Journal of Civil Engineering and Environmental Technology
Print ISSN: 2349-8404; Online ISSN: 2349-879X; Volume 2, Number 7; April-June, 2015 pp. 587-592

http://www.krishisanskriti.org/jceet.html

Advanced Retrofitting Techniques for Reinforced Concrete Buildings

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Abstract—*Past earthquakes in India have revealed that majority of the buildings are not designed Earthquake Resistant. Generally, buildings are designed taking into account only the gravity loads. Also, the current design seismic codes are not fully practiced while designing a building. Hence, a higher degree of damage is expected during an earthquake if the seismic resistance of the building is inadequate. Thus, for these types of buildings, Retrofitting gives out the best possible way in order to minimize the future damage caused due to vibrations produced by an earthquake. The existing building can be retrofitted using various techniques like Jacketting of beams, columns, or joints, or using fibre reinforced polymer sheets, adding shear walls, adding infill walls and base isolation. In this paper, an effort is made to illustrate the different retrofitting techniques available and their suitability for particular conditions. Further, the various local and global retrofitting techniques are presented that increases the strength, ductility and stiffness of reinforced concrete buildings. Also, a list of the various applications of these techniques used in India is highlighted in this paper.*

1. INTRODUCTION

A large number of reasons may involve the need to retrofit of existing structures. It may be the rehabilitation of a structure damaged by an earthquake or other causes, or the strengthening of an undamaged structure made necessary by revisions in structural design or codes of practice [1]. Decision to strengthen a building before an earthquake occurs depends on the building's seismic resistance. There has been much research on the topic of seismic retrofit of structures in recent years. Retrofitting techniques specifically aim to improve the structural capacities (strength, stiffness, ductility, stability and integrity) of a building that is found to be deficient or vulnerable.

2. SEISMIC RETROFITTING

Seismic retrofitting is the modification of existing structures to make them more earthquake resistant under seismic loading, ground motion or soil failure due to earthquakes. Rehabilitation denotes repairing buildings damaged during service or by earthquakes without upgrading the seismic resistance, while seismic retrofitting denotes upgrading the safety of damaged or existing deficient buildings [2].

2.1 Goals of seismic Retrofitting

The goals of retrofitting include the following points [2]:

I. To increase the lateral strength and stiffness of the building.
II. To increase the ductile behavior of the building.
III. To reduce or minimize the irregularities
IV. To enhance the redundancy of the building
V. To ensure adequate stability against overturning and sliding.

2.2 Seismic Retrofit Objectives

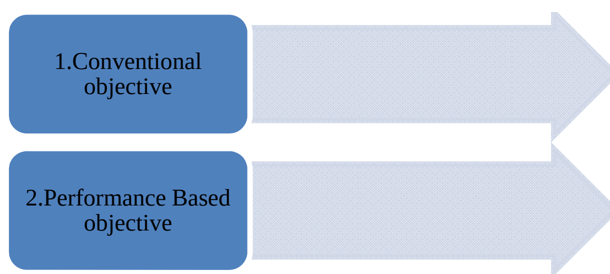

Fig. 1: Seismic Retrofit Objectives

Conventional Objective (Fig. 1): A member of a building is considered to be adequate if the design capacity of the member for an internal force is not less than the demand. After the calculation of the demand and capacity of a member for an internal force, the demand-to-capacity ratio (DCR) is computed. If this ratio exceeds 1.0, it implies that the member strength is deficient, with reference to the code requirement for a new building. Two types of methods are used:

1. Linear elastic method. (Static method)
2. Response spectrum method (dynamic method)

Performance Based Objectives: An objective of a performance based approach relates a target building performance level under a selected earthquake level. For retrofit of ordinary buildings, a minimum performance of Collapse Prevention under MCE can be selected. For important buildings, a dual level performance objective that targets Life Safety under DBE and Collapse Prevention under MCE can be selected. The aim of such an objective is to have a low risk of life threatening injury during a moderate earthquake (as defined by DBE) and to check the collapse of the vertical load resisting system during a severe earthquake (as defined by MCE). To check Life Safety under DBE, performance of the non-structural components also needs to be investigated. The deformations or strains are considered to be better measures than stresses or forces to assess damage. To quantify inelastic deformations, a performance based approach requires a nonlinear lateral load versus deformation analysis. Pushover analysis and nonlinear time history analysis are the static and dynamic methods of nonlinear analysis, respectively.

2.3 Source of Weakness in RC Frame Building

Buckling and bulging are the common phenomenon of RC column failure. The joint are always considered as weaker section of the structure [3]. If sufficient care is not taken for the beam-column or slab-column connection at designing stage as well as at the construction stage, it may lead to the degradation of the building in early age. Factors that are responsible for the degradation of RC element includes: Longitudinal reinforcement is insufficient, Sufficient cover is not provided, Lack of ductile detailing, Not designed for seismic loading, Unexpected overloading, Lateral ties or stirrups are not provided at the required spacing, Poor quality of material used, Quality of workmanship is inferior, Ignorance of vertical or diagonal cracks, spelling of concrete, corrosion in the reinforcement, dampness of surface, Unexpected impact loading, vibration, Lack of ductility, Poor concreting at the connection, insufficient maintenance etc. Sources of weakness in a RC frame structure include the following:

1. Discontinuous Load Path/Interrupted Load Path/Irregular Load Path.
2. Lack of deformation compatibility of structural members.
3. Quality of workmanship and poor quality of materials.

3. RETROFITTING METHODS

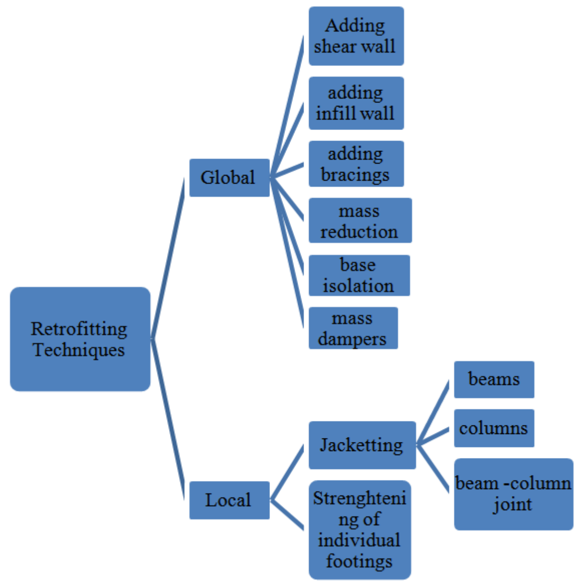

Fig. 2: Retrofitting Techniques

3.1 Global Retrofitting Techniques

It is based on increasing the seismic resistance of existing structure and improving the response of existing un-reinforced masonry buildings. It includes the following techniques.

3.1.1 Adding Shear Wall

The addition of shear wall (Fig. 3) is frequently used for retrofitting of non-ductile reinforced concrete frame buildings. The added elements can be either cast-in-place or pre-cast concrete elements [4]. It is not preferred in the interior of the structure to avoid interior buildings. The longitudinal reinforcement must be placed at the ends of the wall running continuously through the entire height and the reinforcement has to pass through holes in slabs and around the beams to avoid interference. The Wall thickness also varies from 15 to 25 cm (6 to 10 inch) and is normally placed externally. It is suitable to locate walls adjacent to the beam between columns so that only minimum slab destruction is required with connections made to beam at the sides of columns and it may align to the full height of the building to minimize torsion. The advantages of adding shear wall are that it provides large strength and stiffness in the direction of orientation, significantly reduced lateral sway and is easy in implementation and construction. It provides efficiency in term of construction cost and effectiveness in term of minimizing seismic forces. However, there are few drawbacks in adding shear wall. It causes an increase in lateral resistance but is concentrated at a few places. Increased overturning moment at foundation causes very high uplifting that needs either new foundations or strengthening of the existing foundations, increases the dead load of the structure. Closing of formerly open spaces can have major negative impact on the interior of the building or exterior appearance.

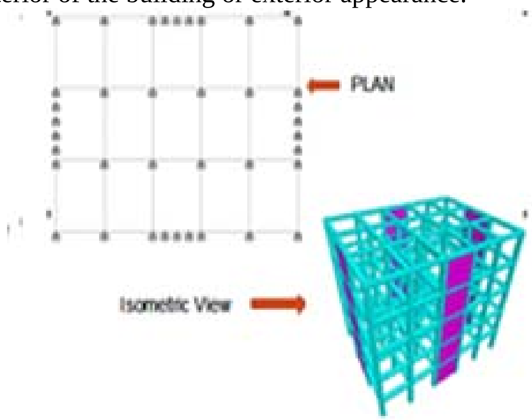

Fig. 3: Adding shear wall

3.1.2. Adding infill wall

There has been much work conducted into the seismic behaviour of infilled frame buildings. The most significant outcome may be the general consensus that brickwork infill wall can have a beneficial effect on the overall seismic performance of the building if it is properly tied into the rest of the building. The partial-height infill walls cause columns to experience non-ductile shear failures rather than respond in a ductile, predominately flexural manner. In such case, a sufficient gap must be maintain between the infill wall (Fig. 4) and the column face to prevent interaction or the column must be detailed to prevent premature shear failure. For reasons of economy, ease of construction, favourable mechanical properties and efficiency of different types of masonry infill, it was concluded that the most promising panel configuration consisted of solid brick laid in mortar reinforced with two mats of welded wire fabric, one bonded to each size of the wall in a layer of cement stucco (mortar). It is used for strengthening of RC frames, especially open storey and most applicable for up to 5 storeyed buildings. It adds significant strength and stiffness to framed structures. However, it adds considerable mass to the structure and need new footings between existing spread footings.

Fig. 4: Adding infill wall

3.1.3. Adding Bracing:

The adding of bracing (Fig. 5) is an effective solution when large openings are required. It increase higher strength and stiffness to the moment resisting frame and the amount of work is less since foundation cost may be minimized. This is used for strengthening almost all types of RC and steel structures. It is Lightweight causing minimum influence on foundation and structures mass. The Steel bracing is usually less stiff than masonry or concrete buildings; therefore, they have to crack significantly before steel braces are effective. The bracing bays will require columns as well horizontal members as collectors to form complete truss. The effective slenderness ratio of brace kept relatively low so that braces are effective in compression as well as tension, suggested ratio are 80 to 60 or even lower

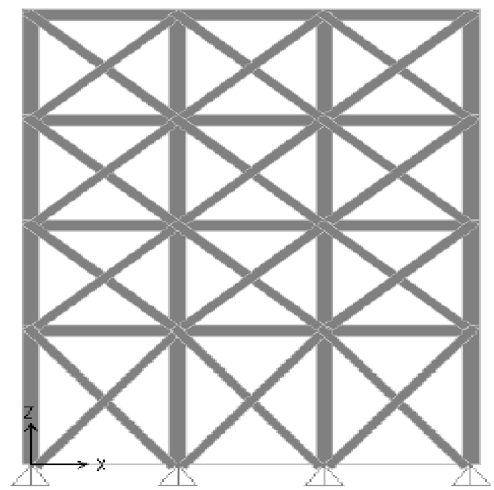

Fig. 5: Adding bracings

3.1.4. Base Isolation

If the building is resting on frictionless rollers and when the ground shakes during an earthquake, the rollers freely roll, but the building above does not move [1]. Thus, no force is transferred to the building due the shaking of the ground and the building does not experience the earthquake forces. Now, if the same building is rested on flexible pads that offer resistance against lateral movements then some effect of the ground shaking will be transferred to the building above. If the flexible pads are properly elected, then the forces induced by ground shaking can be a few times smaller than that experienced by the building built directly on ground. The flexible pads are called base-isolators, whereas the structures that secured by means of these devices are called base-isolated buildings (Fig. 6). The main feature of the base isolation technique is that it implements flexibility in the structure. The isolators are always designed to absorb energy and thus add damping to the system. This helps in further reducing the seismic response of the building. It is mostly suitable for low to medium-rise resting on hard soil.

Table 1: Applications of Control Systems buildings

Location	Building	Year	No. of storeys	Type of control
Japan	Kyobashi Bldg, Tokyo	1989	11	Active Mass Damper
Japan	Century Park Tower, Tokyo	1999	54	Hybrid Mass Damper
Japan	Osaka Resort City 200, Osaka	1993	50	Active Mass Damper
Taiwan	TC Tower, Kaohsiung	1999	85	Hybrid Mass Damper
India	La gardenia towers, south city Gurgaon	2000	7 Towers of 18 storeys	Pall friction dampers

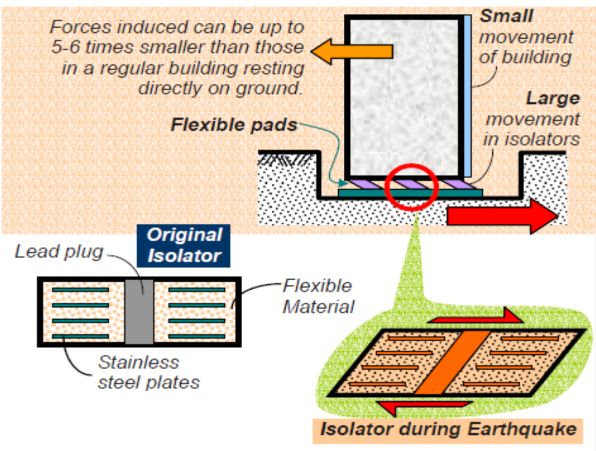

Fig. 6: Base isolation [1]

3.1.5. Mass Dampers

The mass dampers control the seismic damage in buildings and improve their seismic performance. This is done by installing seismic dampers in place of structural elements, such as diagonal braces. These dampers act as hydraulic shock absorbers as in cars, much of the sudden jerks are absorbed in the hydraulic fluids and only little is transmitted above to the chassis of the car.

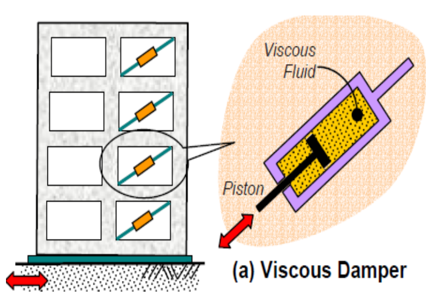

Fig. 7: Mass dampers [1]

When seismic energy is transmitted through them, dampers absorb part of it, and thus damp the motion of the building. Some of the actual applications of these systems worldwide are given in Table 1. The most commonly used different types of dampers (Fig. 7) are:

4. Local Retrofitting Techniques

Local retrofit technique refers to retrofitting of column, beam, joint, slab, wall and foundations. It is based on the reduction of seismic demands. Types of Local Retrofitting Techniques:

- Concrete jacketing.
- Steel jacketing.
- FRP sheet wrapping

4.1. Jacketing Of Beam

Concrete jacketing consists of addition of the layer of concrete, longitudinal bars and closely spaced ties. The jacket increase both flexural strength and shear strength of beam. Four different methods have been employed for jacketing of RC beam:

- Use of dowel connectors and micro-concrete.
- Use of bonding agent and micro-concrete.
- Combined use of dowel connectors, bonding agent and micro-concrete.
- Use of only micro-concrete without dowel connectors and bonding agents.

For Steel Jacketing, Steel sheets are used in beam to increase their flexure and shear strength. A steel sheet is bonded or bolted at the bottom face of the beam. This is considered for the strengthening of beam for gravity load. For seismic load, the shear strength can be enhanced by bonded or bolting sheet on the side face near the two ends of the beam.

4.2. Jacketing of Column

Columns in RC framed buildings may fail under the seismic loading, either in shear or in bending. Shear failure occurred due to the column sizes provided are inadequate to resist the seismic load and also due to the inadequate lateral ties provided. Bending failure occurs because of inadequate amount of steel bars provided vertically in the columns, particularly near the beam column joints or column foundation junctions, and it may also occurred due to poor quality of concrete. An example of typical section showing column Jacketting has been shown in Fig. 8.

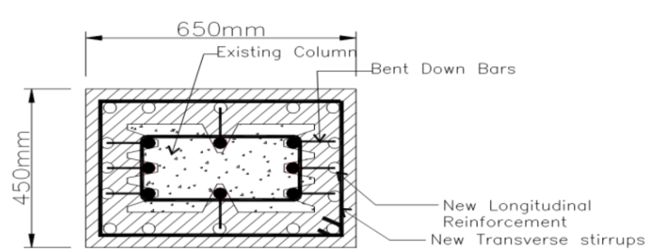

Fig. 8: Typical Section showing Column Jacketting

The original section of the column was 350mm X 550 mm. After designing the jacket for this existing column in SAP 2000, the jacketed column size came out to be 450mm X 650mm. RC Jacketting can be done by using Indian standard code IS 15988:2013.

4.3. Jacketing of Beam Column Joint

Beam-Column joints are the weakest link in RC moment resisting frame. The prime reason behind its failure is the inadequate shear strength of the joints, and this is occurred due to the insufficient and inadequate detailed reinforcement in the joint region. An example of typical section showing Beam-Column Jacketing has been shown in Fig. 9. The section of the column and beam were 160 mm X 300 mm and 160 mm X 350 mm respectively. After designing the steel jacket for this existing column and beam in ANSYS v12, the jacketed B-C joint size came out to be 180mm X 320mm and 180mm X 370mm respectively. The area of steel for beam and column is provided in table 2. Table 3 shows the deformation values. The deformation value for the beam column joint taken from the model given in the paper by Saleh H. Alsayed [5] is 16.71 *mm.* It is observed there is a great reduction of deformation after application of steel plate. Hence, the seismic performance of the beam column joint is significantly enhanced (Fig. 10). Reinforcement detailing of B-C joint is to be done by using Indian standard code IS 456:2000.

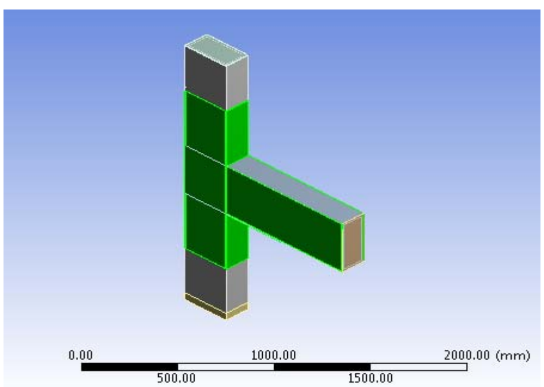

Fig. 9: B-C joint jacketing with steel plates

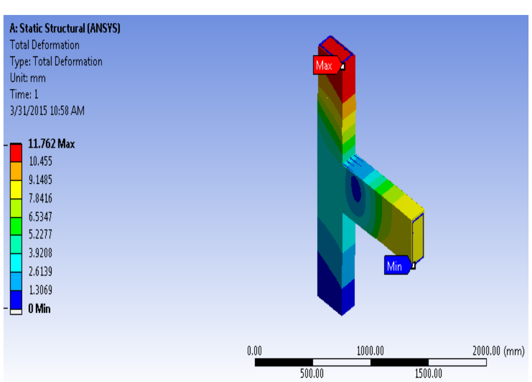

Fig. 10: Deformation after Jacketing

Table 2: Area of steel for beam and column

Load (N)	Area of steel for column (mm2)	Area of steel for beam (mm2)
4240	785	904

Table 3: Deformation before and after jacketing

Load (N)	Deformation (mm)	
	Before steel Jacketting	After steel Jacketting
4240	16.71	11.76

4.3.1 FRP and CFRP Jacketing

The failure of exterior beam column joint in moment-resisting frame buildings is identified due to shear failure of joint during earthquake [5]. For the purpose of improving shear strength, ductility and stiffness of the joint, fibre reinforced polymer (FRP) or carbon fibre reinforced polymer (CFRP) is the best implementation (Fig. 11). For the externally bonding of CFRP or FRP materials epoxy system is used. The epoxy system consists of two components. The first component is resin and other is hardener. It consists of 100 parts of resin and 34.5 parts of hardener by weight or 100 part of resin to 42 Parts of hardener by volume.

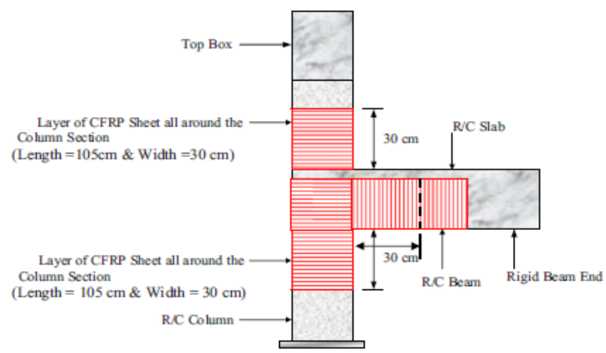

Fig. 11: B-C joint jacketing with CFRP sheets

To remove failure due to mechanical debonding, mechanical anchorage system (Fig. 12) is used. In this system FRP or CFRP sheets are fixed at the joint through two steel plates attached through bolts.

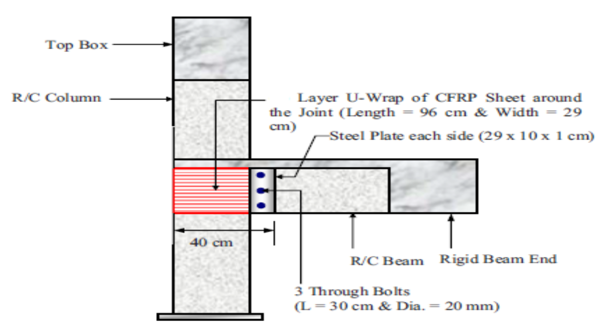

Fig. 12: B-C joint jacketing with mechanical anchorage system

4. CONCLUSIONS

The method of retrofitting gives the following advantages:

1. It increases the seismic resistance of the building.
2. It increases the ductile behaviour of the structure.
3. It increases the lateral load capability of the building.
4. Strength and stiffness of the building is improved.

Thus, applying Retrofitting techniques at the local and global level can help to eliminate a higher degree of damage which was otherwise either impossible or very difficult to achieve. For the purpose of increasing shear strength, ductility and stiffness of beam column joint other material like Textile reinforced mortar (TRM), Glass fibre reinforced polymer (GFRP) and additional cross bars at joints can also be used. The additional cross bars at joint region is an additional method to transfer shear stress.

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