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SELECTIVE COLUMN REHABILITATION OF RC FRAMES

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SUMMARY

Many existing reinforced concrete frame structures were designed to earlier codes with low lateral load resisting capacity. The reinforcement details of these nonductile frames do not normally conform to current understanding of ductile seismic detailing. This type of existing construction is common worldwide and represents a significant hazard to life during earthquakes. The cost of retrofitting these structures to current code standards may be prohibitive. However, the use of selective rehabilitation techniques offers an effective and economical approach to the rehabilitation of this class of structures. In this study, the seismic performance of existing thirty-year old reinforced concrete buildings is assessed. The effectiveness of different rehabilitation strategies for the columns is evaluated as column retrofit of existing deficient reinforced concrete frames is a widely used approach. The selective upgrading strategies includes increasing the column strength, stiffness, improving ductility or a combination of these factors.

A three-storey frame which represents low-rise structures and a 9-storey frame which represents medium-rise buildings, are discussed. In order to eliminate the variability of ground motion input, a probabilistic analysis using Monte Carlo simulation is conducted. A large number of ground motion records scaled to various peak acceleration levels is used. Selective column rehabilitation is introduced in the form of increased strength, stiffness, improved ductility and the combination between strength and stiffness. The performance of existing and rehabilitated frames is analysed using nonlinear dynamic time history analysis. The state of damage to the structure is estimated using a damage index procedure. The drift, base shear, peak ground acceleration and damage levels are used as performance indicators in order to compare the performance of various reinforced concrete frames.

The results of the analysis show that for a low-rise building, increasing the strength of the columns is the most effective rehabilitation technique for reducing drift and damage. Increasing ductility is associated with high drift and the potential for lower damage. Increasing the column stiffness only is found to be detrimental as the structure attracted higher seismic demands. For medium-rise structures, increasing the column strength reduces the drift and damage. Increasing the column stiffness results in small reduction in drift and damage. The improvement of ductility results in modest reduction in damage and marginal effect on the storey drift due to the flexibility of the taller structure.

INTRODUCTION

During the past several decades, losses due to earthquakes have increased around the world at an alarming rate. The number of earthquakes and their strength have not increased but there is an increase in vulnerability due to increase in the density of population centres, rapid urbanization, industrialization and economic activities. In large population centers, there are many structures which were built before modern codes were available. During recent earthquakes such as the 1994 Northridge and the 1989 Loma Prieta earthquakes, the behaviour of reinforced concrete buildings designed to earlier codes or prior to the seismic design requirements did not

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behave satisfactorily because of insufficient lateral capacity and limited ductility due to nonductile detailing. Many of the existing buildings are gravity load designed with little attention paid to the lateral load resistance. These structures are deteriorating with time and many of them are long past their design lives. They represent a significant hazard to life during earthquakes.

There is the misconception among designers that existing structures need to be upgraded to meet current code provisions. The design of a rehabilitation system is not normally conducted following established criteria to provide the specified safety requirement at the minimum cost. Attempting to make existing buildings comply with the current code provisions may be economically prohibitive. Rehabilitation objectives for the structure should rather depend on a performance based criteria to ensure a defined level of damage or to prevent collapse of the building during a specified level of ground motion (SEAOC 1995; and Ghobarah et al. 1997). The selection of the retrofit system and the level of protection to the structure are the important decisions in the design process. To provide the basis for these design decisions, it is necessary to evaluate the effect of various retrofit systems on the performance of the structure and to quantify the upgrade to the seismic performance. This approach will provide effective targeted rehabilitation schemes that are cost effective.

There are many studies on various rehabilitation techniques (Anicic 1994; Endo et al. 1984). However, very little guidance is available for formulating the rehabilitation strategy for the structure. An interesting study on selective rehabilitation of short walls was conducted by Elnashai and Pinho (1998). Column retrofitting is one of the widely used techniques for upgrading the lateral load carrying capacity of reinforced concrete buildings. Several schemes are available for retrofitting reinforced concrete columns. Upgrading the column performance normally involves increasing its strength, ductility, stiffness or in most cases a combination of two or the three parameters. Available test results provide information on the performance of the column. However, it is not clear what is the effect of each strategy on the overall behaviour of the structure in terms of drift and damage potential when subjected to a design ground motion. Although in most cases it is difficult to change the stiffness without affecting the strength and ductility of a column, the effect of the change in each aspect of behaviour will be examined separately in order to investigate the selective and targeted rehabilitation strategies for columns.

The objective of this study is to assess the seismic performance of existing thirty-year old 3-storey and 9-storey reinforced concrete buildings and to evaluate the effectiveness of different rehabilitation strategies for the columns. The selective upgrade strategies includes increasing the column strength, stiffness, improving ductility or a combination of these approaches. The analysis will provide the basis for decisions concerning the rehabilitation strategy for nonductile reinforced concrete frames and the design of selective and cost effective rehabilitation techniques.

METHODOLOGY

Two examples of existing thirty-year old frames are analysed. A three-storey frame represents low-rise structures and a 9-storey frame representing medium-rise buildings. In order to eliminate the variability of ground motion input, a probabilistic analysis using Monte Carlo simulation is conducted (Ghobarah et al., 1998). A large number of ground motion records scaled to various peak acceleration levels is used. In the probabilistic analysis, an artificially generated ground motion is used to evaluate the response of the structure. Using the appropriate probability distribution parameters for material strength and dimensions of the structure, a random set of properties of the structure is generated to be used in the analysis. This approach will provide a basis for comparative evaluation of the performance of various frames. Selective column rehabilitation is introduced in the form of increased strength, stiffness, improved ductility and the combination between strength and stiffness. The load-displacement performance curve for the structure is determined using the nonlinear static pushover analysis. The performance of the existing and rehabilitated frames is determined using nonlinear dynamic time history analysis. A selected damage index relates the peak ground acceleration (PGA) to the probability of exceedance of different damage and drift levels. The selected damage index for use in the analysis is that proposed by Park et al. (1984). The drift, base shear, peak ground acceleration and damage levels were used as performance indicators in order to compare the performance of various reinforced concrete frames.

REHABILITATION STRATEGY

To achieve the rehabilitation objectives of a specified damage level, collapse prevention or life safety, different design strategies may be adopted. The relationship between strength and ductility shown in Figure 1, shows that the required strength diminishes with increasing the ductility because of the improved inelastic behaviour and energy absorbing characteristics of the system. If the structure is to resist a given earthquake with minimal damage to the structure or its contents, the main concern will be the control of drift and the required strength will not be ductility dependent. A maximum drift limit can be established to protect against damage to nonstructural elements. The combination of collapse prevention and various damage levels produce a curve that divides the strength-ductility plane into adequate and inadequate zones as shown in Figure 1. A similar representation was used by Jirsa (1996) to combine collapse prevention and life safety limits on the strength-ductility plot.

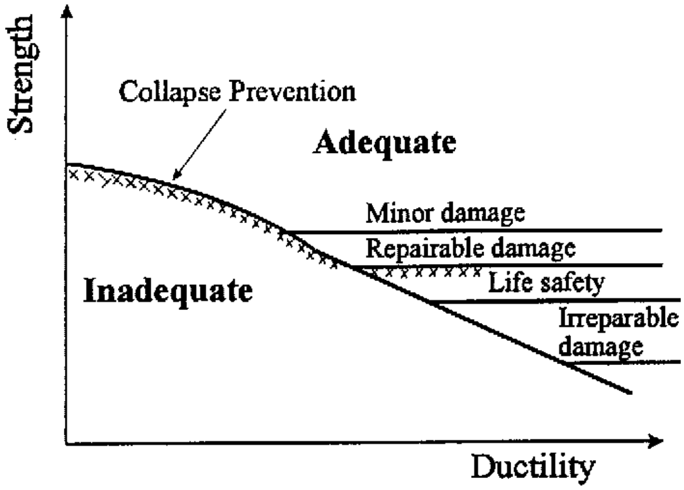


Figure 1 Typical ductility-strength relationship

Collapse Prevention Consideration

Different redesign options to achieve collapse prevention include increasing the stiffness, strength and /or ductility. The corresponding moment-curvature relationship for each rehabilitation scheme is shown in Figure 2. Different strategies are required to suite different types of structures. Increasing the strength is particularly suited for the design of stiff structures. Enhancing the ductility is well suited for brittle members and frames when it is required to improve the seismic resistance of a structure without strengthening it. Increasing the stiffness is particularly suited for the design of flexible structures as it is an effective measure in reducing drift. In practice, the stiffness increase is normally associated with increased strength. Several other strategies such as base isolation and the addition of structural redundancies may also be evaluated. The final selection of a specific scheme will also depend on economical, architectural and structural considerations. However, the present study is focussed on column rehabilitation.

Limited Damage Considerations

To reduce or eliminate damage to a structure or its contents, the deflections of the structure must be limited. The strategies for satisfying this requirement include increasing the stiffness of the structure. Such changes in stiffness may be accompanied by increase in strength. In addition, non-structural elements may be isolated from the lateral load resisting system so that large deformations do not damage them. The change of the structure stiffness during rehabilitation has the impact of reducing the periods of free vibration of the structure. The reduction in the period may be associated with an increase in seismic demand. In most structures a combination of both strategies will be required to reduce the damage to a level that does not interrupt the operation of the building after the earthquake.

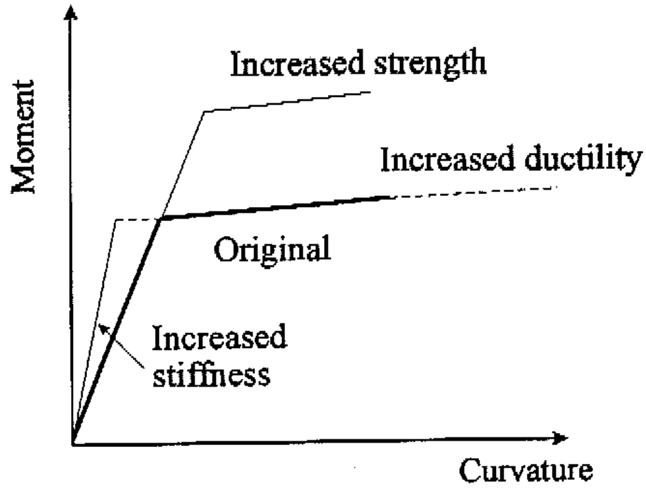
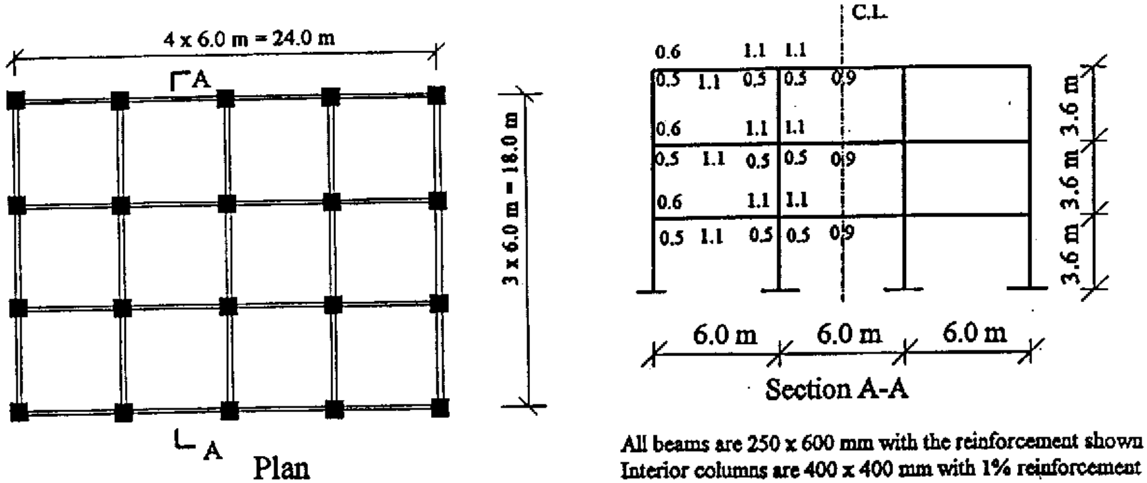


Figure 2 Moment-curvature relationship of various rehabilitation strategies

The described methodology is applied to the analysis of two nonductile reinforced concrete office buildings. Figure 3 shows the layout, elevation and plan of the 3-storey building while Figure 4 shows the design details of the 9-storey building. The frames are gravity load designed in the 1960s. The design live load was taken equal to 2.4 kN/m2. The steel reinforcement yield strength and the concrete compressive strength are 300 MPa and 21 MPa, respectively. The reinforcement detailing includes light shear reinforcement in columns and beams. Dimensions of the columns and beams and their reinforcement details are also shown.



All beams are 250 x 600 mm with the reinforcement shown
Interior columns are 400 x 400 mm with 1% reinforcement
Exterior columns are 300 x 300 mm with 1.25% reinforcement

Figure 3 Layout of the reinforced concrete 3-storey office building

SELECTIVE COLUMN RETROFIT SCHEMES

Four different schemes for retrofitting the columns of the frames are adopted as illustrated in Figure 2. In the first scheme, the strength of all columns is increased by 30% (Frame F1). The second retrofit scheme is designed to increase the ductility of all columns by 100% (Frame F2). In the third scheme the stiffness of the columns is increased by 500% (Frame F3). Since in practice, the stiffness increase is normally associated with a corresponding increase in strength, in the fourth retrofit scheme the stiffness is increased by 500% and the strength is increased by 50% at the same time (Frame F4). The existing frame is denoted Frame F.

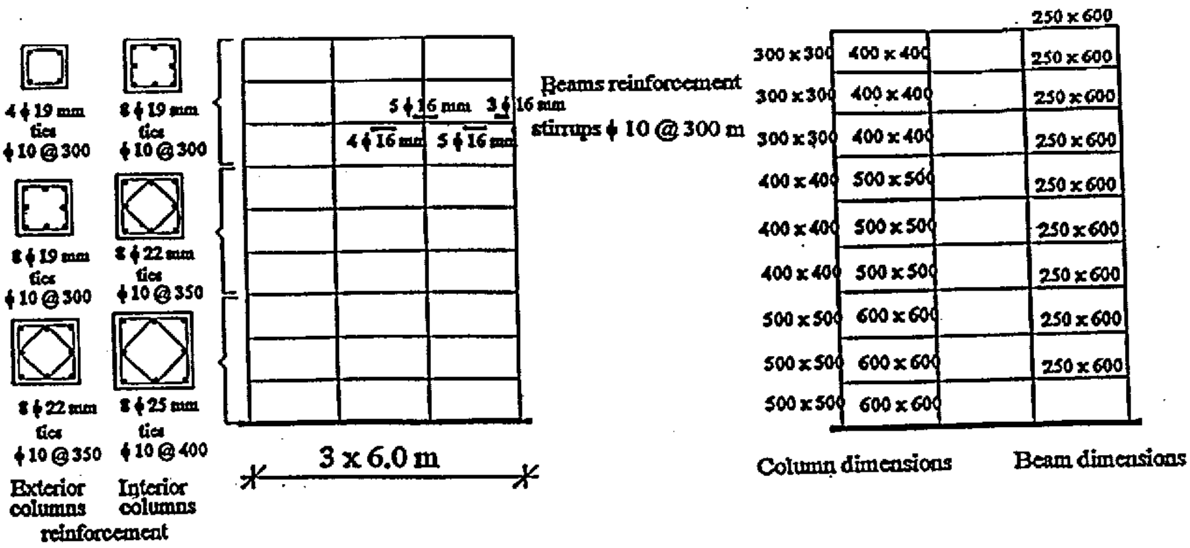


Figure 4 Details of the reinforced concrete 9-storey office building

The performance of the frames is evaluated in terms of the force-displacement results from the static pushover analysis, the maximum storey drift and the damage index for the original existing frame as well as the retrofitted frames. The results of the pushover analysis are presented first, followed by selected results from the probabilistic analysis of the seismic response for some of the retrofitted frames.

PUSHOVER ANALYSIS

The results from the pushover analysis for the 3-storey frame presented in Figure 5, show that the original frame (Frame F) sustained a lateral yield load of approximately 0.14 W and an ultimate lateral load of 0.177 W. The total weight of the structure is denoted by W. The results also show that increasing the strength by 30% (Frame F1) increased the yield load to 0.15 W and the ultimate lateral load to about 0.195 W. The drift corresponding to various values of lateral load is reduced as compared to the drift of the original frame. For example, for a lateral load of 0.15 W, the roof drift equal to 1.4 % and 0.4% for Frame F and Frame F1, respectively.

As would be expected, increasing the column ductility by 100% (Frame F2), has no effect on the yield load. However, the maximum roof drift increased from 4.5% to about 6.2%. The ultimate sustained load was approximately equal to 0.19 W. Increasing the stiffness of the columns without increasing the ductility or strength (Frame F3) reduces the yield load, the ultimate load and the maximum drift of the frame. However, increasing the stiffness of the columns with their strength (Frame F4), which is the practical case, increased the lateral yield load to 0.17 W and the ultimate lateral load to about 0.21 W.

The results from the pushover analysis for the 9-storey frame presented in Figure 6, show that the original frame F sustained a lateral yield load of approximately 0.05 W and an ultimate lateral load of 0.07 W. Increasing the strength by 30% (Frame F1) increased the ultimate lateral load. The drift corresponding to various values of the lateral load are reduced as compared to the drift of the original frame. Increasing the column ductility by 100% (Frame F2) has no effect on the yield load, however, the maximum drift is increased from 4.2% to 5.3%.

Increasing the stiffness of the columns without increasing ductility or strength (frame F3) has little effect on the performance curve of the 9-storey frame. The stiffness increase changes the dynamic characteristics of the structure by increasing its frequencies of free vibration and thus change the seismic demand. This aspect of the behavior of the structure is not accounted for in the pushover analysis.

Results obtained from the nonlinear pushover analysis suggest that upgrading the lateral resistance of structures by increasing strength or strength and stiffness (Frames F1 and F4) are the most effective techniques to retrofit the frame discussed in this application as both approaches result in higher lateral load carrying capacity.

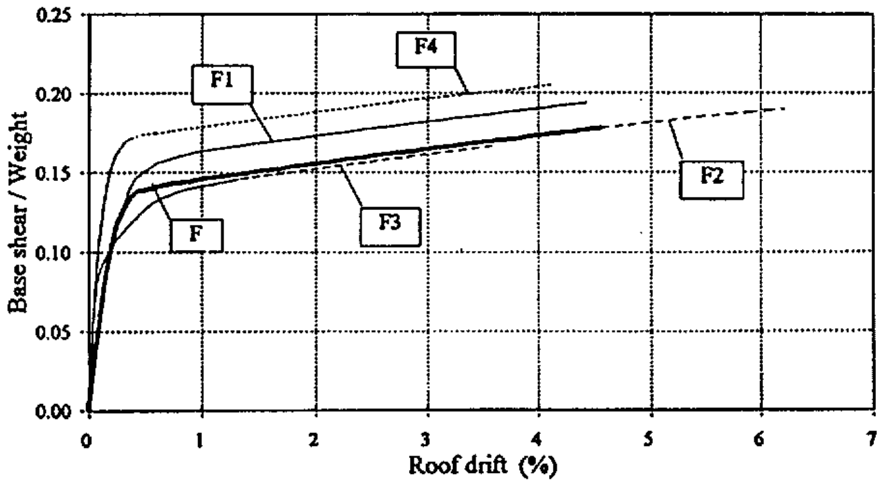


Figure 5 Performance curve from nonlinear pushover analysis of the 3-storey building

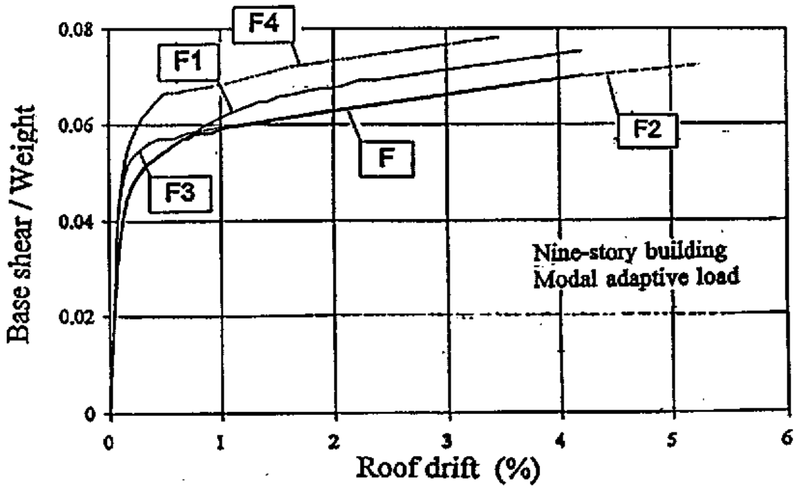


Figure 6 Performance curve from nonlinear pushover analysis of the 9-storey building

SEISMIC ANALYSIS

The original and rehabilitated 3-storey frames are subjected to the generated set of ground motion and a probabilistic analysis is carried out to analyze the effects of increasing columns strength, ductility or stiffness on the damage index and story drift. Figure 7 shows that increasing the strength of the columns (Frame F1) reduces the storey drift for all values of PGA. By increasing column ductility (Frame F2), the frame tends to experience high values of storey drift at PGA levels greater than 0.2 g. By increasing column stiffness (Frame F3), the storey drift increases for high PGA levels. The poor performance of the frame associated with the stiffness increase is due to the increased demand corresponding to stiffness change.

The relationship between the damage index and the PGA for different frames of the 3-storey building is shown in Figure 8. The figure indicates that the mean value of the damage index of the existing frame is reduced for all levels of PGA by either increasing the strength or the ductility. For example, a PGA equal to 0.35 g results in a mean value of the damage index of 0.373, 0.306, 0.281 and 0.45 for Frames F, F1, F2 and F3, respectively. The results indicate an increase in the damage index of 20.6% for Frame F3.

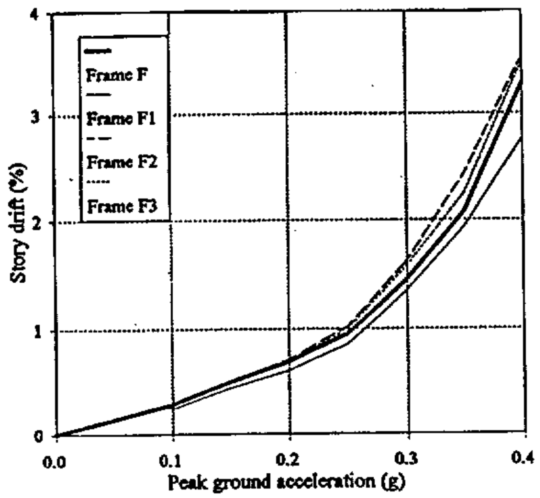


Figure 7 Mean storey drift for 3-storey frame

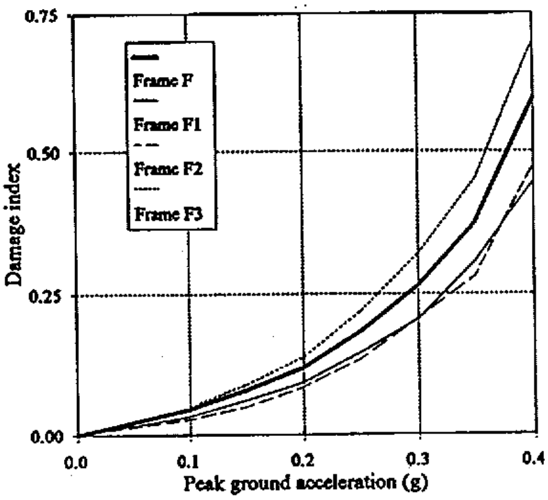


Figure 8 Mean damage index for 3 storey frame

The behavior of the original and rehabilitated 9-storey frames are shown in Figure 9. In this case, all rehabilitation strategies reduce the drift. The maximum reduction of storey drift is for frame F4 with increased stiffness and strength. As expected, increasing the stiffness only (Frame F3) is beneficial in reducing the drift while increasing the ductility of a flexible structure (Frame F2) is a less efficient approach for drift reduction

Figure 10 shows the relationship between the damage to the structure as described by the damage index, and the PGA for different rehabilitation strategies for the 9-storey building. A trend that is similar to the effect of the selective rehabilitation strategies on storey drift is observed. Increasing ductility (Frame F2) results in modest reduction in damage. The highest damage reduction is due to increased stiffness and strength (Frame F4). Increasing the strength only (F1) is more effective in damage reduction than increasing the stiffness only (F3).

As expected, the analysis shows that for both the 3-and 9-storey buildings increasing the strength of the reinforced concrete columns resulted in lower values for the storey drift as well as reduction in damage. The increase of ductility decreases the damage due to the improved energy dissipation capacity. In the case of increased stiffness only, damage is increased for the 3-storey building due to the increased demand. However, reduced drift due to stiffness increase in the 9-storey building was beneficial in damage reduction.

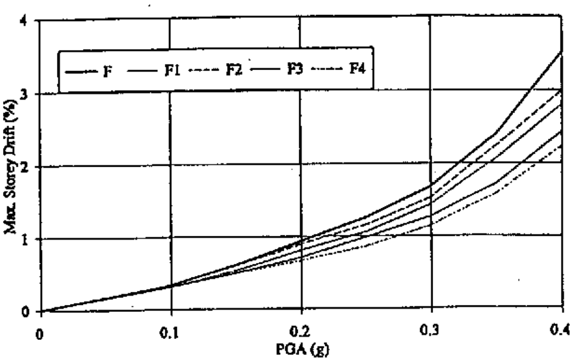


Figure 9 Mean storey drift for 9 storey frame

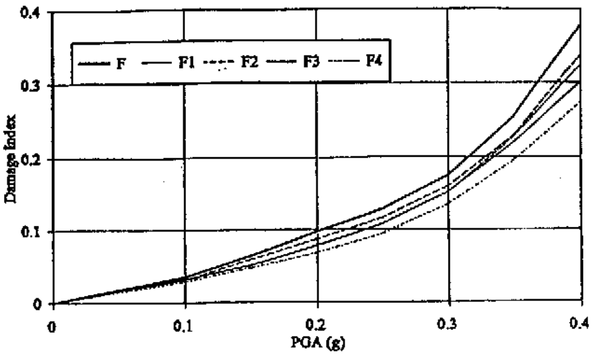


Figure 10 Mean damage index for 9 storey frame

CONCLUSIONS

Seismic rehabilitation of existing deficient structures should be the major current concern in the field of earthquake engineering. It is important to assess the performance of such buildings to design a suitable rehabilitation approach for the structure, if necessary. The cost of rehabilitation of structures to achieve a design level that conforms to current code provisions may be prohibitive. Targeted and selective rehabilitation approaches may form the basis for the development of simple economical schemes for upgrade of the structures in low and moderate seismicity areas. The choice of a specific technique for rehabilitation requires an engineering judgement as it depends on many factors including economic considerations, the function of the building, architectural considerations and the relative simplicity of different methods.

An important outcome of the analysis is that special care has to be taken in the selection and design of a specific selective retrofit technique. It is necessary to evaluate the implications of the retrofit schemes on the performance of the structure. The prediction of drift and damage level provided a simple and effective criteria for the selection and design of the retrofit scheme. By its nature, the pushover analysis does not account for dynamic effects such as stiffness changes which affect seismic demand.

The results of the analysis show that for a low-rise building increasing the strength of the columns is the most effective rehabilitation technique for reducing drift and damage. Increasing the ductility is associated with high drift and the potential for lower damage level. In this case, early collapse may be prevented and the damage level is reduced due to increased energy dissipation. Increasing the stiffness of columns only was found to be detrimental as the frame attracted higher seismic forces. For medium-rise structures, increasing the column strength reduces the drift and damage. Increasing the column stiffness results in modest reduction in drift and damage. The improvement of ductility resulted in modest reduction in damage and marginal effect on the story drift due to the flexibility of the taller structure.

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