SEISMIC RETROFIT FOR REINFORCED CONCRETE STRUCTURES: ANALYSIS / DESIGN TECHNIQUES

Abstract: This report covers the analysis and design for retrofitting the superstructure of reinforced concrete (RC) structures. Retrofitting is currently being performed because there is great risk involved with the present state of many structures located in active seismic areas. Structures that were built under previous design codes are vulnerable to partial or complete failure which endangers the lives of many. Recently, structural engineers have developed various rehabilitation techniques to strengthen the structural capacity of reinforced concrete structures. This report covers the different weak points of the structure that the structural engineer must look for in order to add resistance and ductility to the building. The report then goes on to describe the analysis that the engineer must go through during retrofitting from deciding the future level of performance of the structure to choosing the proper technique for retrofitting.

I. Introduction:

Reinforced concrete buildings from the past have been designed only for gravity loads. This is due to the lack of seismic provisions in codes that were in use before the 1970s. The root of the problem in a structure designed only for gravity loads is the lack of ductility in the structural. Structural engineers understand that it very costly and inefficient to design reinforced concrete (RC) structures to remain elastic during seismic loading. The designer is therefore accepting some safe level of plastic deformation. The capacity of the building to deform up to a safe level without collapsing is described by its ductility. Ductility describes the amount of displacement of a structure into the plastic level versus the yield displacement. It has been observed in recent earthquakes that RC concrete buildings which were designed to earlier codes experienced substantial structural damage due to inadequate lateral load resistance and limited ductility.

There are many different types of retrofitting techniques which in turn have different effects on the structures structural capacity. Some of these effects include: increase resistance, increase stiffness, decrease deformations (drift), increase ductility, and to allow stresses to distribute uniformly throughout the structure. When a building has been identified as a possible candidate for a retrofit, several factors will dictate the type of rehabilitation that will be implemented. First the engineer must meet with owner of the building and decide upon a future level of performance. The criteria for this performance will dictate the level of retrofitted needed. Second some analyses have to be done in order to asses the actual lateral load resistance and potential failure modes of the structure. With this analysis one can identify the weakest and most vulnerable components of the structure. It must be noted here that the design of a new structure varies largely from a retrofit design. In the design of a new structure the designer can implement ductile detailing which eliminates the problem of analyzing the structure for possible non-ductile modes of failure. The analysis for the simulation and evaluation of the behavior of an existing structure is in a state of development and is still short of being reliable and accurate for wide application (A. Ghobarah). Currently we have linear and nonlinear types of procedures for this analysis where we can perform a static or dynamic procedure. The advantages and limitations of these procedures will be discussed below.

After a structure has been analyzed, and its capacity has been quantified and the future needed capacity a retrofit scheme can be selected. The technique to be implemented should be the most efficient and safe procedure available. These techniques have evolved substantially since the 1990s and include retrofits at global or member levels. Their different applications and advantages to reinforced concrete structures will be discussed ahead. Through this report a structural engineer should gain a broader knowledge about the different problems that today's RC structures are facing and some basic information in the techniques to evaluate the structure and retrofitted.

II. Motives for seismic retrofitting:

For the structure to be retrofitted it must have some weak components that would be exposed during seismic loading. Ahead is a discussion of the different problems that a designer would have to look for in a structure to find clues about weak areas of the building or simply problematic configurations that could present a problem if an earthquake were to occur. Figure A shows a typical design a structure in a seismic active area before the 1976 UBC code changes.

Figure A. Reinforcement Details before 1976 UBC

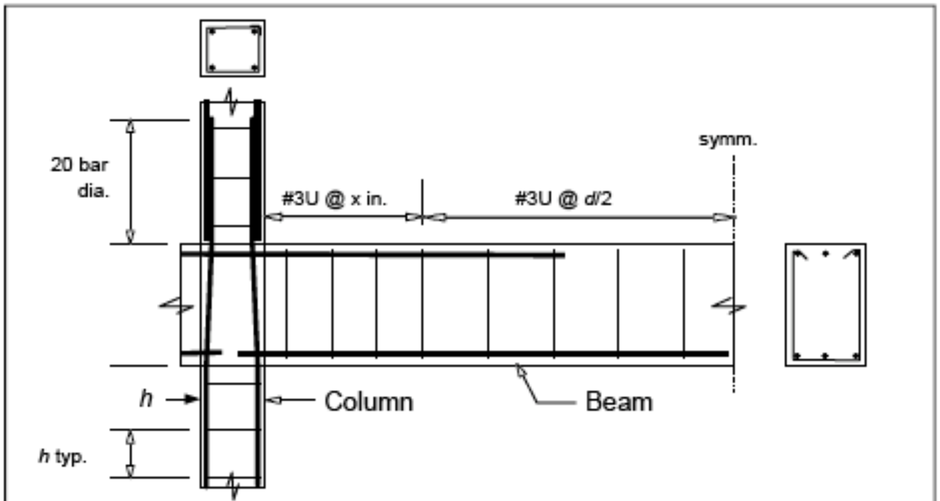


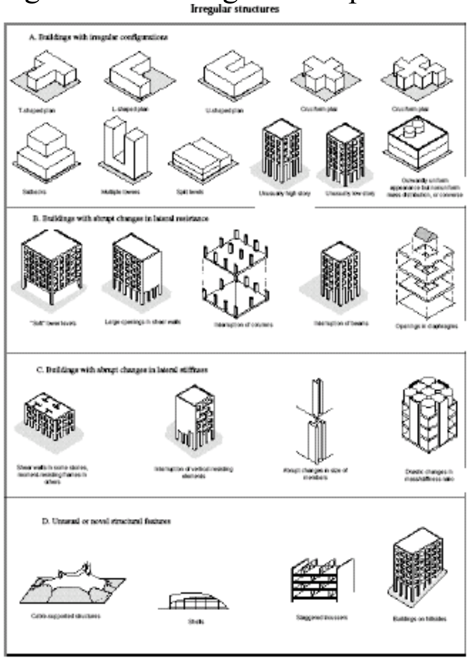
Figure 1 – Typical details before 1976 UBC

a. Architectural and Structural Configuration Problems:
   i. Architectural Configurations:
      1. Geometric Configurations: the following problems refer to the plan view of the structure.
         a. Length: short buildings perform better under seismic waves than long buildings because all the supports are concentrated around a specific area therefore experiencing similar vibrations. Engineers have found that partitioning the building in blocks with seismic expansion joints helps in

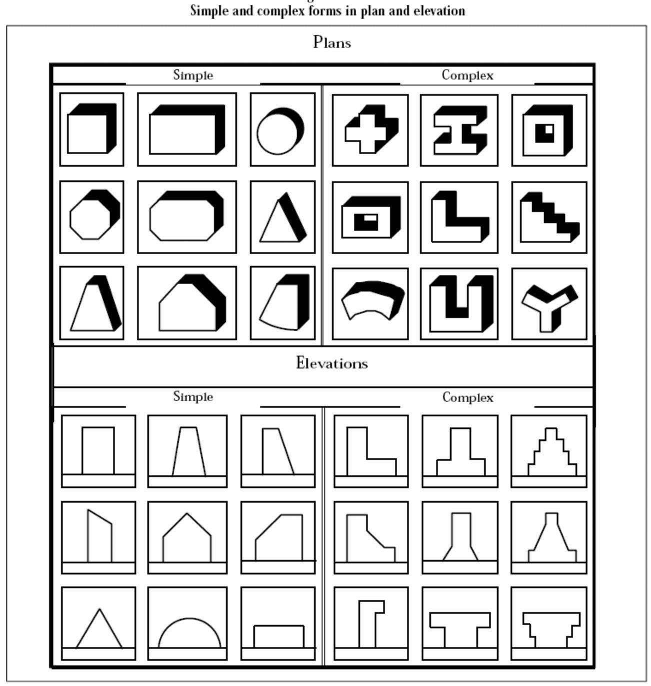
the response of the structure. Long buildings are also usually more prone to torsional or horizontal rotational effects because of differences in transverse and longitudinal movements.

b. Concentration of stress due to Complex Plans: buildings with complex floor plans with H, U, or L shapes tend to concentrate the stress in the transition areas. This produces damage to the non structural elements, the vertical structural, and the diaphragms. The solution is to introduce expansion joints which allow each segment to move independently. Examples of this can be observed in Figure B.

Figure B. Drawings of complex and irregular structures



Graphic interpretation of irregular structures or framing systems, from the Commentary to the SEAOC Recommended Lateral Stress Requirements and Commentary. Reproduced in Arnold, Christopher and Reitherman, Robert, *Building Configuration and Seismic Design* (John Wiley and Sons, New York 1982, p. 8). Reproduced with permission.

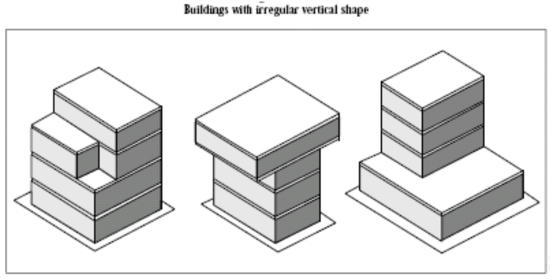


Source: Reprinted from Arnold, Christopher and Reitherman, Robert, ***Building configuration and seismic design*** (John Wiley and Sons, New York: 1982, p. 232).

Figure from www.proventionconsortium.org

2. Vertical Configuration Problem: Setbacks
Given by abrupt changes of stiffness and mass from one story to the next giving way to a non uniform concentration of stress in the areas close to these changes. Figure C shows three examples of this setbacks.

Figure C. Buildings with Setbacks (www.proventionconsortium.org)



ii. Structural Configuration:

1. Weak Columns-Strong Beam: under seismic loading the columns in a RC frame can be observed to form plastic hinges due to stiffer beams connecting into it. The formation of plastic hinges in a column gives story mechanism which usually cause the structure to collapse.

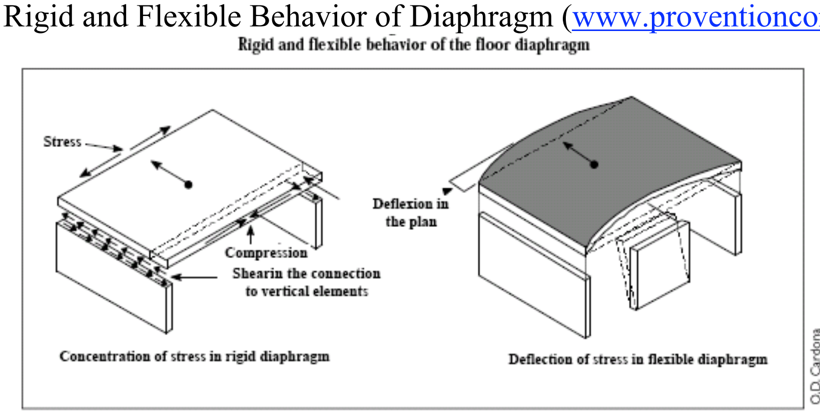
2. Soft Stories: soft stories correspond to those that are less stiff or less resistant. These soft stories are found in levels with differences in height between floors or stories which interrupt vertical structural elements (walls and columns). Soft stories tend to collapse under lateral loading.

3. Lack of Redundancy: a structure with few structural elements or a lack of redundancy will not be able to retransmit stresses when one member fails. It is important to have multiple load paths in order to avoid collapse.

4. Excessive Structural Flexibility: having excessive structural flexibility makes the structure susceptible to large lateral distortions between different stories under seismic loads. The root of these problems comes from long clear distances or spaces between supports. With previous earthquakes, engineers have found that these configurations tend to damage non structural elements attached to contiguous levels, and creates instability of the flexible floors or the building in general.

5. Excessive Flexibility of the Diaphragm: an excessively flexible floor diaphragm (Figure D) involves non-uniform lateral distortions, which are in principle prejudicial to the nonstructural elements attached to the diaphragm. There are several causes that the designer must investigate to understand the root of the problem. First, the flexibility of the diaphragm material. Steel without concrete is the most flexible. Second, the aspect ration (length/width) of the diaphragm can not be too large (greater than 5) or large lateral distortions will result. Third, the stiffness of the vertical structure should not vary too much between the elements in the plan. A better performance is expected in a diaphragm with elements of relatively equal stiffness. Last, openings in the diaphragm are a major cause of flexible areas.

Figure D. Rigid and Flexible Behavior of Diaphragm (www.proventionconsortium.org)



6. Torsion: torsion (Figure E) is produced by the eccentricity existing between the center of mass and the center of stiffness (Provention Consortium). Causes of torsion include the positioning of stiff elements asymmetrically with respect to the center of gravity of the story, and the placement of large masses asymmetrically with respect to stiffness. Usually a combination of the two above is found in most structures. The retrofitter should also keep in mind that dividing walls and façade walls that are attached to the vertical structure are usually very stiff and therefore cause torsion. Through previous research its has been stated that an eccentricity of greater than 10% between the center of mass and stiffness is considered problematic. This eccentricity problem is shown in Figure F. Torsional problems can get more complicated when there are vertical irregularities such as setbacks due to the upper part of the building transmitting an eccentric shear to the lower part which causes downward torsion of the transition level regardless of the structural symmetry or asymmetry of the upper and lower floors (Provention Consortium).

Figure E. Torsion Example

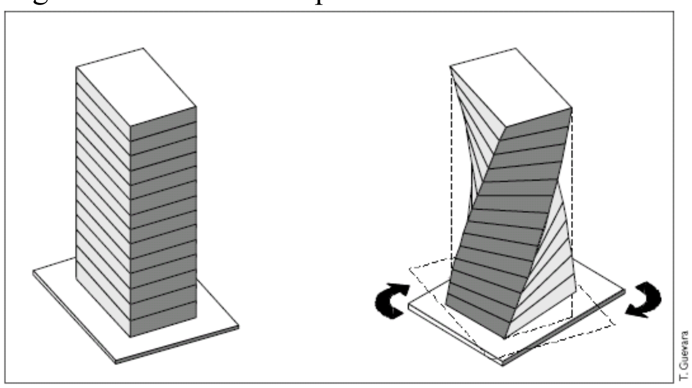


Figure from www.proventionconsortium.org

Figure F. Eccentricity as a cause of torsion

Eccentricity between centers of mass and stiffness increase effects of torsion.

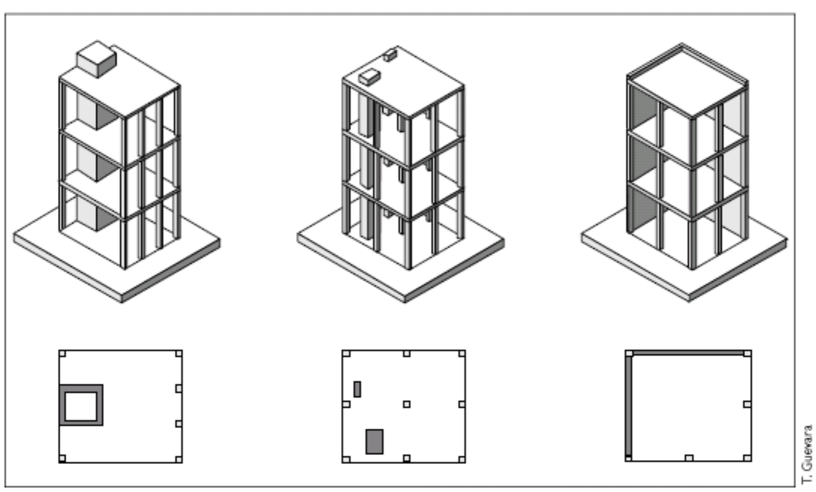


Figure from www.proventionconsortium.org

7. Long Term Effects of Cyclic Loading: cyclic loading due to wind in concrete causes damage, and in any retrofit job this must be taken into account so that the new additions to the structure will have the appropriate strength and ductility when an earthquake occurs. The duration of an earthquake is another important factor that must be taken into account because long earthquakes decrease the stiffness and resistance of the structures due to the many load cycles that it experiences. According to studies conducted in different countries, the duration of an earthquake correlates with its magnitude and the distance from the epicenter (Provention Consortium).

8. Location of structure with respect to fault: knowing the distance from site to design fault will be very important to the engineer because it will give him information on the magnitude and type of earthquake that the structure could be subjected to. For example a structure very close to a fault may experience pulse vibrations which is very dangerous for any RC structure. Knowing the distance and the history of the fault will also provide other important information such peak ground accelerations (PGA) for which the structure must be retrofitted to withstand.

9. Soil Properties and foundation conditions: the foundation plays an important role in retrofitting since it must be able to take the new loads and stresses which will be carried down sometimes through new paths.

10. Incomplete load path: the structural engineer must verify structural plans to look for incomplete load paths which under relatively large stresses could cause a member to fail and the structure to collapse.

11. Adjacent buildings for potential pounding: the possible maximum displacement of adjacent buildings must always be take into account in order to avoid structures pounding against each other while they oscillate under seismic loading.

12. Concrete or steel material deterioration with time and use: exposed steel reinforcement causes corrosion, and also concrete exposed to harsh conditions like salt water will be most likely in need of retrofitting. The lost of strength, and ductility in the steel and the concrete could give way to brittle failure under lateral loading.

13. Vulnerability of non structural components: non structural components such as walls and parapets could present a hazard if not properly attach to the structure. Most important these components could impede some structural elements such as columns to deform in a ductile manner.

14. Non-ductile detailing:
    a. Inadequate Column Shear Capacity: this is found in columns which do not have enough transverse reinforcement ties which provide shear resistance

and confinement. In previous non seismic construction these ties were not always detailed as close ties, and there spacing was larger than that needed to withstand earthquake loads.

b. Lap Slices: the lap slices of the column main reinforcing bars are normally located just above the floor level for convenience of construction (A. Ghobarah). Very high moments and stresses are found in this area due to lateral load. These lap slices were designed in compression and were not confined with closely spaced ties. This has been found to give anchorage failure of the spliced bar.

c. Joint shear resistance: in previous codes the joint shear resistance region was designed without any transverse reinforcement. It has been found that the exterior connections of beams and columns are more likely to fail than those of the interior frame because the interior connection is usually confined by the four connecting beams.

d. Anchorage of beam positive reinforcement at the beam-column joint: it was normal practice as given by the codes to discontinue the bottom reinforcement of a beam when approaching a support or to give it an insufficient embedment length. During lateral loading the continuation of this bottom reinforcement will aid the beam to stay connected to the column.

e. Inadequate beam shear resistance: the ties that prevented shear cracks were designed only for gravity loads, and were usually widely spaced along the beam. This permits plastic hinges to spread out throughout the beam compared to a beam designed for seismic loading were the hinge will form at a specified confined location (usually not to close to the connection).

f. RC structures can also experience brittle column failure through shear failure or compression crushing of concrete due to combined axial, flexural, and P-Δ effects.

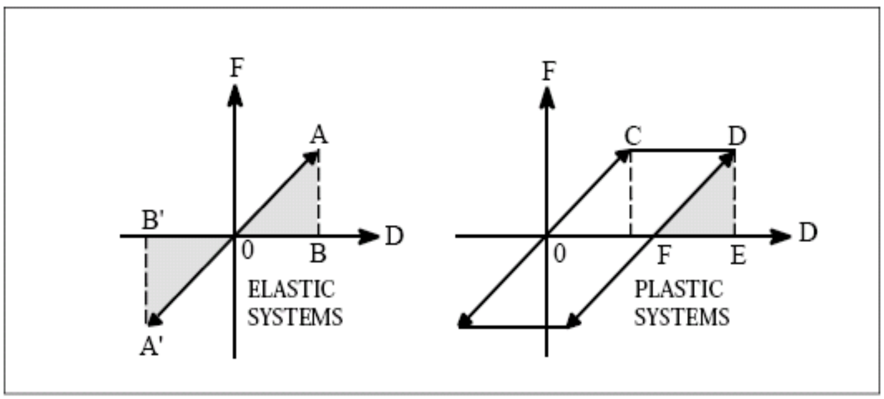
This characteristics include: increase resistance, increase stiffness, decrease deformations (drift), increase ductility, and to allow stresses to distribute uniformly throughout the structure. Most seismic codes are defined in terms of ductility so it is very important for the engineer to have an idea of the desired ductility level. Ductility which is defined as the ratio of displacement at failure to the yield displacement plays a crucial role in the retrofit of RC structures. The following table provides a description for different values of ductility. Figure G presents the difference between a perfectly elastic system, and the hysteretic behavior of a more real plastic system.

Table 6-6 Component Ductility Demand Classification

Maximum value of DCR or displacement ductility	Descriptor
< 2	Low Ductility Demand
2 to 4	Moderate Ductility Demand
> 4	High Ductility Demand

Figure G. Difference between Elastic and Plastic Systems

Absorption and dissipation of energy



III. Evaluation of Seismic Performance of Current Structures:

Once the engineers has identified possible problematic areas that must be retrofitted he/she must meet with the owner an decide upon a certain level of retrofit. This level will dictate how much work and care must go into the retrofitting job. There are four performance levels of construction: fully functional, operational, life safety, and near collapse

i. Fully Functional: at this level the building will be expected to remain in good conditions for normal use. It may have some limitations, but all the main supply systems and basic services must continue to operate. To comply with this performance it is necessary to have redundancy and emergency equipment.

ii. Operational: the structural capacity will function almost at the same structural capacity level that it did before the earthquake. Very limited damage to structural or nonstructural components will be observed. Access routes and safety systems such as stair and elevators should remain in operation. It is expected that people can remain in the building but a detailed inspection of the building is necessary after the event in order to perform some necessary repairs before the buildings is back to its full capacity.

iii. Life Safety: at this performance level significant structural damage will be observed. The building will not collapse because the structural members should not have completely failed. Even thou the building is stable, no one should stay inside due to the falling of rubble or non structural components. Aftershocks could cause collapse.

iv. Near Collapse: the structure will most likely suffer a partial or complete collapse. It is unlikely that structure could be retrofitted, and there will be serious risks for anyone inside the structure.

After a level of performance has been selected that structural engineer must asses the current capacity of the RC structure. There are various types of procedures available to engineers ranging from linear and nonlinear analysis to deformation based and reliability analyses that can be used for RC structures. The following types of analyses vary in complexity and will therefore give the designer a broad range of results varying in accuracy and reliability.

a. Human Inspection and Experience: First the experienced structural engineer will examine the structure for expected modes of failure or know member deficiencies. This examination will consist of visiting the site at least once and examining the structural and architectural plans.

b. Linear Analysis:

i. Static Procedure: If the Linear Static Procedure (LSP) is selected for seismic analysis of the building, the design seismic forces, their distribution over the height of the building, and the corresponding internal forces and system displacements shall be determined using a linearly elastic, static analysis in accordance with this section (FEMA 356). When using this method the structure is modeled with linear elastic stiffness. It will be modeled with equivalent damping values consistent with components responding at or near yield level.

ii. Dynamic Procedure: a wide range of computer software is available to perform this relatively simple procedure, but the results will not be very helpful in analyzing a possible retrofit since the RC structure is dependant on the inelastic displacement and deformation up to collapse. An example of a linear dynamic procedure is the response spectrum approach. It is based on the linear force response of an equivalent single-degree-of-freedom system. This procedure has many limitations such as not accounting for different failure modes and its sequence; also it does not provide information on the degree of damage or the ultimate collapse mechanism of an existing damaged RC structure.

c. Non-Linear Analysis

i. Static Procedure (Push-Over Analysis): in the push over analysis the structure is subjected to a lateral load that represents approximately the relative inertial forces generated at locations where large amounts of mass are found such as floor levels. The non-linear static load pattern is increased in steps and the lateral load-roof displacement response is increased until a specified level is met or collapse occurs. The designer will record internal forces and deformations found in the structure at the specified level of displacement, and these stresses will then be compared with the stresses in the structure after it is retrofitted for a specified performance. The results of this type of analysis will be influenced by the distribution of the lateral loads on the structure. Current practice simulates the dynamic real inertial load by an equivalent static load. For structures which would experience first mode motion, the lateral load is modeled as a uniformly distributed load along the stories or as an inverted triangular type load distribution. For medium and high rise buildings were higher motion modes will be experienced the load distribution should assimilate the real load patterns seen in the time-dependant distribution of inertia forces. If the load patterns are not updated with the progress of inelasticity they will fail to account for the redistribution of inertial forces due to local inelasticity and hinging mechanisms. Researches have come up with some adaptive load patterns which include story loads proportional to the lateral deflected shape of the building, using square root of the sum of squares load pattern based on a combination of mode shapes derived from secant stiffness at each load step and applied story loads proportional to story shear resistance at the previous loading step (A. Ghobarah).

- Advantages: the push over analysis will provide the following information:
  - Force demands of potential brittle elements
  - Deformation demands for elements that have to deform elastically
  - Identifies critical regions and the consequences of strength deterioration of elements in this region
  - Identifies strength discontinuities in plan or elevation
  - Interstory drifts which account for strength or stiffness discontinuities and P-Δ effects
  - Estimate of global drift in order to ensure no pounding against adjacent structures
  - Verifies completeness and adequacy of load path.

- Limitations:
  - Analysis can get very complex especially if 3-D modeling is needed.
  - Choosing an appropriate lateral load when higher modes are considered.
  - A procedure to account for the effect of the vertical load component of the seismic vibrations is yet to be implemented into the push over analysis.
  - The accuracy of the results may be in question for special or irregular structures.
  - It may not give precise information about the structure seismic demand (ductility demand).

ii. Dynamic Procedure: the inelastic dynamic process employs a dynamic time history dependant procedure past the elastic limit up to collapse. Currently designers have two methods to complete this procedure: microscopic finite element analysis, and macroscopic phenomenological models. It is not usefull to analyze an entire structure with Microscopic finite element analysis because of the computational power required so it is mostly used to model specific elements in the structure. Currently the results of an inelastic dynamic procedure are doubtful due to many uncertainties in the input. The current limitations which give uncertainty are the characterization of ground motion, determination of material properties, variations in the geometrical dimensions and assignment of acceptable limits on structural behavior.

d. Deformation-based assessment:
   In this procedure the displacement capacity of the structure is evaluated against displacement demand or a target deformation criterion. With this procedure the flexural strength is used to determine the base shear capacity and failure mechanism. With the shear capacity known one can check whether the failure mode is shear or flexure. The specified rotation capacity of the expected plastic hinge gives way to the calculation of the story drift capacity. Assuming an equivalent single degree of freedom the yield and ultimate deformation capacity of the structure as well as its ductility can be determined from the displacement spectra. The ductility demand is used to asses the vulnerability of the structure.

e. Reliability Assessment
   This procedure involves performing nonlinear dynamic analysis of the building many times. It accounts for uncertainties in different parameters such material strength, component dimensions, and ground motions by using Monte Carlo simulation. The simulation is carried out by using a large number of actual records scaled to different levels of peak ground acceleration (PGA). Nonlinear dynamic time history analyses are performed using the set of ground motion records. The state of damage in the structure is predicted using damage indices (A. Ghobarah). This process is the most complete representation of the actual behavior of the structure, but it is time consuming.

In order for the structural engineer to compared the results of the structural capacity of the existing building with a qualitative description of the desired future performance level he/she must take into account various performance indicators. Serviceability, yield, and ultimate limit states are defined by local and global criteria in order to asses the performance of structures beyond the first yield and up to ultimate limit state (A. Ghobarah).

a. Serviceability Limit State: involves concrete crack control by specifying limits on the concrete and on the steel strains. It can also involve deformation control by limiting inter-story or roof drift levels.

b. Yield Criteria: these criteria are specified by the local yield of reinforcing steel in tension or at a global level by the response of an equivalent elastic-plastic single degree of freedom system.

c. Local Ultimate Limit State: These criteria includes rupture of reinforcement steel by subjecting the steel to ultimate failure strain, concrete crushing by exceeding the failure strain of compression, bond slip due to cracks which are controlled by the strain at which the member cover spalls off, the deformation capacity of the member as specified by its ultimate curvature capacity or the inelastic rotation capacity of the joints, ultimate shear given by the strength of the steel, shear supply and demand analysis, and local damage index which is very useful to quantify the lateral load carrying capacity and the reserve capacity of the existing structure. It is very important to take into account the order in which the limits of the discussed criteria are achieved because this will dictate the mode of failure of the structural component.

d. Global Ultimate Criteria: Includes maximum deformations levels which can be analyzed as the maximum drift at roof level or maximum inter-story drift. These criteria can also be defined by the global index approach such as the instability index or the global damage index.

IV. Seismic Retrofit Techniques

Before choosing a technique the engineers must be aware of the limitations he boundaries he/she will encounter in the job. The rehabilitation objectives must be selected by the building owner or code official prior to evaluation of the existing building and selection of a retrofit, if needed (J.W. Bai). Limitation Factors Controlling Retrofit Techniques:

i. Physical and Functional Aspects: retrofitting should not affect the operations of those that work or live in the structure, and it should be structurally and aesthetically compatible and complementary to the existing structure. The retrofit should take carefull considerations not to damage the non structural elements in the buildings

ii. Aspects of Structural Safety: retrofit must reduce possible seismic damage to an acceptable level. It must give adequate stiffness, strength, and ductility

iii. Construction Techniques: retrofitting techniques need to be gear towards the specific environment and problem in order to not disturb the operations of the structure.

iv. Cost versus importance of structure: high costs are associated with retrofits were the level of safety is at its peak value and when the retrofit must be completed fast and with minimal effects on the buildings activities.

v. Performance Objective: In the seismic assessment of existing structures, it is sometime desirable to compare the capacity of the structure against performance objectives (A. Ghobarah). This objective will be defined by the desired level of acceptable damage or to prevent collapse during an earthquake with certain probability of exceedance. The performance level chosen must take into account safety of the occupants or that the structural can continue operations after the earthquake. Currently as specified by codes the minimum level of performance expected from a structure is to accept some damage but not to the point of collapse. Structures can also undergo much more expensive retrofitting as necessary. An example of highest possible level of retrofit could be performed for a hospital in a city which is far away from any other medical help. Another important factor affecting the retrofit is deciding what earthquake loadings the structure has to withstand. For the highest level of retrofitting the controlling seismic loading can be that of the known highest level of shaking possible at the location or it can also be defined by the probability of exceedance of a certain earthquake magnitude.

vi. Available workmanship: complex and effective retrofits need experienced and knowledgeable workers. If the proper personnel is not available, the retrofit should maybe just involve more traditional accepted techniques.

vii. Reversibility of the retrofit: in some cases the owner of the structure might not be able to afford the perfect retrofit but has intentions of carrying out a complete retrofit in the future. In these cases the engineer should take into account that future retrofits will take place, and his design should be done in way so that future engineers can easily retrofit the structure without undergoing major complications.

viii. Level of quality control: there is great uncertainty associated with the quality of materials used in construction. Concrete and steel must undergo a stringent level of quality in order to ensure proper retrofit. Also, welding requires great level of quality control.

ix. Political or Historical Significance: sometimes the political or historical significance plays an important role in retrofitting. Only certain techniques can be used in the case of historical significance, and maybe only certain materials could be used in the case of political influence.

x. Sufficient capacity of foundation system: the foundation must be able to resists the new seismic loads that it is being retrofitted for.

Finally the engineer can choose the retrofitting method. By this point the engineer knows the weak areas of the structure and its current structural capacity, has a target performance level, and understands the limitations that he/she will have while performing the work. Structure Level Retrofit-Global: with this approach the structural modifications are geared towards achieving that the displacement or design demands of structural and nonstructural elements are less than their capacities. The following are some common global retrofitting schemes for RC structures.

Figure H. Global Retrofit

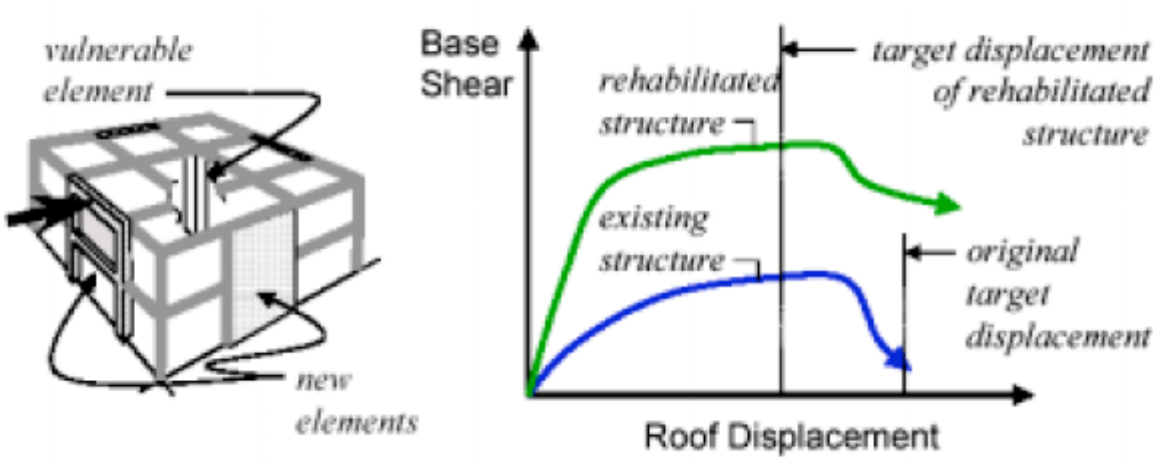


Figure from J. P. Moehle

a. Addition of structural walls (exterior and interior): the objective of this method is to reduce lateral drifts, as well as to avoid story mechanisms. The walls must be distributed along the floor plan to achieve a stable regular building configuration. It is also important to take into account the transfer on inertial forces to the walls through floor diaphragrams, struts, and collectors. The retrofit must be able to integrate and connect the wall into the existing frame, and transfer the loads to the foundation.

b. Diagonal Steel braces: increases global strength and stiffness and reduces drift of RC structures. One advantage of this retrofitting scheme is that in general no changes need to be made to the foundation because the steel braces are installed between existing members, but the foundation must always be checked for increased loading at the location of the braces. It is very important for the designer to analyze the details of the connection of the brace and buckling possibilities.

c. Base isolators: The objective of this type of retrofit scheme is to isolate the structure from the ground motion during earthquake events (J.W. Bai). Typically this bearings or isolators are installed between the foundation and the superstructure therefore controlling vibrations by isolating the foundation. Researchers have found this technique to be especially effective for relatively stiff low rise buildings with heavy gravity loads.

Figure I. Rubber Bearing

d. Addition of Buttresses: gives confinement and reduces drift. Buttresses are placed perpendicular to the face of the building. Buttresses are also useful in preventing tall, narrow buildings from overturning. These are not very popular usually due space limitations.

e. Addition of Interior or Exterior Moment Resisting Frame (Dual System): sometimes it is possible to attach a new frame to the old structure.

Figure J. Examples of Global Retrofits

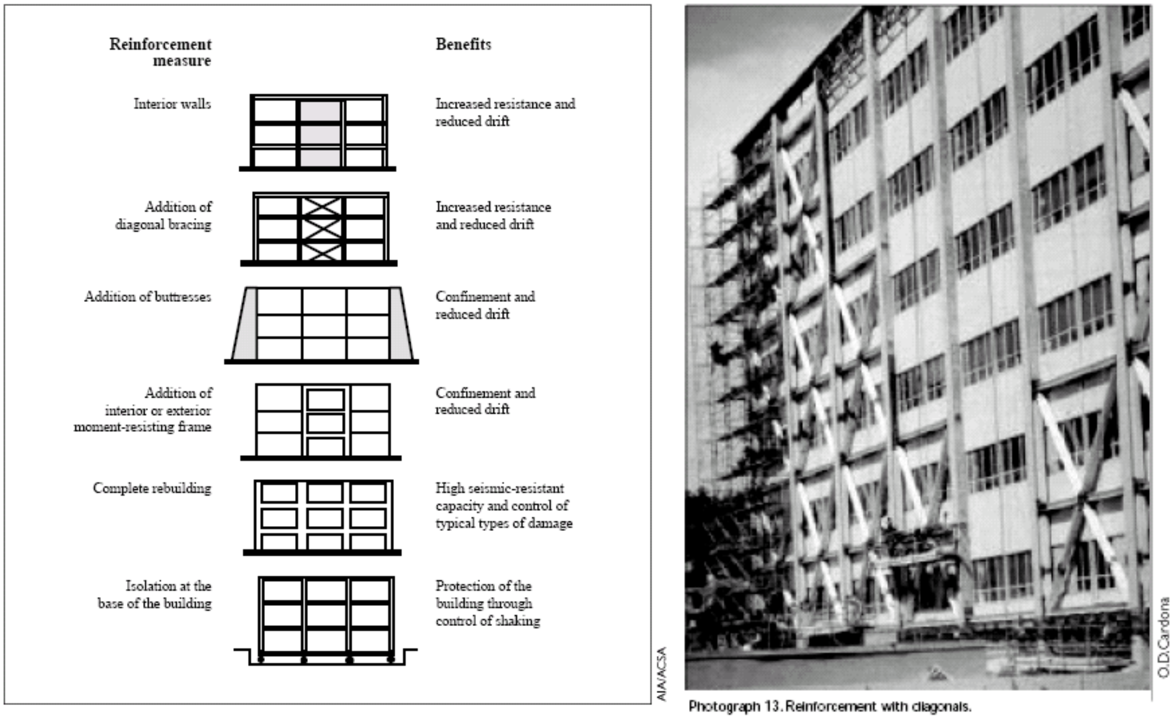


Figure from www.proventionconsortium.org

f. Friction Devices: These devices have strengthening properties as well as damping characteristics. At low deformations (before slip) the structure is stiffened, and at larger deformations just strengthen (A.M. Reinhorn, M.C. Constantinou, C. Li). The designer must take into account the durability and longevity of the friction devices. Metal to metal friction characteristics may change with time due to corrosion. The following materials when in contact are known to cause corrosion: steel on steel, and bronze or brass on steel.

g. Fluid Viscous Dampers: fluid dampers (Figure K) consist of stainless container filled with silicon fluid, a stainless piston with bronze orifices and accumulators. The forces produce by a pressure difference across the piston head. The resistant force is proportional to the velocity of the piston. During seismic loading the fluid would get compressed which would develop a restoring force, which essentially stiffens the structure. This stiffening can be prevented or diminished by using an accumulator. Another fluid viscous device is the use of viscous walls which have shown to produce low stiffness at low frequencies (high periods). The higher stiffness found in these walls may produce an increase in story shears.

Figure K. Viscous Damper

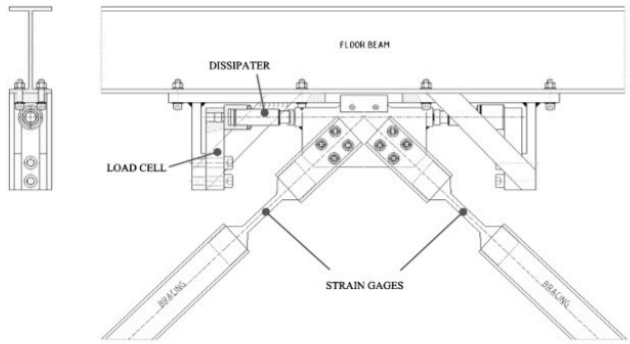


Figure from Molina, Sorace, Terenzi, Maginette, Viaccoz

h. Viscoelastic Devices: These devices consist of bonded viscoelastic layers of acrylic polymers. The use of viscoelastic dampers in RC structures has proven effective to reduce large amounts of energy. One limitation that the designer must take into account is that this devices then to change their elastic behavior with small change in temperature.

Member Level Retrofit-Local: the purpose of this approach is to increase the capacity of specific structural members so that they will not reach their design limits. This type of retrofit shown in Figure L might represent a more cost effective scheme compared to the global level retrofits because only certain components of the structure would be retrofitted. In this following section the techniques are presented under each type of structural member since a designer would retrofitting a column would only be interested in the column retrofit techniques.

Figure L. Local Retrofits

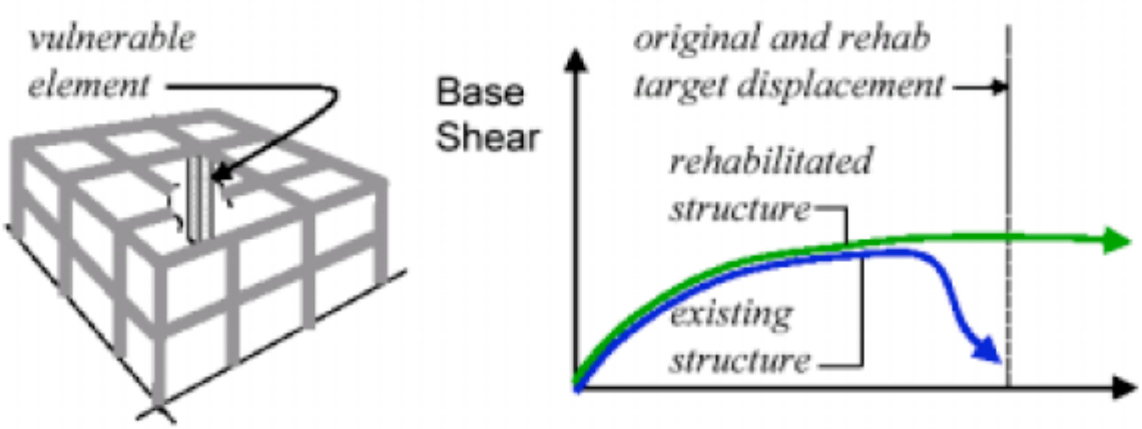


Figure from J. P. Moehle

a. Column and Beams:
   i. Steel sections can be attached to the RC columns so the new column acts as a composite column with increased ductility.

ii. Fiber Reinforced Polymers Composite (FRPC) Jackets: this technique is implemented to increase columns or beams shear and flexural strength so that they do not fail and cause story mechanisms. FRPC unidirectional sheets are wrapped around the columns as jackets to confine the columns and this confinement prevents the formation of plastic hinges. For non-ductile columns designers are retrofitting them by passing new longitudinal reinforcement through the floor systems and encasing it concrete jackets.

iii. Welding: lap slices of column longitudinal reinforcement can be improved by several techniques including removal of cover concrete and welding overlapped bars, confining the lap by steel or reinforced concrete jackets.

b. Column-Beam Connection:

i. Steel cases have been made to retrofit beam-column connections.

ii. FRPC technique has also proven effective to retrofit beam-column joints by wrapping the connection in FRPC. Component strength should be taken to not exceed any limiting strength of connections with adjacent components. Jackets should be designed to provide increased connection strength and improved continuity between adjacent components (FEMA 356).

iii. Epoxy: epoxy has been used to repair cracks in slab-column connections. Epoxy has proven to restore load capacity, but does not restore the initial stiffness of the connection. Epoxy and Carbon Fiber Reinforced Polymer (CFRP) in combination can restore both peak lateral load capacity and initial stiffness of the connection.

c. Slab:

i. Concrete Capitals or Steel Plates: punching shear failure due to transfer of unbalanced moments has been found to be very common in RC slabs. To retrofit a slab column connection designers are adding reinforcing drop panels in the form of steel plates on both sides of the slab or adding concrete capitals around the slab-column area. Both techniques have proven to strengthen the connection around the critical perimeter.

d. Shear Walls:

i. Steel Strips: steel strips can be used to retrofit concrete walls by increasing their in-plane strength, ductility and energy dissipation capacities. Also the anchor bolts along the vertical strips can be placed to provide lateral support to the end bards of the existing reinforced concrete/masonry walls, helping to eliminate their premature buckling (M. Taghdi, M. Bruneau, M. Saatcioglu).

ii. Frictional Wall Damper: the frictional wall damper (Figure M) consists of Teflon slider and a RC wall. The proposed damper can be effective in mitigating the seismic responses of RC frame structures and in avoiding damage to the RC structural members (C.G. Cho, M. Kwon).

Figure M. Friction Wall Damper

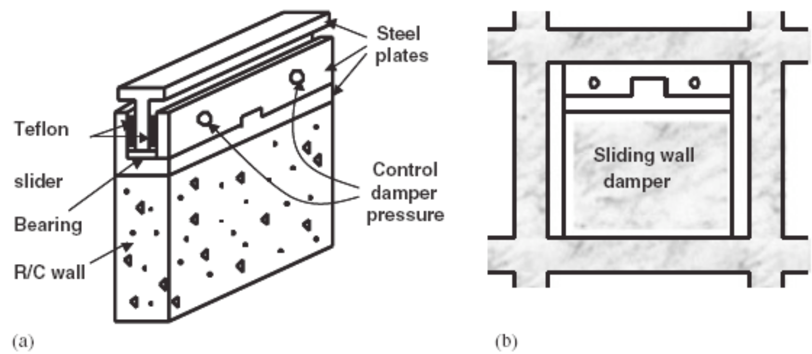


Figure from C.G. Cho, M. Kwon

e. Post-tensioning existing beams, columns, or joints using external post-tensioned reinforcement. Post- tensioned reinforcement should be unbonded within a distance equal to twice the effective depth from sections where inelastic action is expected. Anchorages should be located away from regions where inelastic action is anticipated, and should be designed considering possible force variations due to earthquake loading (FEMA 356).

f. Foundation: foundation rehabilitation is not covered in details in this literature review, as this paper focuses on the retrofitting of the superstructure. Details for retrofitting the foundation can be found on FEMA 356 C6.13.4.1&2. Some of the retrofitting techniques include enlarging the foundation laterally, provide tension hold-downs, increase depth of foundation, improving existing soil, adding grade beams, and adding piles to support the foundation.

V. Conclusion

In this report the analysis and design for retrofitting the superstructure of (RC) structures was discussed. In order to bring structures up to current seismic codes and appropriate safety levels different local or global level retrofits are being performed. Structural engineers have developed various rehabilitation techniques to strengthen the structural capacity of reinforced concrete structures. Due to the nature of earthquakes to find the path of least resistance and their ability to exploit that weak area it is the structural engineer objective to add resistance and ductility to the building. The technique to be implemented should be the most efficient and safe procedure available. The different techniques presented aim to increase resistance, increase stiffness, decrease deformations (drift), increase ductility, and to allow stresses to distribute uniformly throughout the structure. At a global level, techniques such as base isolators, brace additions, shear walls, viscoelastic devices, etc were discussed. At the local (member) level the retrofits were categorized under their respective members and include the use FRPC jackets, post tensioning steel, steel plates, and the addition of steel reinforcement, etc. The info presented is merely an introduction to the broad field of seismic retrofitting, and it is complement with the Appendix which contains an example of a push-over analysis and an actual retrofit of a column

VI. References

F. J. Molina, S. Sorace, G. Terenzi, G. Magonette, B. Viacozz, Seismic Tests on Reinforced Concrete and steel frames retroffited with dissipative braces, Earthquake Engineering and Structural Dynamics, 2004; 33:1373-1394

I.N. Robertson, G. Johnson, Repair of Slab-Column Connections Using Epoxy and Carborn Fiber Reinforced Polymer, Journal of Composites for Construction ASCE, September/October 2004

J. Paterson, D. Mitchell, Seismic Retrofit of Shear Walls with Headed Bars and Carbon Fiber Wrap, Journal of Structural Engineering ASCE, May 2003

C.G. Cho, M. Kwon, Development and modeling of a frictional wall damper and its applications in reinforced concrete frame structures, Earthquake Engineering and Structural Dynamics, 2004; 33:821-838

K.S. Lee, C.P. Fan, R. Sause, J. Ricles, Simplified design procedure for frame buildings with viscoelastic or elastomeric structural dampers, Earthquake Engineering and Structural Dynamics, 2005; 34:1271-1284

M. Taghdi, M. Bruneau, M. Saatcioglu, Seismic Retrofitting of Low Rise Masonary and Concrete Walls Using Steel Strips, Journal of Structural Engineering ASCE, September 2000

Ghobarah, Seismic Assesment of Existing RC structures, Prog. Struct. Engng Master, 2000, 2:60-71

J. P. Moehle, State of Research on Seismic Retrofit of Concrete Building Structures in the US, US-Japan Symposium and Workshop on Seismic Retrofit of Concrete Structures-State of Research and Practice

K.W. Neale, FRPs for Structural Rehabilitation: a survey of recent progress, Prog. Struct. Engng Master, 2000, 2:133-138

J. W. Bai, Seismic Retrofit for Reinforced Concrete Building Structure, Consequence-Based Engineering (CBE) Institute Final Report, August 2003

Prevention Consortium, Chapter 2 – Structural Vulnerability:
http://www.proventionconsortium.org/files/mit3-chapter2.pdf#search='chapter%202%20structural%20vulnerability'

FEMA 274-NEHRP Commentary on the NEHRP Guidelines for the Seismic Rehabilitation of Building

FEMA Evaluation of Earthquake-Damaged Concrete and Masonry Wall Buildings, FEMA 306-308, 1999

FEMA 310-Handbook for the Seismic Evaluation of Buildings: A Prestandard

FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings

FEMA 357-Global Topics Report on the Prestandard and Commentary for the Seismic Rehabilitation of Buildings

S. D. Kim, W. K. Hong, Y. K. Ju, A modified dynamic inelastic analysis of tall buildings considing changes of dynamic characteristics, The Structural Design of Tall Buildings, 8: 57-73, 1993

MA Aschheim, JP Moehle, A. Lynn, Earthquale Performance Assessment of Concrete Structures, Construction Research Communications Limited 1999

Carrillo, Seismic Isolation for Small Reinforced Concrete Structures: A Preliminary Investigation of Material Cost, New Mexico State University

M. Saiid, F. Martinovic, B. McElhaney, D. Sanders, F. Gordaninejad, Assesment of Steel and Fiber Reinforced Plastic Jackets for Seismic Retrofit of Reinforced Concrete Columns with Structural Flares, Journal of Structural Engineering ASCE, April 2004

R. Perera, S. Gomez, E. Alarcon, Experimental and Analytical Study of Masonary Infill Reinforced Concrete Frames Retrofitted with Steel Braces, Journal of Structural Engineering ASCE, December 2004

C. P. Antonopoulos, T.C. Triantafillou, Experimental Investigation of FRP-Strenghtened RC Beam-Column Joints, Journal of Composites for Construction, February 2003

Y. Xiao, H. Wu, G.R. Martin, Prefabricated Composite Jacketing of RC Columns for Enhanced Shear Strength, Journal of Structural Engineering, March 1999

H. M. Santhi, GMS Knight, K. Muthumani, Evaluation of Seismic Performance of Gravity Load Designed Reinforced Concrete Frames, Journal of Performance of Constructed Facilities ASCE, November 2005

S Hans, C Boutin, E Ibraim, P Roussillon, In Situ experiments and seismic analysis of existing buildings. Part I: Experimental investigations, Earthquake Engineering and Structural Dynamics, 2005, 34:1513-1529

AM Reinhorn, MC Constantinou, C Li, Use of Supplemental Damping Devices for Seismic Strengthening of Lightly Reinforced Concrete Frame, NIST Workshop 1995

S Bruno, C. Valente, Comparative Response Analysis of Conventional and Innovative Seismic Protection Strategies, Earthquake Engineering and Structural Dynamics, 2002, 31:1067-1092

W. Liao, C.H. Loh, S. Wan, Earthquake Responses of RC Moment Frames Subjected to Near-Fault Ground Motions, The Structural Design Tall Buildings, 10:219-229, 2001

AE Schultz, SS Welton, LE Rey, Long Term Effects on Response of Reinforced Concrete Columns to Cycloc Loading, Journal of Structural Engineering ASCE, September 2004