Rehabilitation and strengthening of structures for lateral loads

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ABSTRACT: In several countries, there are plans for systematic strengthening of infrastructure and public buildings such as bridges, schools, government buildings, utilities and power plants. However, there remains a large stock of vulnerable residential buildings that are in obvious need of rehabilitation. Recently, much research work and advances have been made in retrofitting techniques for structural elements such as beams, columns, beam-column joints and walls. The use of several techniques and materials such as advanced composites has been evaluated, tested and proven effective in the strengthening of structural components. In addition, energy dissipating and bracing systems have been developed. The objective of this study is to provide an evaluation of the element strengthening and systems approach to retrofitting of structure. To increase the effectiveness of rehabilitation and strengthening techniques and reduce their cost, selective and systems approach to rehabilitation and strengthening are examined.

1 INTRODUCTION

Over the past few decades significant progress has been made in the field of retrofit and rehabilitation of structures. Many existing structures were designed and built before the development of recent codes. Over time, structures suffer deterioration, wear and tear, corrosion of reinforcement steel or increase in applied loads. Recent events such as the 1999 Koceali, Turkey, the 2008 Wenchuan, China and the 2010 Chile earthquakes demonstrated that vulnerable buildings represent a high risk to life. To reduce the risk to life and considerable economic loss, existing structures need to be evaluated and strengthened. In several countries, there are plans for systematic strengthening of infrastructure and public buildings such as bridges, schools, hospitals, government buildings, utilities and power plants. However, there remains a large stock of vulnerable residential buildings that are in need of rehabilitation. The application of successful rehabilitation techniques to residential buildings is lagging for several reasons including the high cost and interruption to occupants and the function of the structure.

There are several approaches to the rehabilitation and strengthening of structures depending on the building configuration, materials of construction and the structural system. Recently, much research work and advances have been made in retrofitting techniques for structural elements such as beams, columns, beam-column joints and walls. Several techniques and materials such as jacketing and advanced composites has been tested, evaluated and proven effective in the retrofit of structural components. Selective and systems approach to rehabilitation and strengthening have been investigated. These techniques are effective and reduce the rehabilitation cost. The objective of this study is to provide an evaluation of element strengthening as compared to systems approach to rehabilitation of structures.

2 ELEMENT REHABILITATION

The moment resisting frame is one of the most common structural systems in many existing low to medium-rise residential and industrial buildings. Gravity load designed frames contain a number of non-ductile reinforcement details, as illustrated in Figure 1. The deficiencies include:

a. Short length and inadequate confinement of the column lap splice.
b. Insufficient embedment length of the bottom reinforcement at the beam-column joint.
c. Lack of joint shear reinforcement.
d. Inadequate shear reinforcement in beams and columns due to wide spacing of stirrups and ties.

The rehabilitation of such buildings is necessary to minimize the risk to occupants and reduce the potential for economic loss. An optional retrofit system is to strengthen beams, columns and beam-column joints. In general, the philosophy of improving the behaviour should include improvement of the ductile behaviour of the frame. This can be achieved by eliminating brittle failure modes and allowing ductile failure to occur. Therefore improvement of the seismic behaviour of deficient frames may involve shear strengthening of the beams and confinement of the plastic hinge regions of beams and columns and the retrofit of the beam-column joints to prevent joint shear failure.

For two decades extensive research efforts were directed to the rehabilitation of various structural elements such as beams, columns, beam-column joints and structural walls. different techniques have been studied to increase flexural, shear or torsional strength and ductility of various structural elements. Flexural strengthening of beams was initially conducted by Kaiser (1989), Saadatmanesh and Ehsani (1990), Triantafillou and Pelvris (1992). Berset (1992), Al-Sulaimani at al (1994) an, Chajes et al (1995) conducted the research on shear retrofitting of beams. Ghobarah et al (2002) studied torsional strengthening of beams using advanced composites. An example of the shear retrofit application of a reinforced concrete bridge girder is shown in Figure 2.

Strengthening of circular and rectangular columns using reinforced concrete, steel jackets and advanced composite materials were investigated by many researchers including Saadatmanesh et al (1996) and Ghobarah and Galal (2004). Wrapping columns with horizontal fibres for confinements also improved the shear capacity of the column. In the case of rectangular columns, limited improvements in the overall behavioural parameters such as maximum load, ductility and energy dissipation capacity were achieved. The reason for the limited success is the problem associated with confining of rectangular sections.

Ghobarah and Said (2001, 2002), El-Amoury and Ghobarah (2002), Ghobarah and El-Amoury (2003) investigated the behaviour of retrofitted beam-column joints using advanced composites to eliminate joint shear failure. Example of eliminating joint shear failure and instead transferring the failure to ductile beam hinging, is shown in Figure 3.

Testing of retrofitted structural walls using fibre reinforced polymers was successfully conducted by Khalil and Ghobarah (2005). The behaviour of the wall was simplified by considering the wall as consisting of two end columns elements carrying the moment in the form of axial forces and the middle part of the web resisting the applied shear. Wall retrofit is designed as confinement to the end column elements and shear reinforcement of the web. An example of wall retrofit is shown in Figure 4.

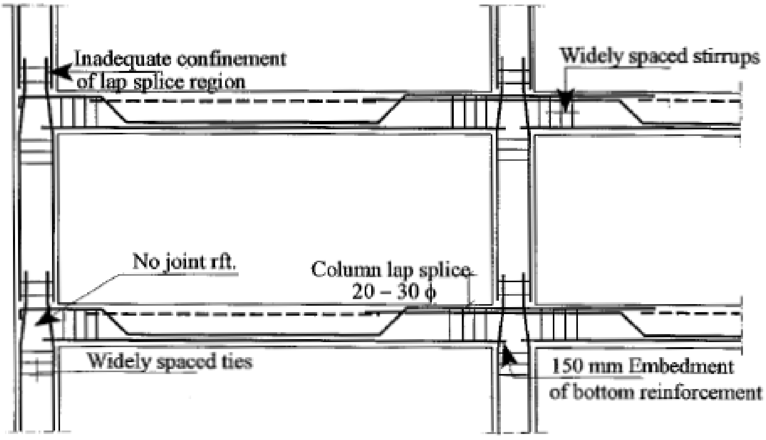


Figure 1. Typical deficiency in existing moment resisting frames.

Figure 2. Shear strengthening of a concrete bridge girder

Figure 3. Beam hinging in a rehabilitated joint.

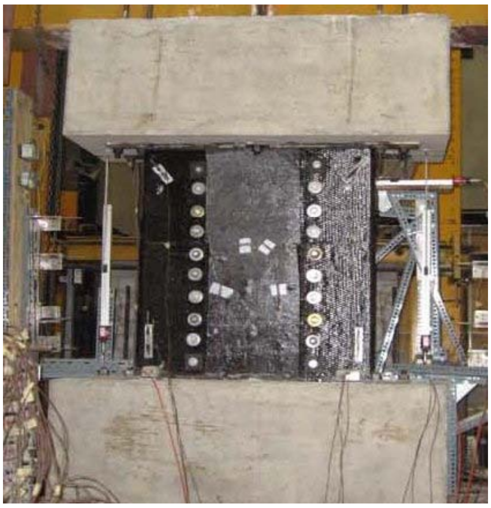


Figure 4. Front view of the rehabilitated wall

3 SYSTEMS APPROACH TO STRENGTHENING

The technology exists for the effective rehabilitation of various structural elements. However, practical applications of such techniques to the RC frame are not an easy task because of the large number of beams, columns and beam-column joints. This is a labor intensive and costly undertaking that will interrupt the function of the building for a long period of time. Systems approach to the rehabilitation of structures may involve selective rehabilitation of specific elements. The elements to strengthen are determined from analyzing the behaviour of the entire structure. As an alternative, the strengthening techniques may involve the addition of a separate structural system capable of carrying part of the load or the entire vertical or lateral loads. The new system would be designed to prevent collapse of the structure. Some of the effective systems include the introduction of concentric or eccentric steel bracing systems, structural walls or base isolation. As examples of systems approach to rehabilitation, two of the applications will be addressed; a) the selective rehabilitation; and b) the use of concentric steel bracing system.

3.1 Selective rehabilitation

A three story RC frame was gravity load designed to the pre-seismic ACI -318 (1963) code. The dimensions and reinforcement of the beams and columns are shown in Figure 5.

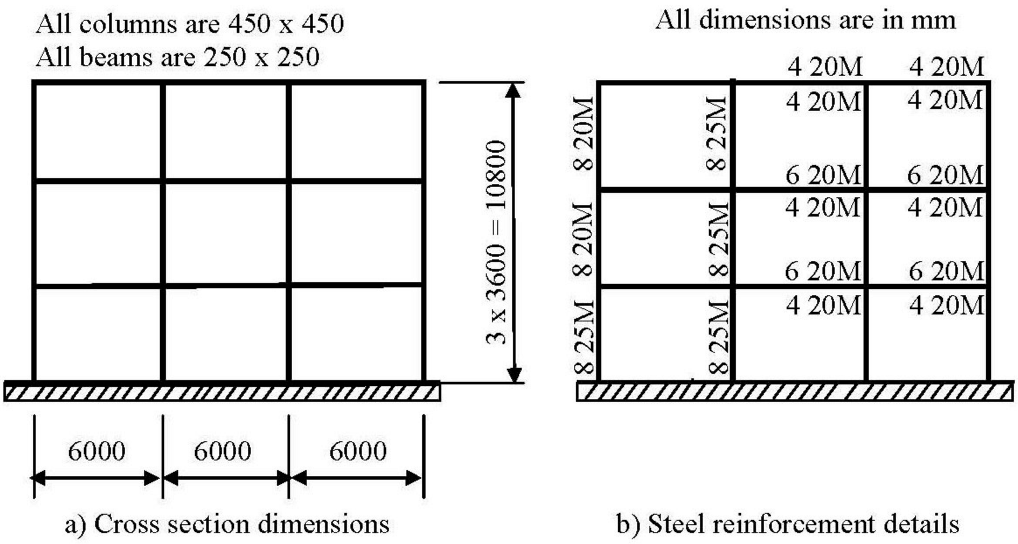


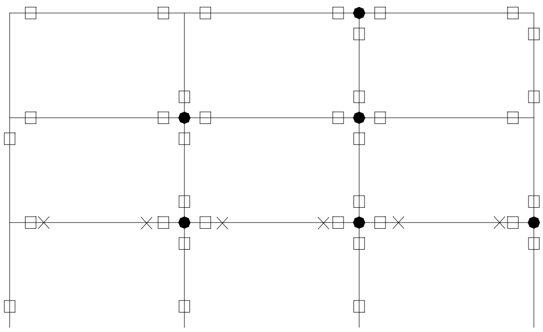
Figure 5. Dimensions and reinforcement of the three-story frame.

The lateral load carrying capacity of the frame as designed was assessed by pushover analysis and nonlinear dynamic analysis using the PC-ANSR computer code. Two earthquake records: the 1940 El Centro and the 1985 Mexico records, scaled to different peak ground accelerations (PGA) were used as input to the time history analysis. The inelastic behaviour of the frame is shown in Figure 6. In the figure, the component failures leading to the frame collapse were identified. Two rehabilitation strategies were applied to the frames. The first strategy consisted of jacketing all the beam-column joints using fibre reinforced polymers, FRP. A second rehabilitation strategy was adopted to selectively rehabilitate the six specific beam-column joints identified in Figure 6. To simplify the interpretation of results, all other deficiencies were assumed to have been addressed. Again the rehabilitated frames were analyzed using pushover and nonlinear dynamic time history analyses using two actual earthquake ground motions scaled to different peak ground accelerations. The fully and selectively rehabilitated frames were analyzed to compare their behaviour to that of the existing frame. The pushover analysis and final softening damage index were used to assess the lateral load carrying capacity and the potential damage to these frames. The selective use of FRP jackets for the frame joint rehabilitation was found to reduce drift and damage as it reduces shear deformations and the opening of joint cracks. The final softening global damage index was selected for its simplicity. This damage index (DI) is based on measuring the change in the fundamental period of the structure due to changes in stiffness relative to the initial condition. The final softening damage index is defined as:

$$DI = 1 - \left(\frac{T_{initial}}{T_{final}}\right)^2 \qquad (1)$$

where $T_{initial}$ and T_{final} are the fundamental periods of free vibration before and after application of the seismic loading, respectively. The damage index varies from 0 for no damage to 1.0 at collapse. At a value of 0.75, the frame is considered to be on the verge of collapse.

As example of the results, the relationship between the applied PGA and the resulting damage index for the three frames is shown in Figures 7. The figure shows a plot of the variation of the level of damage as represented by the damage index with ground motion intensity as represented by the PGA.



• Joint shear failure × Bond slip failure □ Concrete softening failure

Figure 6. Inelastic behaviour of the 3-story frame.

The rehabilitation technique involving jacketing all the frame joints reduced the damage index from 0.89 for the existing three-story frame subjected to El Centro earthquake scaled to PGA of 0.75 g, to 0.5 while the selective rehabilitation technique reduced the damage index to 0.74 at the same load level. The full-rehabilitation technique reduced the damage index from 0.91 for the existing three-story frame subjected to Mexico earthquake scaled to PGA of 0.75 g to 0.77 while the selective rehabilitation technique reduced the damage index to 0.86 at the same load level. The damage level of the rehabilitated frame indicates that it may be saved from collapse by the rehabilitation of all the joints and by selective rehabilitation. In the case of a frame where all the beam-column joints were rehabilitated, the resulting damage is small up to PGA of approximately 0.4 g. After this level, the damage increases rapidly due to the opening of the shear cracks. Similar trends in the results were obtained for the maximum interstory drift and base shear.

The selective rehabilitation represents half the effort and close to half the cost of the full rehabilitation, since 6 out of 12 joints were retrofitted. The improvement in the frame response due to the selective rehabilitation was less than half that of the full rehabilitation.

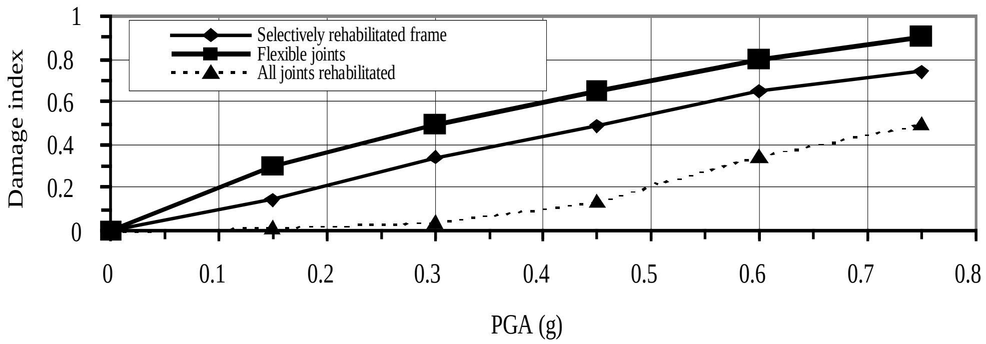


Figure 7. Damage relationship for the 3-story frames due to the El Centro earthquake scaled to different PGA.

3.2 Concentric steel brace

The deficient reinforced concrete frame can be strengthened by installing concentric steel brace in the different bays. An example of a steel brace installed in a bay of a frame is shown in Figure 8. Steel bracing may be installed in one or several stories along the height of the frame. The seismic responses of four rehabilitation cases R1, R2, R3, and R4 shown in Figure 9 were evaluated to study the effect of the brace distribution along the building height. In the bracing case R1, the brace members were selected as round hollow sections (HSS 114 × 8) and were distributed uniformly over the frame height. This case represents the common practice in brace design and will be used as a reference case. For the other three rehabilitation cases, the brace properties (P_c / P_y), (P_r / P_c), radius of gyration (r) and total area are kept constant. The selected brace properties in this particular design were: modulus of elasticity = 200,000 MPa, yield strength, f_y = 350 MPa, P_c / P_y = 2.41, P_r / P_c = 0.33, r = 37.7 mm and KL/r = 113, where P_y is the brace yield load, P_c was the initial buckling load, and P_r is the residual buckling load. Details of the analysis and design are given by Abou Elfath and Ghobarah (2000).

To compare the efficiency of the four rehabilitation systems on equal basis, the total brace area was maintained constant. The parameter Γ_i represents the brace area distribution along the height. Case R1 has a uniform distribution of brace area along the height. Rehabilitation case R2 has a decreasing brace area over the height. The steel brace area in the first story is half the total brace area used in R1. The steel brace areas used in the second and third stories of case R2 are 1/3 and 1/6 of the total brace area, respectively. In the rehabilitation case R3, the total brace area is distributed equally between the first two stories, while in the fourth case R4 the total brace area is distributed only in the first story. The performance of the four rehabilitation cases was investigated by the pushover analysis using DRAIN-2DX computer code. The inverted triangular lateral load distribution was selected which is similar to the lateral design load distribution suggested by the design codes. Example of the results is shown in Figure 10. The figure shows the base shear variation with the roof drift ratios of the existing and the rehabilitated buildings. The ratios between the initial stiffness of the rehabilitation cases R1, R2, R3, and R4 and that of the existing building are 3.7, 3.7, 3.0, and 1.8, respectively. Bracing one or two of the building stories caused lower increase in the rehabilitated building stiffness by comparison to the cases when all the building stories are braced. The ratios of the increased lateral capacity to the capacity of the original existing frame was calculated as 2.0, 2.5, 2.3, and 1.3 for the rehabilitation cases R1, R2, R3, and R4, respectively.

Figure 8. A reinforced concrete frame strengthened using a concentric steel brace.

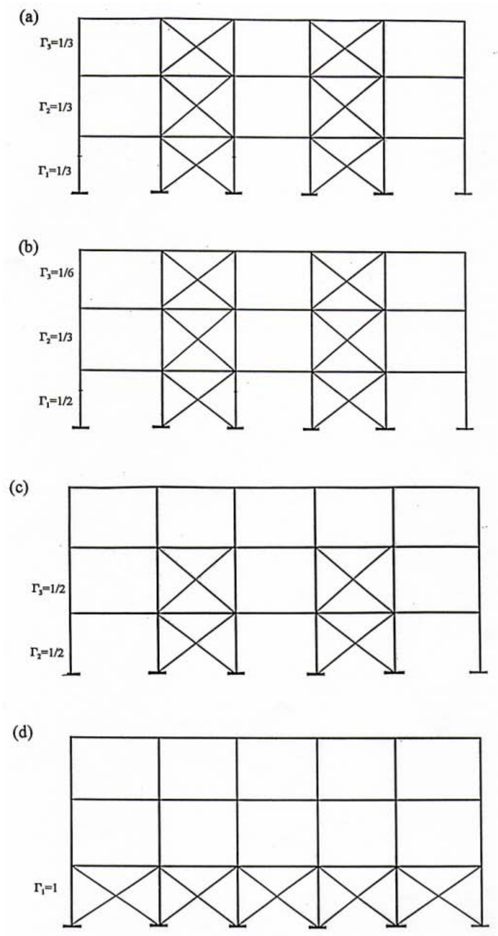


Figure 9. Rehabilitation cases for nonductile 3-story building: (*a*) case R1; (*b*) case R2; (*c*) case R3; (*d*) case R4.

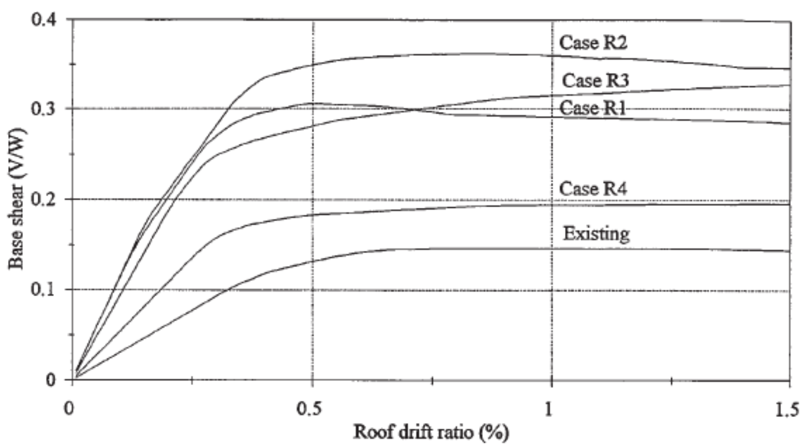


Figure 10. Performance curves of the various rehabilitation cases from the pushover analysis.

Instead of using concentric steel brace for the retrofit of reinforced concrete moment resisting frame, eccentrically braced steel system or structural wall system could be used. In these cases similar behaviour of the retrofitted system was obtained.

4 CONCLUSIONS

- The rehabilitation of all structural elements of a deficient reinforced concrete nonductile frame is not practical because of the large number of elements involved.
- Selective rehabilitation strategy that focuses on strengthening critical beam-column joints was found to be cost effective when compared to the rehabilitation of all the joints.
- The systems approach to rehabilitation by designing steel bracing system or adding structural walls is effective in the strengthening of existing vulnerable nonductile low- to medium-rise buildings. There was improvement in the seismic performance of all the rehabilitation cases in spite of the increase in the seismic demand due to change in the building stiffness. However, rehabilitation cases involving abrupt change in stiffness due to the brace, result in poor seismic performance.
- Adding steel bracing uniformly along the height of an existing nonductile building may not represent the optimum solution. The distribution of brace strength over the height of the building should be selected to obtain a uniform distribution of storey drift.

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