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Study of Various Local and Global Seismic Retrofitting Strategies - A Review

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Abstract— **Recent earthquakes, starting with the 1971 San Fernando Earthquake in California, left major destructions, damaged the infrastructure, and raised questions about the vulnerability and design practice of structures, especially concrete structures. Design codes have being updated to include seismic previsions but structures build before 1971 have to be retrofitted. The focus of this paper is reinforced concrete (RC) structures. Surveys done after earthquakes have shown that the major problem with concrete structures is columns. Other critical structural elements include, but are not limited to, gravity design frames, footings, shear walls, connections, and beams. There are two major categories of retrofit options for concrete structure; local and global methods. Local methods focus at the element level on a particular member that is deficient and in improving it to perform better. Global methods concentrate at the structure level and retrofit to obtain a better overall behaviour of the entire structure. The different systems presented all have some advantages and disadvantages and the option chosen for the retrofit depends on the existing structure requirement. Finally a brief note is made on the development and use of Hybrid intervention schemes.**

Keywords—Seismic Retrofitting, Local and Global methods, Hybrid intervention, Jacketing, Base isolation, Shear Wall, Bracing

I. INTRODUCTION

After earthquakes, surveys have analyzed damaged and collapsed structures to understand their failure mechanisms. There are two major types of retrofit methods that can be used. The first are local methods that focus on the member level. They include an analysis of the structure to find the deficient elements and the retrofit of these elements. Local retrofit methods include the addition of concrete, steel, and composite. The second set of methods is a global approach that retrofits the entire structure to improve its overall behaviour. Those methods include addition of shear walls or steel bracings, or the use of base isolation. The results of the damage survey will be presented first. Then attention will be given to the retrofit methods, their description and advantages, as well as example of their application. The local methods will be presented first followed by the global ones. Earthquake causes different shaking intensities at different locations and the damage induced in buildings at these locations is also different. Thus, it is necessary to construct a structure which is earthquake resistant at a particular level of intensity of shaking, and assimilate the effect of earthquake. Even though same magnitudes of earthquakes are occurring due to its varying intensity, it results into dissimilar damaging effects in different regions. Hence, it is necessary to study variations in seismic behavior of multistoried RC framed building for different seismic intensities in terms of various responses such as lateral displacements, story drift and base shear.

Keeping in view the recent events of Nepal earthquake, 2015 which is more commonly referred to as the Gorkha earthquake, this thesis is aimed towards positing positive retrofitting measures that can be applicable to the Indian subcontinent. This earthquake claimed the life of nearly 9,000 people and injured nearly 22,000. It occurred at 11:56 Nepal Standard Time on 25 April, 2015 with a magnitude of 7.8 Richter scale and a maximum Mercalli Intensity of IX (Violent). Its epicenter was east of Gorkha District at Barpak, Gorkha, and its hypocenter was at a depth of approximately 8.2 km (5.1 mi). It was the worst natural disaster to strike Nepal since the 1934 Nepal–Bihar earthquake. The ground motion recorded in Kathmandu valley was of low frequency which, along with its occurrence at an hour where many people in rural areas were working outdoors, decreased the loss of property and human life. The earthquake also triggered an avalanche on Mount Everest, killing 21, making April 25, 2015 the deadliest day on the mountain in history. The earthquake triggered another huge avalanche in the Langtang valley, where 250 people were reported missing. Hundreds of thousands of people were made homeless with entire villages flattened, across many districts of the country. Centuries-old buildings were destroyed at UNESCO World Heritage Sites in the Kathmandu Valley, including some at the Kathmandu Durbar Square, the Patan Durbar Square, the Bhaktapur Durbar Square, the Changu Narayan Temple, the Boudhanath stupa and the Swayambhunath Stupa.

Fig. 1 - Damage at Durbar Square, Kathmandu after Gorkha earthquake

The Indian subcontinent has a history of earthquakes. The reason for the intensity and high frequency of earthquakes is the Indian plate driving into Asia at a rate of approximately 47

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mm/year. The following is a list of worldwide earthquakes for the past 10 years. Only earthquakes of magnitude 6 or above are included, unless they result in damage and/or casualties, or are notable for some other reason. All dates are listed according to UTC time. Maximum intensities are indicated on the Mercalli intensity scale and are sourced from United States Geological Survey (USGS) ShakeMap data. Major events took place in Ecuador, Italy, Taiwan and Indonesia this year, while the strongest tremor was observed in Papua New Guinea. For the first time since 2008, no quake had a magnitude of 8 or higher.

Among these, various prominent earthquakes struck India. Apart from the before mentioned Gorkha earthquake, Kashmir earthquake of 7.6 Richter scale (8th August 2005), Gujarat earthquake of 7.7 Richter scale (26th January 2001), Chamoli earthquake of 6.8 Richter scale (29th March 1999), Jabalpur earthquake of 5.8 Richter scale (22nd May 1997), Latur earthquake of 6.2 Richter scale (30th September 1993) and Uttarkashi earthquake of 6.8 Richter scale (20th October 1991) are the most destructive ones.

II. STRUCTURAL FAILURE DURING EARTHQUAKES

2.1 Columns and Piers

The 1971 San Fernando earthquake left many structures damaged with columns and piers failures that often resulted in the collapse of the structure. Some of the major deficiencies in both columns and piers are listed below.

a.) Inadequate flexural strength: Before 1971 lateral force coefficients were generally less than 10% resulting in high potential ductility demand.

b.) Inadequate flexural ductility: This type of failure comes from a lack of confinement of the concrete core followed by a failure in the plastic hinge region. This defect is a major design flow and is directly linked to pre-1971 practices which required, for transverse reinforcements of columns, No. 4 bars spaced 12 in (0.3m) on center. This was applied to every column regardless of geometry (circular or rectangular) or dimensions. Also, the general practice was to close the transverse reinforcements by lap-slice. This technique does not provide good anchorage for the rebar and under pressure the bars deform and open up. More effective techniques for closing rebar include welding or anchoring (bending back into the concrete core). Those deficiencies limit the ultimate curvature in the plastic hinge region of the column to the strain at which the cover concrete starts spalling.

c.) Undependable flexural capacity: Longitudinal lap-slices were only designed for compression and are often located near the ends of columns. It was found that during earthquakes the longitudinal bars could also be subjected to high tension and that the locations where their slices are located are the same areas where plastic hinges will develop. (Current practices have lap slice located in the central portion of the column and designed as tension splice). Also, the length of the lap slices were traditionally 20 bar diameters which is insufficient to develop yield strength in the bars (especially when larger diameter bars are used). All of those elements lead to rapid reduction of flexural strength during cyclic loading.

d.) Inadequate shear strength: Shear failure develops principally in columns with a small height-to-depth ratio, those are either columns that were designed to be short or longer columns that are partially restrained by non-structural elements over a portion of their height (captive columns). Pre-1971 designs were based on elastic methods and used less severe shear requirements. As a result, the shear strength in columns is often less than that needed to develop flexural strength in the member. Shear failure are often brittle, they occur in the form of major diagonal cracking along the entire length of the column, along with the yielding of the longitudinal reinforcement.

Fig. 2 - Columns failure during earthquakes

2.2 Reinforced Concrete Frame

Practices for the design of frame structures in low to moderate seismic regions have been to design the structures for gravity load only disregarding lateral loads. This creates several deficiencies which are analyzed below.

a.) Weak column/strong beam behaviour: Columns are weaker than their joining beam. This creates a structure with potential failures in a soft-story or column sideway mechanisms.

b.) Columns deficiencies are similar to the one discussed before.

c.) Deficient Beam-column joints: They have little to no transverse shear reinforcement and the positive (bottom) beam reinforcement is discontinued in the joints.

A gravity design frame will exhibit low-lateral strength resistance. This allows for large deformations and large inter-story drifts during moderate earthquake. In larger earthquakes, and because of the inadequate ductility of the columns, the frame will experience a brittle soft story or column sideway mechanism [5].

Fig. 3 - Soft story collapse in 1999 Kocaeli - Golcuk earthquake [2]

2.3 Other structural elements

There exists several other structural elements that have been observed to fail during earthquakes. Footings, shear walls, and coupling beams are just a few that might also experience deficiencies. Often, their failures though damaging will not result in the immediate collapse of the entire structure.

a,) Footing failure: Many older footings were only designed for gravity loads. As a result, they have several deficiencies. First, they are often undersized and vulnerable to overturning moments. Secondly, they do not have top reinforcements making them subjective to brittle failures. Thirdly, they are vulnerable to shear in both the footing and in the footing-column joint area. Finally, pile footing in older designs often did not have structural connections between the piles and the pile cap [6].

b,) Coupling beam and shear walls: Shear walls are most often damaged in shear and exhibit X-pattern cracks. Coupling beams can have inadequate capacity; particularly shear capacity, which are insufficient to develop flexural yielding of the beam [7].

Fig. 4 - Shear wall failure during earthquakes

III. SEISMIC RETROFITTING STRATEGIES

Seismic retrofit (or rehabilitation) strategies have been developed in the past few decades following the introduction of new seismic provisions and the availability of advanced materials (e.g. fiber-reinforced polymers (FRP), fiber reinforced concrete and high strength steel) [7]. Retrofit strategies are different from retrofit techniques, where the former is the basic approach to achieve an overall retrofit performance objective, such as increasing strength, increasing deformability, reducing deformation demands while the latter is the technical methods to achieve that strategy, for example FRP jacketing.

- Increasing the global capacity (strengthening). This is typically done by the addition of cross braces or new structural walls.
- Reduction of the seismic demand by means of supplementary damping and/or use of base isolation systems [8].
- Increasing the local capacity of structural elements. This strategy recognizes the inherent capacity within the existing structures, and therefore adopt a more cost-effective approach to selectively upgrade local capacity (deformation/ductility, strength or stiffness) of individual structural components.
- Selective weakening retrofit. This is a counter intuitive strategy to change the inelastic mechanism of the structure, while recognizing the inherent capacity of the structure [9].
- Allowing sliding connections such as passageway bridges to accommodate additional movement between seismically independent structures.
- Addition of seismic friction dampers to brace weak structures and provide damping.

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 occurs around the world every year. Such events lead to damage to the concrete structures as well as failures. It is the modification of existing structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes. The retrofit techniques are also applicable for other natural hazards such as tropical cyclones, tornadoes, and severe winds from thunderstorms. The biggest problem faced by structural engineers is a lack of standards for retrofitting methods – Effectiveness of each methods varies a lot depending upon parameters like type of structures, material condition, amount of damage etc. These techniques can be broadly classified as given below. Primary aim of strengthening a structure is to increase its load bearing capacity with respect to its previous condition. Only those aspects related to flexure are discussed here. Established techniques which have been in use successfully for a number of years are recognized as follows:

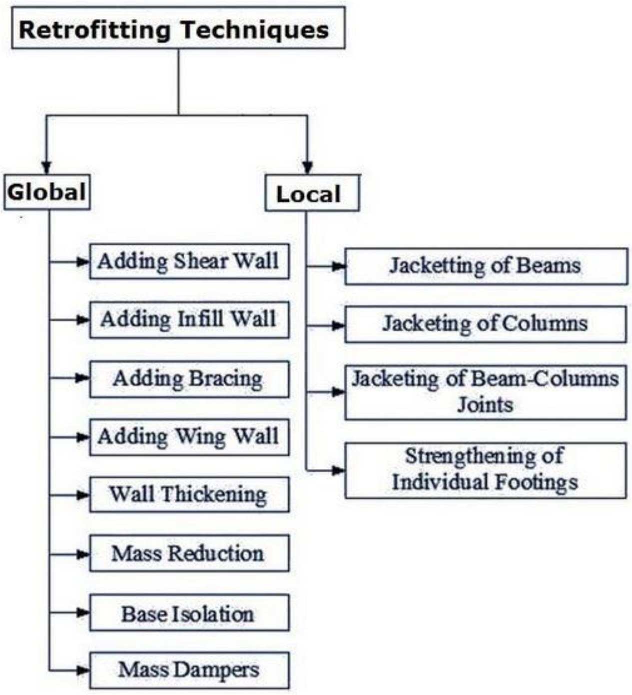

Fig. 5 - Classification of various seismic retrofit strategies

IV. LOCAL SEISMIC RETROFIT

4.1 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 join 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-tension of the new longitudinal reinforcements.

Fig. 6 - Column retrofitting by concrete jacketing [3]

4.2 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 [9].

Fig. 7 - Application of shotcrete

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 [10]. 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.

4.3 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.

Fig. 8 - Polymer composite application

It is uses in the resurfacing deteriorated structures and as a compound in the repair of concrete structures [12]. Even though it presents several advantages PC is more expensive and does not solve the extensive labour issue of using regular concrete.

4.4 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 behaviour with increase ductility, shear strength, and energy dissipation. This method is now widely used in the United States and in Japan.

Fig. 9 - Steel jacketed column

The principal behind this technique is that the steel jacket acts as a 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

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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 behaviour. 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 [17]. 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.

4.5 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, type of reinforcement, type of matrix, tooling, process, and market economy. The most common composite used in civil engineering applications are jackets or sheets.

Fig. 10 - Installing Prefabricated Fiberglass jacket [11]

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 offseted 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.

V. GLOBAL SEISMIC RETROFIT

5.1 Addition of 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 behavior. 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.

Fig. 11 - Adding Shear Walls to existing structures

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.

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Fig. 12 - Cast-in-place infill walls

5.2 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.

Fig. 13 - Building retrofitted using steel frames

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 [18]. 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 [19].

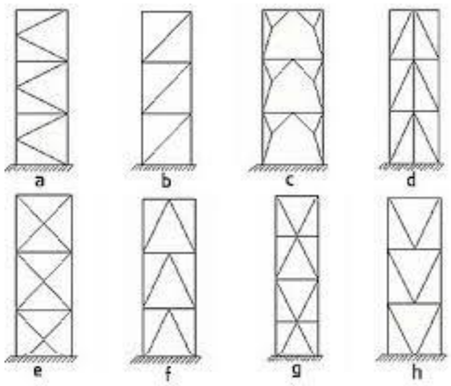

Fig. 14 - Different possible arrangements of braces

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.

5.3 Base isolation

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 he 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.

Fig. 15 - Lead Rubber Bearings

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.

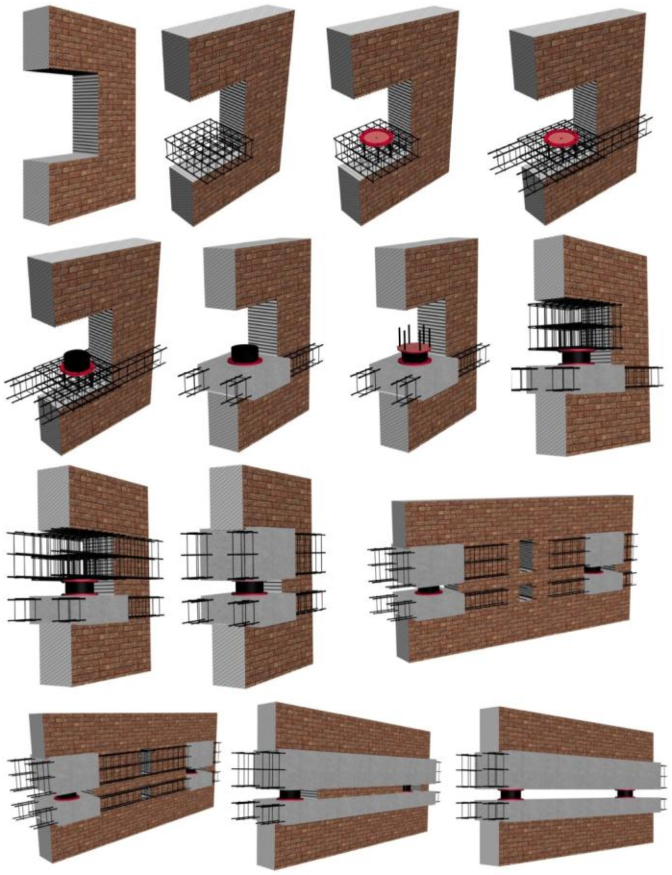

Fig. 16 - Stages of installing isolators in a masonry building (Melkumyan et al, 2015)

VI. 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 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.

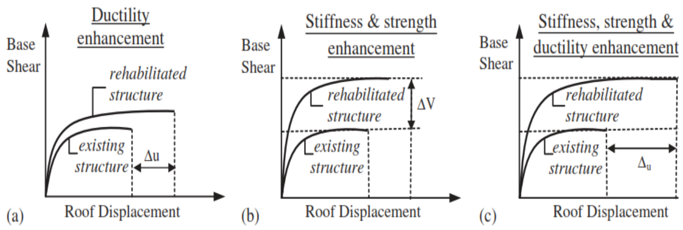

Fig. 17 - Alternative seismic retrofitting strategies

As shown in Figure 18, 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 non-traditional retrofitting strategies are listed below:

(a) 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.

(b) 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.

(c) 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.

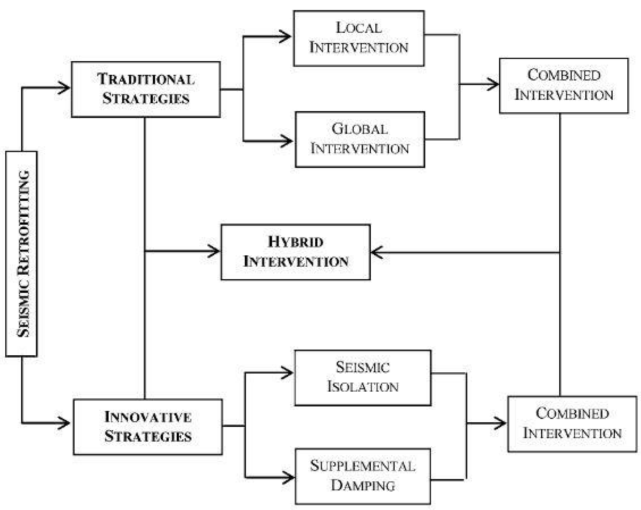

Fig. 18 - Hybrid intervention

A study carried out by Roy et al, 2013, focused on a seismically deficient 3 story URM structure assumed to be located in the moderate seismic zone of Bangladesh is taken as a reference to present a comparative analysis of traditional vs non-traditional strategies o seismic upgradation. Depending on the expected seismic performance level, 5 possible retrofitting schemes were chosen and designed by the authors for the building and then compared in terms of cost of construction. The prime objective of their research was to identify the cost effective retrofitting options based on the level of performances. The output of their study is presented below:

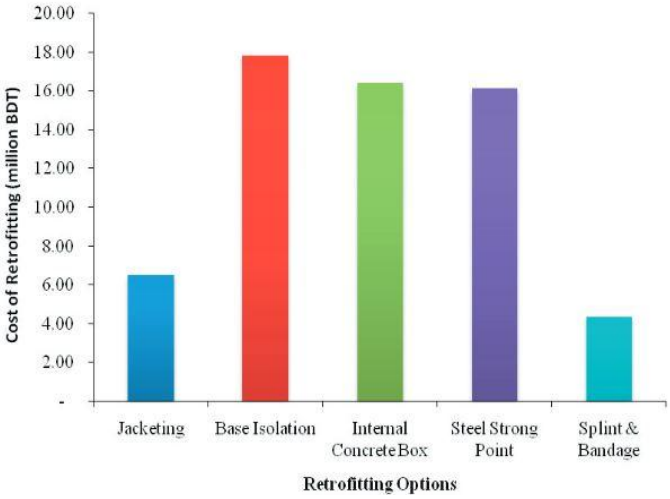

Fig. 19 - Cost comparison of different retrofitting schemes

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.

VII. SUMMARY & CONCLUSIONS

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.

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