walls are very popular for seismic retrofitting of concrete buildings. A simple and cost-effective way of adding walls is to infill with reinforced concrete (RC) selected bays of the existing frame, especially on the perimeter. Although the method is widely applied, there are still open issues about the retrofit design and certain aspects of the seismic response of the retrofitted building.

Addition of new RC walls is one of the most common methods used for strengthening of existing structures. This method is efficient in controlling global lateral drift, thus reducing damage in frame members. During the design process, attention must be paid to the distribution of the walls in plan and elevation (to achieve a regular building configuration), transfer of inertial forces to the walls through floor diaphragms, struts and collectors, integration and connection of the wall into the existing frame buildings and transfer of loads to the foundations. Added walls are typically designed and detailed as in new structures. To this end, in the plastic hinge zone at the base they are provided with boundary elements, well-confined and detailed for flexural ductility. They are also capacity designed in shear throughout their height and overdesigned in flexure above the plastic hinge region (with respect to the flexural strength in the plastic hinge zone, not the shear strength anywhere), to ensure that inelasticity or pre-emptive failure will not take place elsewhere in the wall before plastic hinging at the base and that the new wall will remain elastic above the plastic hinge zone.



Figure No. 7 Adding Shear Walls to existing structures

Case Study 2: Polymer Concrete Composite

Another development in the concrete field is the use of polymer concrete (PC). PC are made from a polymer binder (usually a thermosetting polymer) mixed with a mineral filler; either sand (for mortar), or aggregates, gravel or crushed stone (for concrete). The material has several advantages such as high strength, low permeability, excellent resistance to chemicals and abrasion, and good adhesive properties. However, its disadvantages are cracking due to restrained volume changes, poor resistance to ultra-violet light, creep at high temperature, and additional cost.

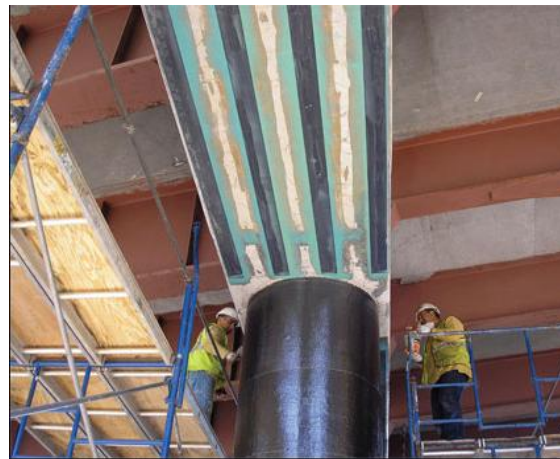


Figure No. 8 Adding Shear Walls to existing structures

It is used in the resurfacing deteriorated structures and as a compound in the repair of concrete structures. Even though it presents several advantages PC is more expensive and does not solve the extensive labour issue of using regular concrete.

Case Study 3: Concrete Jacketing and Section Enlargement

Section enlargement consists in placing additional concrete around an existing structural element to increase its seismic resistance. This is the oldest method of seismic retrofitting. Typical applications include bridge deck, column wrapping, and joint strengthening. This method is easy and economically effective, but labor intensive. Adding traditional concrete has been used as a means of retrofit for many years. It is used to reinforce columns either by themselves or in the context of retrofitting gravity designed frames. It can also be used for other structural features such as foundation. It is used mainly when strengthening is needed. As discussed earlier, columns are one of the structural elements that are often in need of retrofit in both buildings and bridges. This method has been used for a number of years and was, for example, widely applied after the 1985 earthquake in Mexico City. Numerous studies have been done in the past but this method has been proven and research has moved on to other materials. One example of such past studies was completed in 1994 by M. Rodriguez and R. Park [8] on 4 RC columns at a 7/8 scale. Different detailing and different situation (pre-damage vs. non damage) were tested and the results showed that the retrofitted columns exhibited higher strength and stiffness as well as higher durability and very good energy dissipation. They also showed that neither the detailing, nor the original state of the column, had much influence but that what was important was good surface preparation. Another variation of column retrofitting is to wrap the columns with a concrete jacket with added longitudinal and transverse reinforcements and in post-tensioning of the new longitudinal reinforcements.

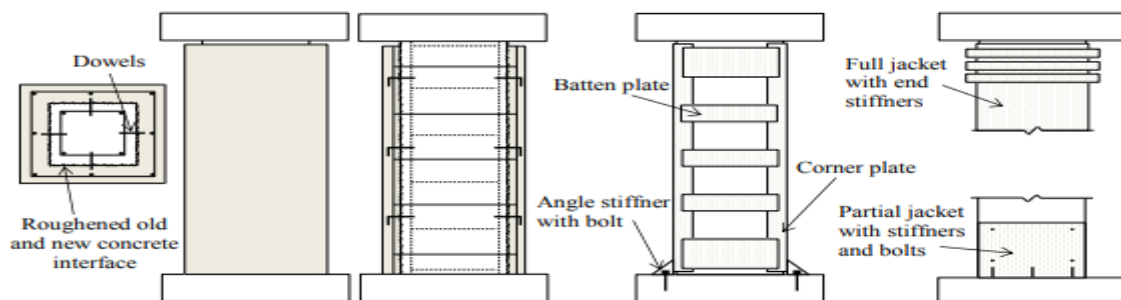


Figure No. 9. Strengthening scheme examples: a) concrete jacketing, b) steel cage, c) steel jacketing

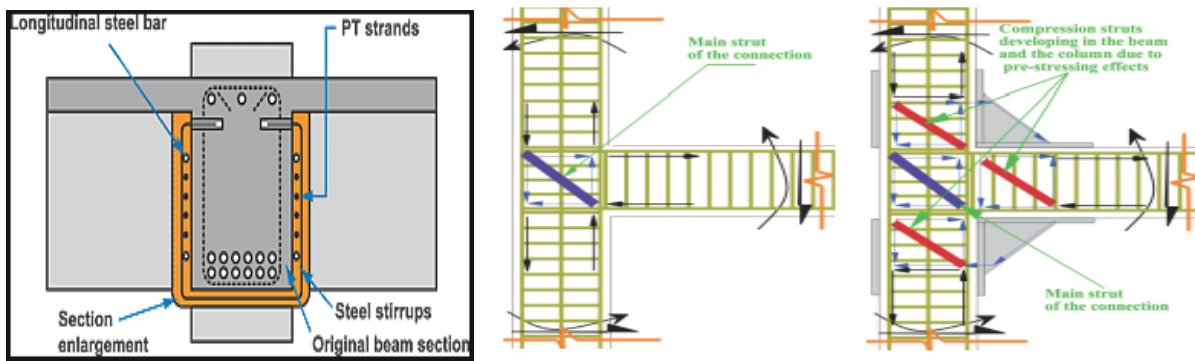


Figure No. 10. Strengthening scheme examples: a) Section Enlargement, b) Concrete Jacketing at Beam Column Joint

Case Study 4: Shotcrete

A later development in section enlargement is shotcrete. It is a mortar or concrete pneumatically projected at high velocities onto surfaces. It was introduced in 1911 and has been used in retrofit applications for over 50 years. The invention of the shotcrete gun has been attributed to Carl E. Akeley and shotcrete comes in both wet and dry mixed forms. Especially shotcrete technique has been used for hilly areas to prevent the land sliding along the highways. But for old times these methods used for strengthening or retrofitting of RCC structures.



Figure No. 11 Application of shotcrete over Masonry surface



Figure No. 12 Application of shotcrete over RCC Retaining wall Surface

Shotcrete's main advantage is it eases of application especially in hard to access areas which result in a reduction of construction time and cost. It has a dense composition and has low shrinkage and low permeability which gives it a good durability. The main disadvantage of using shotcrete is that special attention and procedure is required in order to achieve a good quality product. These include placing thick sections in layers, using of a blow-man to help reduce rebound (when the shotcrete hit a hard surface some of the larger aggregate tend to ricochet and gather in the same spot), and requiring quality control and inspections. Finally, it should be noted that with shotcrete, as with all modes of repairs, attention must be given to the bond area and to the surface preparation of the existing concrete surfaces.

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Case Study 5: Steel Jacketing

Steel jacket can be used to retrofit both column and joints. Column retrofit will be discussed first. After the 1971 San Fernando Earthquake, reinforced columns were recognized as a structural element that needed more attention. Retrofit of columns using steel jackets has been extensively studied in the 1990's, mainly in the context of bridge columns. This research was primarily founded by CALTRAN (California Transportation Department). They have shown that this technique provides good overall behavior with increase ductility, shear strength, and energy dissipation. This method is now widely used in the United States and in Japan.

The principal behind this technique is that the steel jacket acts as passive confinement reinforcement. The jacket will prevent the concrete from dilating, forcing it in lateral compression and increasing its compressive strength, its effective ultimate compressive strain, and its ductility. For circular columns, the method uses two semicircular half sections that are field welded along the entire height of the jacket. A gap of about 1 inch (2.5 cm) is left between the column and the jacket. It is filled with a cement-based grout that will ensure a good bonding and composite behavior. Use of expensive grout instead of the cement base one does not improve the performance. A gap of 2 inches (5 cm) is also left between the bottom of the columns and the top of the footing to avoid possible bearing of the jacket on the footing. For rectangular columns the retrofit options are to either use a rectangular jacket or a circular (or elliptical) jacket. In the case where a rectangular jacket is used the procedure is the same, and two L shaped panels are field welded together. For circular (or elliptical) jackets, the gaps created are larger and should be filled with concrete instead of grout. It should also be noted that depending on the application conditions and failure mechanisms partial jacket or steel collar may be used.

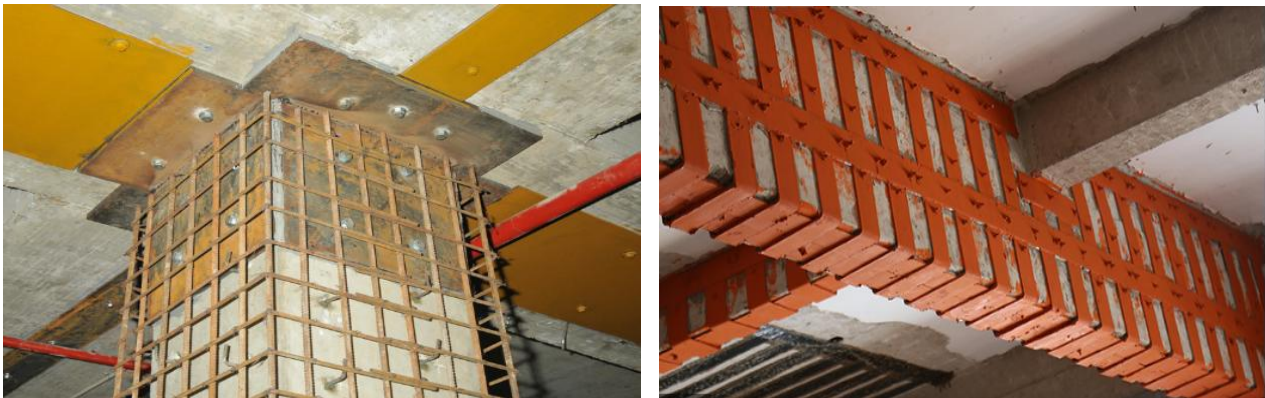


Figure No. 13 Application of Sticking steel plate of reinforcement concrete beam and slab

Case Study 6: Composites Jacketing

Composites are new materials and research in the subject is ongoing, especially for applications in the civil engineering field. Composites are non-isotropic and are made of a mixed between fibers and resin or epoxy. For every application, a specific design and composition has to be calculated. This is a complex process that requires the simultaneous consideration of component geometry, production volume, and type of reinforcement, type of matrix, tooling, process, and market economy. The most common composite used in civil engineering applications are jackets or sheets.

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Figure No. 14 Installing Prefabricated Fiberglass jacket

When using composite the general expectations are light weight, high stiffness or high strength to weight ratio, as well as corrosion resistance, durability, low thermal expansion (at least in the fiber direction), and low maintenance. They can be used in marine environments and are usually applied without much disruption to the building or its occupants (often the structure does not have to be closed). The largest disadvantage is the high initial material cost. High strength high modulus fiber such as carbon can be very expensive (but that can be offered by considering the durability/ no maintenance capacity). Also composite are hard to inspect. Simple eye inspections might not reveal defects underneath the surface and complete inspections (with such methods as X-ray) can prove to be costly. Finally, since composites are just now developing in the civil engineering field, there is a lack of design criteria and code requirements such that structural engineers have to either rely on the design services of the material supplier, or on developing their own based on their research and experience. It should be noted that throughout the world (Europe, USA, Canada, and Japan) there are bodies that have been set up to draw up guidelines and design rules to deal specifically with the design of strengthening concrete structure using composites.

Case Study 7: Steel Bracings

Steel bracing can be a very effective method for global strengthening of buildings. Some of the advantages are the ability to accommodate openings, the minimal added weight to the structure and in the case of external steel systems minimum disruption to the function of the building and its occupants.



Figure No. 15 Application of Steel Bracings

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Alternative configurations of bracing systems may be used in selected bays of a RC frame to provide a significant increase in horizontal capacity of the structure. Concentric steel bracing systems have been investigated for the rehabilitation of non-ductile buildings by many researchers. Using the eccentric steel bracing in the rehabilitation of RC structures has lagged behind concentric steel bracing applications due to the lack of sufficient research and information about the design, modeling and behavior of the combined concrete and steel system. Further research is needed in several areas such as testing of the RC beam–steel link connection details and design as well as the development and implementation of link elements models in analysis software. Post-tensioned steel bracing can be used for the seismic upgrading of infilled non-ductile buildings limited to low-rise and squat medium-rise buildings

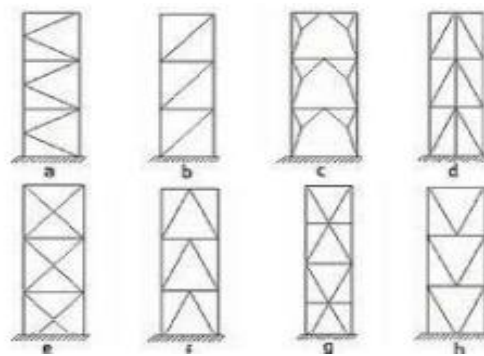


Figure No. 16 Different possible arrangements of braces

Development of a complete strategy guiding the retrofit solution through established objectives or criteria is an ongoing effort of the earthquake engineering research community. In general, seismic rehabilitation may aim to either recover or upgrade the original performance or reduce the seismic response. In the first case, the retrofit schemes that will be chosen have to reinstate the structural characteristics at member level and have negligible impact on the global response. The crack injection (epoxy resin injection or grout injection) technique and the member replacement (substitute part of the damaged member) may apply. When the seismic demand is to be reduced, this can be achieved by adopting base isolation techniques or by providing the structure with supplemental dissipation devices.

Case Study 8: Base Isolation System

Seismic isolation is mostly adopted for rehabilitation of critical or essential facilities, buildings with expensive and valuable contents and structures where performance well above performance levels is required. Seismic isolation system significantly reduces the seismic impact on the building structure and assemblies. Generally, the isolation devices are inserted at the bottom or at the top of the first floor columns. Retrofitting mostly requires traditional intervention; in the first case the addition of a floor in order to connect all the columns above the isolators while in the second case the strengthening of the first floor columns (enlarging of the cross-sections, addition of reinforcing bars or construction of new resistant elements). Nevertheless, inserting an isolator within an existing column is not so simple because of the necessity of cutting the element, temporarily supporting the weight of the above structure, putting in place the isolators and then giving back the load to the column, without causing damages to persons and to structural and non-structural elements.

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Figure No. 17 Different possible arrangements of braces

Recently, efforts have been made to extend this valuable earthquake resistant strategy to inexpensive housing and public buildings. The results of a joint research program conducted by the International Rubber Research and the Development Board (IRRDB) of United Kingdom show that the method can be both cost effective and functional for the protection of small buildings in high seismicity regions. A comparative study conducted by Bruno & Valente [20] on conventional and innovative seismic protection strategies concluded that base isolation provides higher degrees of safety than energy dissipation does, regardless of the type of devices employed. Moreover the comparison between conventional and innovative devices showed that shape memory alloys based devices are far more effective than rubber isolators in reducing seismic vibrations.

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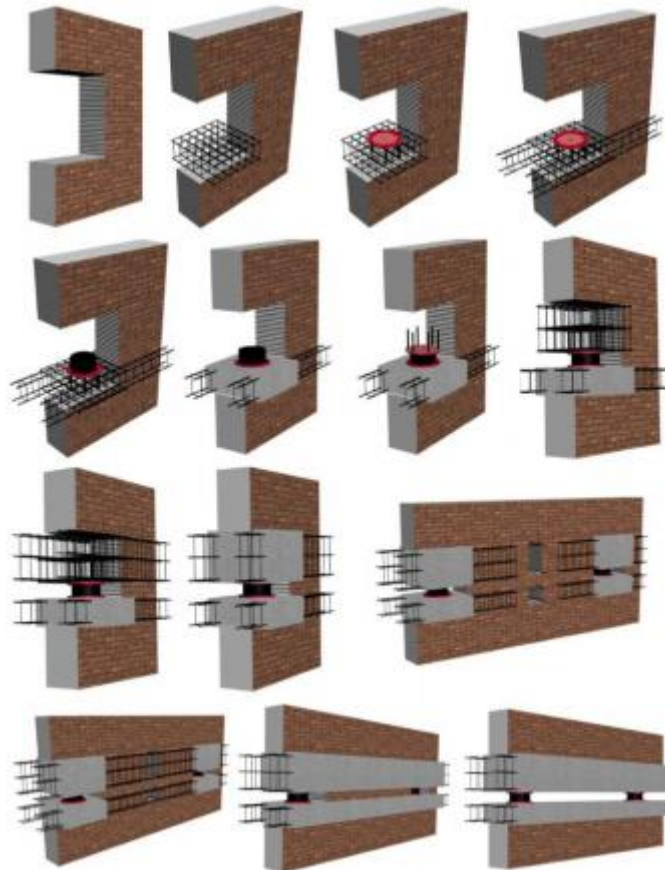


Figure No. 18 Stages of installing isolators in a masonry building (Melkumyan et al, 2015)

Case Study 9: Non-Metallic Fiber Composites/Fiber Reinforced Composites (FRC)

Commonly used forms of FRC viz. Pre cured CFRC (Carbon Fiber Reinforced Composite), Glass Fiber Reinforced polymer Composites (GFRC) rebar, glass fibre roll, etc. Fiber Reinforced Polymer (FRP) composites comprise fibers of high tensile strength within a polymer matrix such as vinyl ester or epoxy. FRP composites have emerged from being exotic materials used only in niche applications following the Second World War, to common engineering materials used in a diverse range of applications such as aircraft, helicopters, spacecraft, satellites, ships, submarines, automobiles, chemical processing equipment, sporting goods and civil infrastructure. The role of FRP for strengthening of existing or new reinforced concrete structures is growing at an extremely rapid pace owing mainly to the ease and speed of construction, and the possibility of application without disturbing the existing functionality of the structure. FRP composites have proved to be extremely useful for strengthening of RCC structures against both normal and seismic loads.

XVII. ALTERNATIVE RETROFIT STRATEGIES

In the case of the seismic upgrading, the aim of the retrofit strategy as an operational framework is to balance supply and demand. The supply refers to the capacity of the structural system, which has to be assessed in detail before selecting the intervention scheme. The demand is expressed by either a code design spectrum or a site-specific set of records as a function of period and shape of vibration characteristics of the upgraded system. By modifying strength, stiffness or ductility of the system alternative retrofit options are obtained. Ductility enhancement applies to systems with poor detailing (sparse shear reinforcement, insufficient lap splicing), stiffness and strength enhancement to

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systems with inherently low deformation capacity (so as to reduce displacement demand), whereas stiffness, strength and ductility enhancement apply to systems with low capacity or where seismic demand is high. Various alternatives to the traditional local and global methods of seismic upgradation are also available. Enhancing the ductility, stiffness or both are some of the more commonly studied and reported of these methods.

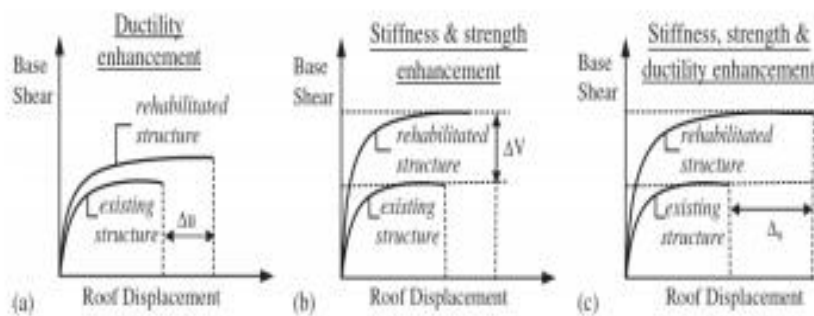


Figure No. 19 Alternative seismic retrofitting strategies

As shown in Figure 20, a combination of different local and global methods lead to the rise of a Hybrid retrofitting scheme. The present scenario of earthquakes occurring all over the world has made it crucial to research these hybrid interventions in detail to find out the optimum technique providing both efficiency and economy. Some other nontraditional retrofitting strategies are listed below:

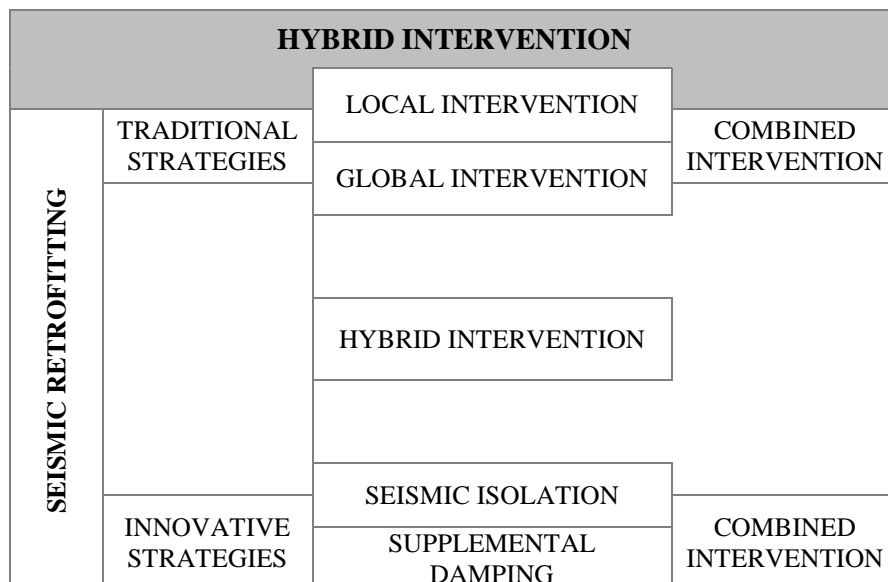


Figure No. 20 Hybrid Intervention

Internal Concrete Box: This option is more suitable for the structures of historical importance. In this method all the internal walls and floors are removed and a new earthquake resistant R.C.C structure is constructed inside the existing outer brick wall. The outer wall is connected to the internal R.C.C structure by shear connectors. The method is very straight forward and would serve the purpose during a seismic event to Immediate Occupancy structural performance level.

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Steel Strong Point: This option includes the incorporation of a new steel stiff frame within the walls, floors and roofs of the existing structure. The basic intent is to stiffen and connect the building elements (foundation, wall, floor and roof) so that they move as a single entity under seismic loading. This method of retrofitting is cost effective, relatively less destructive to existing structure and would provide the structure with lowest level of structural performance.

Splint and Bandage: This option provides a midway option between options jacketing and steel strong point strategies, giving the building at least Life Safety Performance Level and even up to Damage Control Level. This option requires the addition of vertical and horizontal steel strips placed around the building, inside and outside, to restrain and support the existing structure during an earthquake. As this system requires only discreet areas of additional reinforcement, the architectural appearance of the building is likely to be quite different. This method of retrofitting is cost effective and quick.

Splint and Bandage was found to be the most effective in so far as 'Life safety' level and it is uncertain whether the retrofitted structure will perform in subsequent events. Expensive retrofitting options are more suitable for structures requiring the external facade to be intact during a seismic tremor. Though these options are costly and require more time in construction, retrofitting by these methods will enable the structure to withstand multiple earthquake events.

XVIII. ENVIRONMENTAL

The goal of sustainable rehabilitation is the modernization of the existing building stock to meet the demands of present times and simultaneously focus on technical and ecological aspects as well as lengthening the life-span and conserving the building's heritage. In addition to aesthetic and economic questions, energy efficiency and environmental impacts are important factors in the decision-making process regarding the retrofitting of an existing building.

The safety, durability and energy efficiency of buildings is a transnational problem and as such, a concentrated effort is required to address it. Research around the proposed area will contribute to the key aims of the policy –sustainable growth through the preservation of the environment – by increasing the lifetime of existing buildings and reduction of consequent occupancy disruption (during the renovation of the building) by 100% and loss of use by 10%, there by directly minimizing the drain on non-renewable natural resources (reduction of use of cement and aggregates by 50%, oil by 10%). Also the Kyoto protocol and European vision 2050 is supported through the reduction of CO₂emissions from cement and steel production by 50% less concrete usage and lower reinforcement and repairs requirements.

The significance of accounting for seismic risk in the environmental assessment of house underwent either energy retrofitting, or energy plus seismic retrofitting was presented by Belleri and Marini.. Their findings are presented in Fig 5.1, where the energy consumption, operational cost, and carbon Emission, along other variables, are expressed as a function of the building; the seismic impact is represented as an expected loss, expressed as annual energy consumption, bring the seismic event uncertain in nature. Figure 5.1a considers a building energy retrofit intervention (R_E) targeting the nearly zero energy building performance. This intervention does not affect the building seismic behavior the building seismic behavior, Therefore is a seismic event (X) occurs during the building life, there is an additional cost associated to the building post-earthquake repairs, which represents the actualization of the expected seismic loss. Interestingly the graph shows that, depending on the relevance of the annual energy consumption associated to the seismic risk, the nearly zero energy performance could be only theoretically attained, whereas actual consumption could be higher. Noteworthy, typical procedures adopted to evaluate the environmental impacts of buildings neglects this contribution, which could have even a greater impact when considering the problem at the district level. Figure 5.2b considers both building energy and seismic retrofit intervention ($R_{E,S}$). After the seismic retrofit the expected seismic loss is significantly reduced, therefore is a seismic event (X) occurs after the structural retrofit intervention, the additional cost due to the building repair is much lower than in the previous case. It is worth noting that unlike sole energy refurbishment interventions, in the second case the structural retrofit allows the extension of the building structural service life as mentioned before.

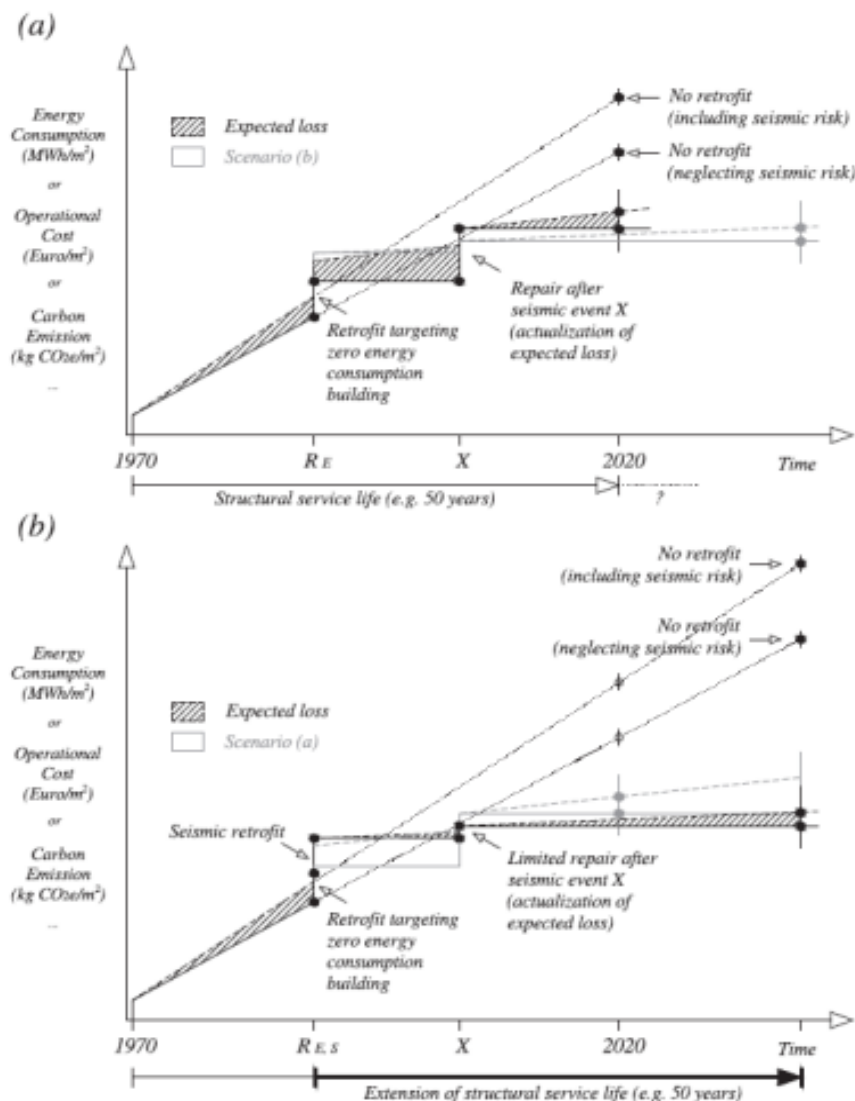


Figure 21: Impact of energy consumption, operational cost and carbon emission during building life cycle. (a) Energy Retrofit intervention and (b) Energy + Seismic retrofit interventions

XIX. SUMMARY & CONCLUSIONS

The seismic and energy retrofitting of existing Indian buildings with innovative materials and solutions was addressed in this report. The need for retrofitting of old buildings emanates from their substandard design in terms of earthquake resistance and thermal insulation, as revealed during strong earthquakes or due to their high energy consumption (Heating and Cooling). This paper explored innovative methods for the retrofitting of buildings by conducting a state – of – the – art review on advanced materials and solutions for enhancing the safety, energy and resources efficiency of the deficient EU residential buildings. The summary and main conclusions of the paper are presented below, as follows:

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Concrete structures built before the 1970's need to be retrofitted to withstand earthquakes. Six different methods of retrofit divided into two major categories, local and global, were presented. Local methods include addition of concrete, steel, and composite to a specific member to improve its response in a seismic event. All three methods are effective each and also have some disadvantages: concrete is labor intensive, steel requires high maintenance during the life of the structure, and composites have high initial cost. Global methods retrofit the entire structure at once by adding shear walls or steel braces, or by using base isolation. Shear wall are labor intensive and expensive. Steel brace can be easier to implement but present some connection problems. Base isolation is effective and works well, but cannot be applied to all type of structures. The choice of the method depends on the building, on its specific requirements, as well as its condition, location, and geometry. Several methods should usually be considered and compared to find the appropriate best one. To provide greater flexibility in the retrofit scheme, Hybrid methods should be used in which several methods can be combined and implemented together, combining the advantages of each.

There is an increasing need to develop an understanding of materials and design considerations in the use of composites for the rehabilitation of concrete components. Although composite layers can be easily bonded onto concrete and can be made to closely follow the contours the structure, care has to be taken to ensure that good detailing practice is followed to ensure against premature failure. The development of fracture mechanics based design principles in conjunction with criteria for the selection of materials (fiber, resin, adhesive) and their form is seen to be a critically needed step towards the efficient and safe use of these techniques.

The use of FRP for repairing and strengthening the plain cement concrete and reinforced cement concrete has been analyzed in this study. The following conclusions can be drawn from this study.

A number of techniques to utilize the maximum efficiency of FRP were examined in this paper such as number of layers of FRP, FRP strips with and without FRP anchorage, fully and partially confinement of the FRP, FRP strips anchored with mechanical fasteners, FRP strips at horizontal and inclined pattern, Near Surface Mounting (NSM), Externally Bonded Reinforcement (EBR) and Externally Bonded Reinforcement On Groove (EBROG).

Strengthening techniques increased the load carrying capacity of the specimen and shear cracks produced at 45 degree were restricted. Also, the width and length of the cracks was reduced.

The mechanisms used increased the ultimate load in FRP concrete beams and interfacial failure plane got shifted from FRP concrete interface to the concrete interface. Different groove sizes were tested in EBROG technique, results showed that with increase in dimension of groove the bond strength was decreasing. These techniques proved very effective on the flexural behavior of concrete. Flexural response was significantly enhanced and deflection noted was also reduced.

Risk assessment and retrofit include aspects of almost all of earthquake engineering, requiring close co-operation between disciplines, particularly in the area of acceptable risk. The growing understanding of the risk from existing buildings by owners and government is creating a demand for more efficient and reliable analytical methods, as well as innovative techniques for retrofit. A benchmark analytical tool is needed to test and set limitations on simplified nonlinear procedures. Reliable and consistent simplified linear or force based procedures are also needed for small, regular buildings.

When considering the entire spectrum of components and elements used in seismically deficient existing buildings, little cyclic test data is available from which analytical acceptability criteria can be set. A systematic program is needed to fill in the most significant gaps. For consideration of near – collapse conditions, much information is needed to determine gravity-load carrying ability of elements under severe deformations. The relationship between local and global failures and collapse needs further definitions in order to not penalize redundant structures that may experience one or more local components failures.

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Despite the rapid advances in published guidelines and standards for evaluation and retrofit, engineers must continue to temper their decisions with experience and judgement, primarily based on field observations of real structures under loadings from real ground motions.

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He is continuously involved in Technical research, development and analysis of new concepts evolving in **Technical, Project Management, Quality Management system, Structural Technologies and construction aspects**. Aspiring researchers for new horizons of trends in Civil, Water, Environment, Safety and Structural engineering.