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STRUCTURAL PERFORMANCE ASSESSMENT OF AN EXISTING REINFORCED CONCRETE BUILDING RETROFITTED WITH INVERTED Y-SHAPED BRACES

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Structural Performance Assessment of an Existing Reinforced Concrete Building Retrofitted with Inverted Y-Shaped Braces

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Orhan KALKAN

ABSTRACT

STRUCTURAL PERFORMANCE ASSESSMENT OF AN EXISTING REINFORCED CONCRETE BUILDING RETROFITTED WITH INVERTED Y-SHAPED BRACES

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In this study, the efficiency of inverted Y-shaped eccentric steel bracing systems with different link lengths for seismic retrofitting of seismically insufficient reinforced concrete building were investigated. For this, since most of the buildings in the existing building stock of our country were constructed before 1998 and were designed according to 1975 seismic design code, firstly, a reinforced concrete building having a symmetric geometry in plan in compliance with 1975 seismic regulation was selected as a case study. As a retrofit scheme, inverted Y-shaped braces were inserted into the external bays of the existing building. In the seismic strengthening of the original building, inverted Y-bracing was designed considering three different steel link lengths. The analytical frame model having nonlinear properties of structural members of the existing and retrofitted buildings was performed. The performance of the existing and retrofitted structures under earthquake loading was comparatively examined through nonlinear static and nonlinear time history analyses. From the results of the analysis, it was found that the seismic performance of the existing reinforced concrete building with inadequate detailing exhibited considerable improvement after retrofitting with eccentric braces. The results also indicated the importance of the selection of the link length in the design of inverted Y-shaped eccentric steel braces for seismic retrofitting.

Keywords: Earthquake, Eccentric steel brace, Reinforced concrete building, Retrofitting, Structural performance

ÖZET

TERS Y ÇAPRAZLARLA GÜÇLENDİRİLMİŞ MEVCUT BETONARME BİR BİNANIN YAPISAL PERFORMANSININ DEĞERLENDİRİLMESİ

KALKAN, Orhan
Yüksek Lisans Tezi, İnşaat Mühendisliği Bölümü
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Bu çalışmada, deprem dayanımı yeterli olmayan betonarme bir yapının farklı bağlantı elemanı boyuna göre tasarlanmış ters Y tipi dış merkezli çelik çapraz sistemlerle güçlendirilmesinin etkinliği araştırılmıştır. Bilindiği üzere, ülkemizdeki yapı stoğunu oluşturan birçok yapı 1998'den önce ve 1975 deprem yönetmeliğine göre yapıldığından, öncelikle 1975 yönetmeliğine uyumlu deprem dayanımı yetersiz simetrik betonarme bir bina örnek olarak araştırmada kullanılmıştır. Binanın güçlendirilmesinde ters Y çaprazlar yapının her iki doğrultusundaki dış akslarına yerleştirilmiştir. Güçlendirmede kullanılan çaprazlar üç farklı bağlantı elemanı boyuna göre tasarlanmıştır. Mevcut ve güçlendirilmiş yapılar için yapı elemanlarının lineer olmayan davranışının da göz önüne alındığı analitik modeller oluşturulmuştur. Mevcut ve güçlendirilmiş çerçeve yapıların lineer olmayan statik ve lineer olmayan zaman tanım alanında analizleri yapılarak, deprem performansları karşılaştırılmalı olarak incelenmiştir. Elde edilen analiz sonuçlarına göre, deprem dayanımı yetersiz mevcut betonarme yapının dış merkezli çelik çaprazlarla güçlendirme sonrası deprem performansında önemli ölçüde iyileşmeler gözlenmiştir. Ayrıca, sonuçlar ters Y tipi dış merkezli çelik çaprazların tasarım parametrelerinin yapının deprem davranışı üzerinde etkili olduğunu göstermiştir.

Anahtar kelimeler: Deprem, Dış merkezli çelik çapraz, Betonarme bina, Güçlendirme, Yapısal performans

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LIST OF SYMBOLS/ABBREVIATIONS

K	Stiffness
FRP	Fiber reinforced polymer
PGA	Peak ground acceleration
M_u	Ultimate moment
V_u	Ultimate shear force
M_p	Plastic moment
V_p	Shear force
t_w	Web thickness of flange section link
E	Modulus of elasticity
f_y	Yield strength
f_{ck}	Compressive strength
e	Length of link element
RC	Reinforced concrete
FRP	Fiber reinforced polymer
BF	Bare frame
INF	Infill frame
SBF	Steel braced frame
b_f	Flange width
t_f	Flange thickness
GFRP	Glass fiber reinforced polymer
CFRP	Carbon fiber reinforced polymer

CHAPTER 1

INTRODUCTION

1.1. Background

After 1999 İzmit earthquake, the majority of the reinforced concrete (RC) structures designed in accordance with 1975 earthquake regulations or earlier ones have been subjected to moderate to heavy damage and more than 18.000 people lost their lives, our country's economy has been subjected to a loss of 20 billion dollars (USGS, 2000). In our country, the earthquake code (ABYYHY, 1998) was revised in 1998 considering higher earthquake loads and conditions which will ensure the fulfillment of ductility of reinforced concrete buildings, but the buildings constructed before 1998 are still insufficient against a forthcoming major seismic event. In order to avoid the risk of possible negative consequences of the earthquakes, some applicable strengthening techniques should be determined to minimize loss of life and property for insufficient earthquake resistance structures.

In order to resist lateral earthquake loads of frame structures, shear walls or steel bracing are frequently used. It is common to employ steel bracing in steel frame structures and shear walls in RC structures. However, in recent years there have been several studies for the use of steel bracing in RC structures, especially for the retrofitting purposes (Hou and Tagawa, 2009; Promis et al., 2009; Di Sarnoa and Elnashai, 2009; Li et al., 2009; Symth et al., 2004). Moreover, the use of steel bracing systems for seismic retrofitting of RC frames offers some benefits such as the ability to accommodate openings, minimal added weight to the structure, and minimum disruption to the function of the building and its occupants. In general, two types of steel bracing systems, namely concentric and eccentric are used for the retrofitting of nonductile RC buildings. (Goel and Masri, 1996; Maheri and Sahebi, 1997; Abou-Elfath and Ghoborah, 2000; Maheri et al., 2003; Symth et al., 2004; Güneyisi and Altay, 2004; Güneyisi and Altay, 2005; Youssefa et al. 2007; Mazzolani, 2008). However, it was pointed out that the use of the eccentric steel bracing systems has lagged behind the concentric steel bracing applications due to the lack of sufficient research and information about the design, modeling and the behavior of the combined reinforced concrete and steel system (Ghobarah and Abou-Elfath,2001).

Therefore, in the present study, inverted Y-shaped eccentric steel bracing was utilized for seismic retrofitting of the existing reinforced concrete building. For this purpose, 3 story reinforced concrete building was selected as a case study. Inverted Y-shaped bracings designed with different link lengths were inserted into external bay of the building. The seismic performance of the original and three retrofitted cases were evaluated by means of nonlinear static and dynamic analyses.

1.2. Outline of the Thesis

Chapter 1- Introduction: Aim and objectives of the thesis are presented.

Chapter 2- Literature review: A literature survey based on this thesis is provided. For this, firstly, the studies on strengthening of reinforced concrete structures against earthquakes in the literature are described. Secondly, the utilization of different strengthening methods is given. Afterward, the properties and use of Y-type steel braces in strengthening applications in the literature are summarized.

Chapter 3- Analytical study: This chapter yields a description of analytical models of the case study of inverted Y-type steel braces. Additionally, the methodology used in the analysis and design of the structures before and after retrofit is summarized and details of every step are given in this chapter. Moreover, the properties of modelling of existing and retrofitted frames in the analysis are described in this chapter.

Chapter 4- Results and discussion: Results obtained from the nonlinear static and dynamic analyses are presented. Discussion on the results of the analysis is given in this chapter.

Chapter 5- Conclusions: Conclusions based on the results of this study are summarized.

CHAPTER 2

LITERATURE REVIEW

2.1. Strengthening of reinforced concrete structures

2.1.1. Strengthening methods

There are numerous circumstances in which a reinforced concrete structure would need retrofitting or rehabilitation because of the lack of strength (flexure, shear, etc.), stiffness, ductility, and durability. Some of the general situations where a structure requires strengthening during its lifespan are given below (Motavalli and Czaderski, 2007):

- Strengthening against the earthquake to assure current code requirements,
- Upgraded loading conditions; damage caused by accidents and environmental situations,
- Initial design flaws, and
- Change of usage, etc.

Comprehensive examinations after the earthquakes occurred in the recent years which caused very severe damage to building or observations on the evaluation reports of the buildings before or after retrofit revealed that some structural weaknesses in the reinforced concrete buildings were commonly observed in Turkey. In particular, the mid-rise (3-8 stories) reinforced concrete frame type buildings had the following very general weak points: i) insufficient lateral rigidity, ii) design defects, iii) reinforcement arrangement defects, and iv) low-quality concrete, etc. (Earthquake Council, 2004).

The primary objective of strengthening is to improve the seismic performance of structures based mainly on the earthquake regulations. In addition, the seismic retrofitting method needs to provide or increase the performance level of the existing reinforced concrete structures so as to prevent collapse of the structure under the earthquake excitations. The strengthening of structural systems by using conventional or traditional methods can be achieved as the strengthening of beams, strengthening of columns, strengthening by reinforced concrete shear walls, and strengthening by steel braces (Celep, 2002).

The beams having insufficient capacity can be strengthened in various ways. For example, the beam which has not adequate reinforcement at mid-span is retrofitted by using steel strip or carbon fiber-reinforced polymer strip at the bottom of the beam. Additionally, existing beams can be strengthened by enlarging from one or two side if it is necessary. Figure 2.1 shows some examples of the reinforced concrete beam strengthening. Similarly, for the column having insufficient load carrying capacity, its cross-section can be increased and the capacity is increased by using added new longitudinal and transverse reinforcement. The use of concrete jacketing for retrofitting columns is the most favorable way as compared to that of steel strip. Figure 2.2 shows some illustrations of strengthening of the column by applying concrete jacketing (Celep, 2002).

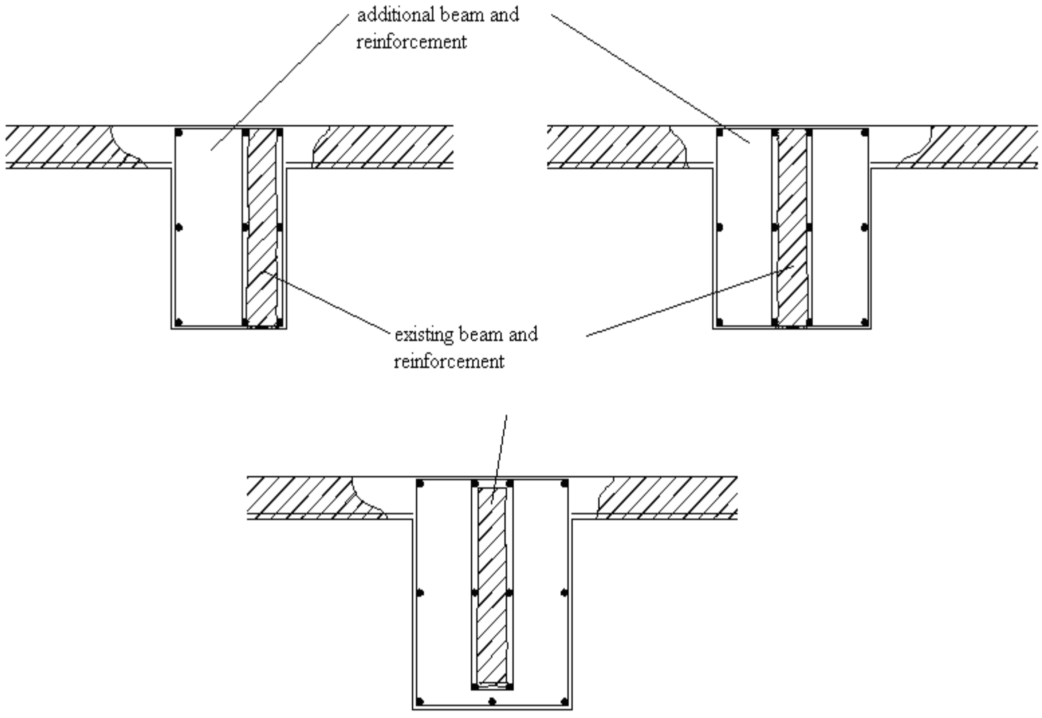


Figure 2.1 Strengthening of the beam (Celep, 2002)

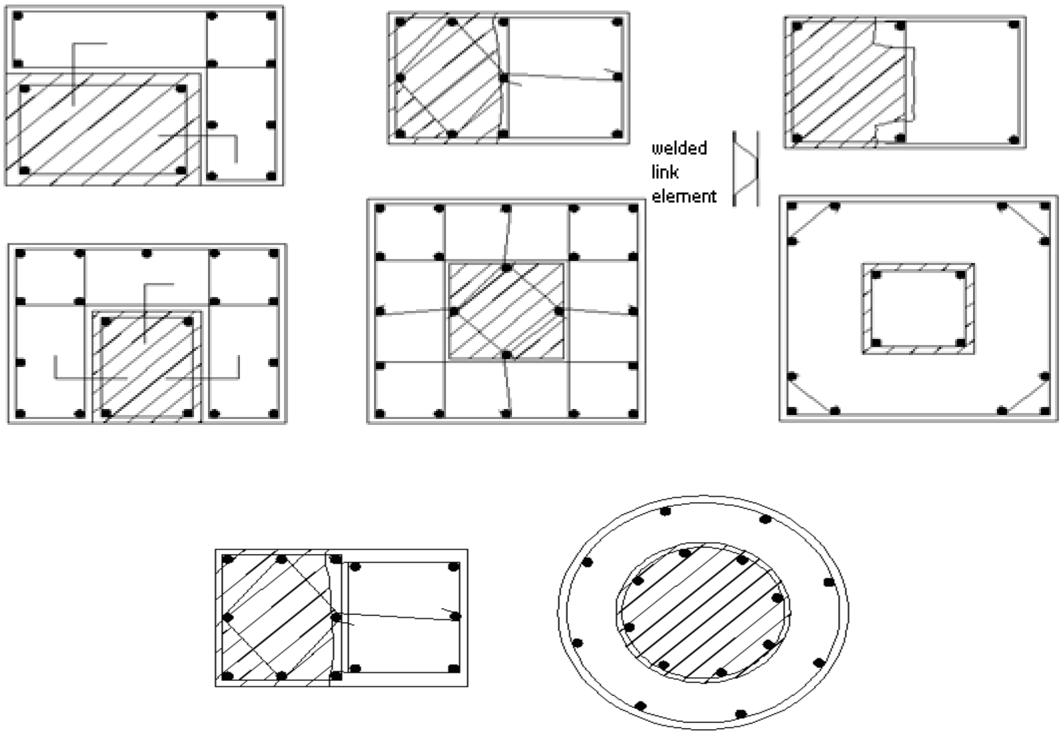


Figure 2.2 Strengthening of the column (Celep, 2002)

Moreover, the strengthening with reinforced concrete shear walls not only results in improving the load carrying capacity of existing system in terms of the seismic safety but also limiting the lateral deflections of the structural system. It is reported that the occurrence of torsional effects and accumulation of adverse effects on a certain region can be prevented by placing properly the location of shear walls in the structures. The shear wall is placed between two columns, so creation of end points of shear walls is easily achieved. However, in special cases, it can be considered as a connecting of one side on one column. In this case, the end of shear wall should be arranged on other side. In Figure 2.3, a layout and arrangement of reinforcement for shear wall is shown (Celep, 2002).

The steel bracing systems can also be used for retrofitting purposes instead of reinforced concrete shear walls. In this situation, most simple application is to place steel elements adjacent to beam and column nearby steel braces which is placed on beam-column plane. In practice, concentric steel braces and eccentric steel braces can be used (Celep, 2002).

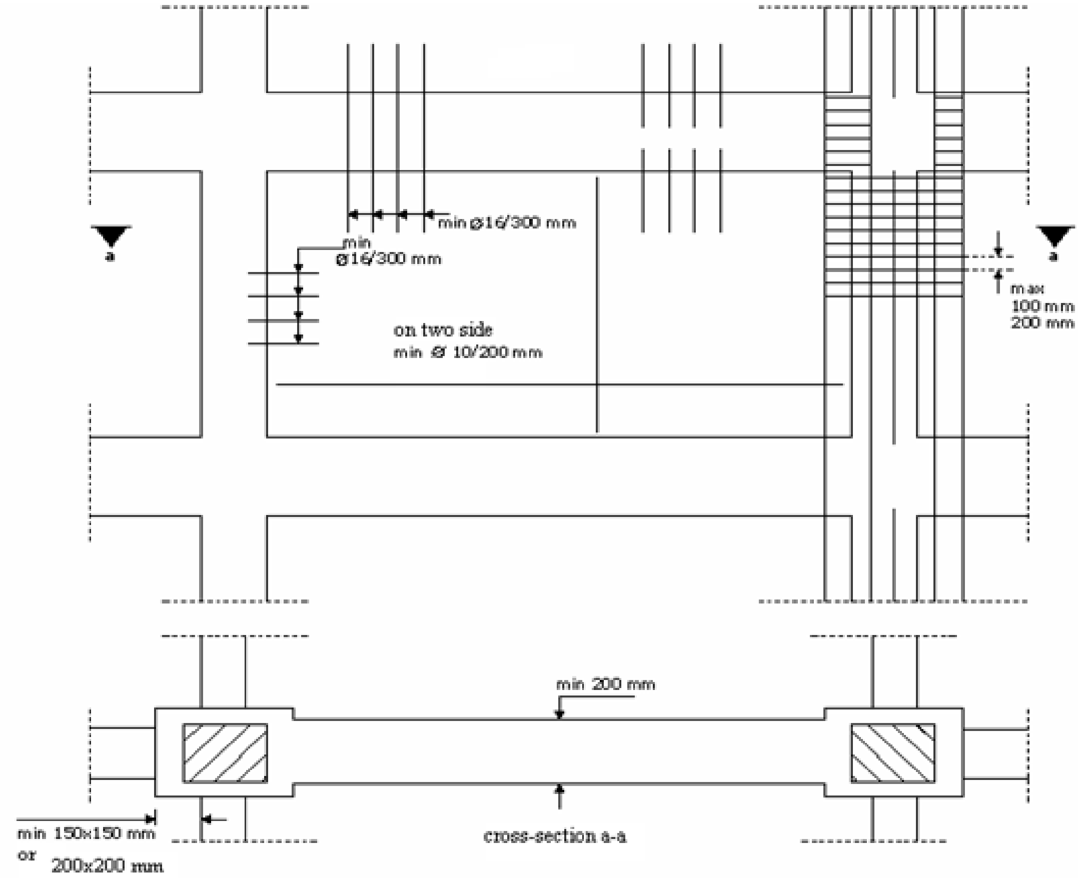


Figure 2.3 Strengthening with shear wall (Celep, 2002)

The efficiency of fiber reinforced polymers (FRPs) in strengthening or repairing of the components of the reinforced concrete (RC) structures has been studied in the past decade to a great detail. Among different methods proposed for repairing or upgrading of the RC structures, the utilization of externally bonded FRPs has increased extensively, particularly in recent years. The inherent benefits of FRPs cause them as a more reliable candidate for seismic strengthening of RC components as compared with the traditional techniques. They comprise high tensile strength, low specific weight, high resistance to corrosion, and simplicity of application (Ronagh and Eslami, 2013).

Beams, plates, and columns of the RC structures can be retrofitted in flexure through the utilization of FRP composites bonded to their tension zone applying epoxy as a general adhesive for this intention. The direction of fibers is parallel to that of high tensile stresses. Both FRP strips and sheets (wet-lay up) are applied. Figure 2.4 indicates the application of the flexural strengthening of a RC girder of a building in

Poland using carbon FRP strips. Moreover, the crosswise application of a RC deck on the top and bottom side and around the columns is illustrated in Figure 2.5 (Motavalli and Czaderski, 2007).

Figure 2.4 Flexural retrofitting of concrete girders of a cement manufacturing plant in Poland utilizing carbon FRP strips (Motavalli and Czaderski, 2007)

Figure 2.5 Retrofitting of a concrete deck of a structure using carbon FRP strips on the top and underside of the deck (Motavalli and Czaderski, 2007)

Shear retrofitting is frequently supplied by bonding the external FRP reinforcement on the sides of the webs with the principal fibre direction perpendicular or with an angle of e.g. 45° to the member axis. The typical installation of FRP sheets for the shear strengthening of the rump of the Duttweiler bridge in Zurich Switzerland in 2001 and the placing of carbon fibre fabrics in the shear zone of a bridge above the railway to Laziska power plant in Poland in 2003 are shown in Figures 2.6 and 2.7, respectively (Motavalli and Czaderski, 2007).

Figure 2.6 Use of carbon FRP L-shaped plates for shear strengthening of Duttweiler bridge ramp in Zurich, Switzerland (Motavalli and Czaderski, 2007)

Figure 2.7 Application of carbon FRP fabrics for shear strengthening of DK 81 bridge in Poland (Motavalli and Czaderski, 2007)

Under an earthquake, three failure modes of RC column that can happen by reason of cyclic axial and lateral loads are shear failure, flexural plastic hinge failure, and lap splice failure. Lack of transverse reinforcement can result in shear failure, which is both brittle and catastrophic in nature. Shear capacity of insufficient columns can be considerably improved by supplying externally bonded FRP laminates with fibers in the hoop direction as illustrated in Figure 2.8 (Sarker et al., 2011).

Figure 2.8 Utilization of FRP for seismic strengthening of reinforced concrete columns (Sarker et al., 2011)

Parikh and Modhera (2012) conducted an experimental study on use of glass fiber reinforced polymer (GFRP) sheet on preloaded strengthened reinforced concrete beam for improvement in flexural strength. In their study, two sizes of RC beams with 15 GFRP retrofitted RC beams and 2 control beams were tested. The performances of the beams were evaluated by means of four point bending test. Figure 2.9 shows the failure pattern of the beam while Figure 2.10 indicates the failure photos of the beam under testing. It was found that the preload level had very effective on the stiffness, toughness, and ductility of the retrofitted beam.

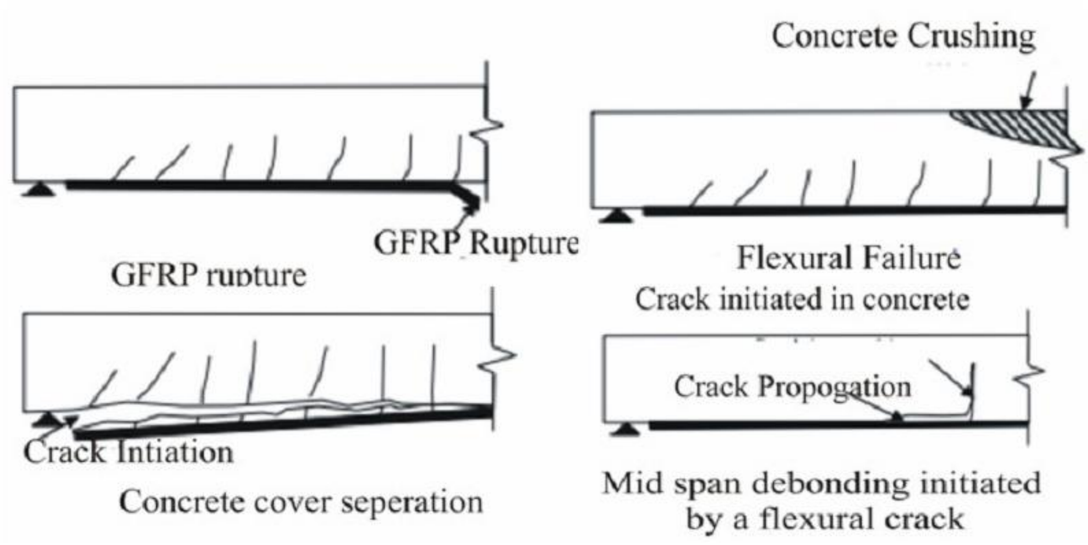


Figure 2.9 Typical failure patterns of the beams (Parikh and Modhera, 2012)

Figure 2.10 Photographic view of the beam under testing (Parikh and Modhera, 2012)

Sadone et al. (2012) evaluated the influence of externally bonded fiber reinforced polymer (FRP) on retrofitting of reinforced concrete columns. They proposed a new retrofitting system for flexural retrofitting of the column. This retrofitting approach was developed considering carbon fiber reinforced polymer (CFRP) plates bonded longitudinally and anchored at the column-stub junction. The suggested system was confirmed by an experiment conducted on full-scale RC columns. Figure 2.11 demonstrates the dimensions and reinforcing of the column. The anchoring principle of the flexural retrofitting of the column by applying CFRP sheets is given in Figure 2.12. Moreover, Table 2.1 shows the properties of CFRP used. It was reported that the suggested anchoring system was a capable of constructive disposition for the strengthening of columns under cyclic loading, however, the system was required to be enhanced.

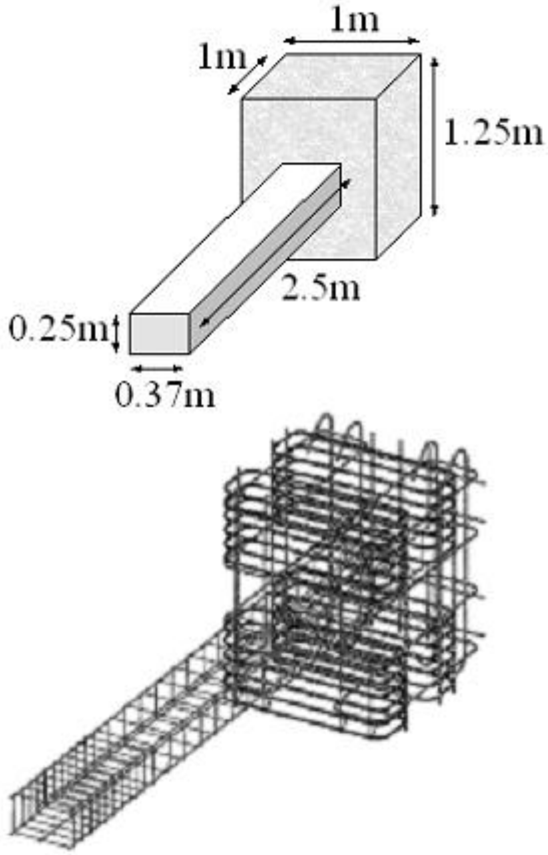


Figure 2.11 Dimension and reinforcing cage of the RC column (Sadone et al., 2012)

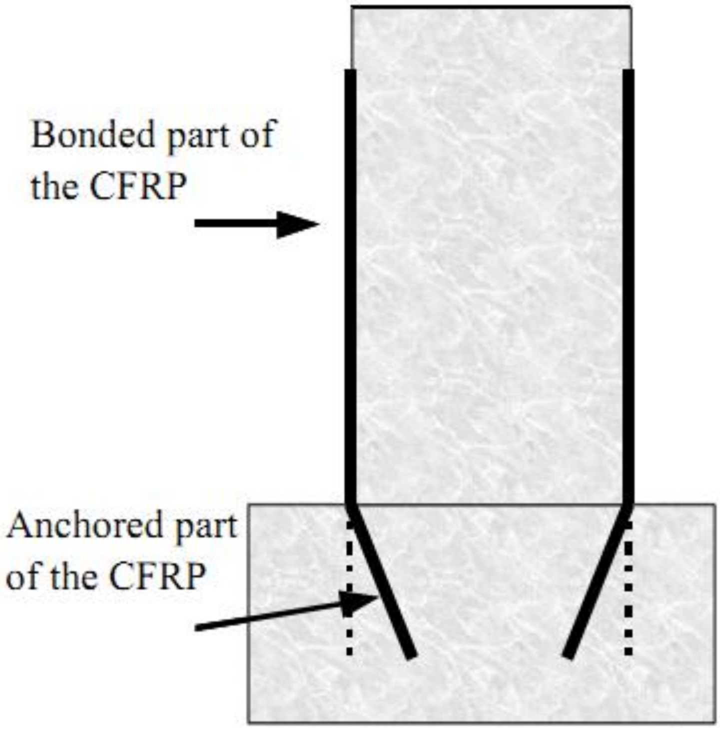


Figure 2.12 Anchoring principle of the flexural retrofitting of the column (Sadone et al., 2012)

Table 2.1 Properties of FRP reinforcement used in strengthening the column (Sadone et al., 2012)

		CFRP sheets	
Thickness	Width	Young's modulus	Ultimate strain
0.48 mm	300 mm	105.000 Mpa	0.01
		Pultruded plates	
Thickness	Width	Young's modulus	Ultimate strain
1.2 mm	50 mm	160.000 Mpa	0.007

2.1.2. Strengthening with structural steel braces

Steel braced frames are lateral load resisting systems in which concentric and eccentric braces are used in the frames. The joints between columns and beams can be designed to be hinged or rigid. The lateral load carrying capacity of such systems is achieved by means of the flexural strength resistance as well as more or entirely axial force resistance of elements. Steel braced frames are divided into two classes as concentric or eccentric steel braced frames, depending mainly on layout of braces. Figures 2.13 and 2.14 demonstrate the placement of concentric and eccentric steel braces in frame systems, respectively (DBYYHY, 2007).

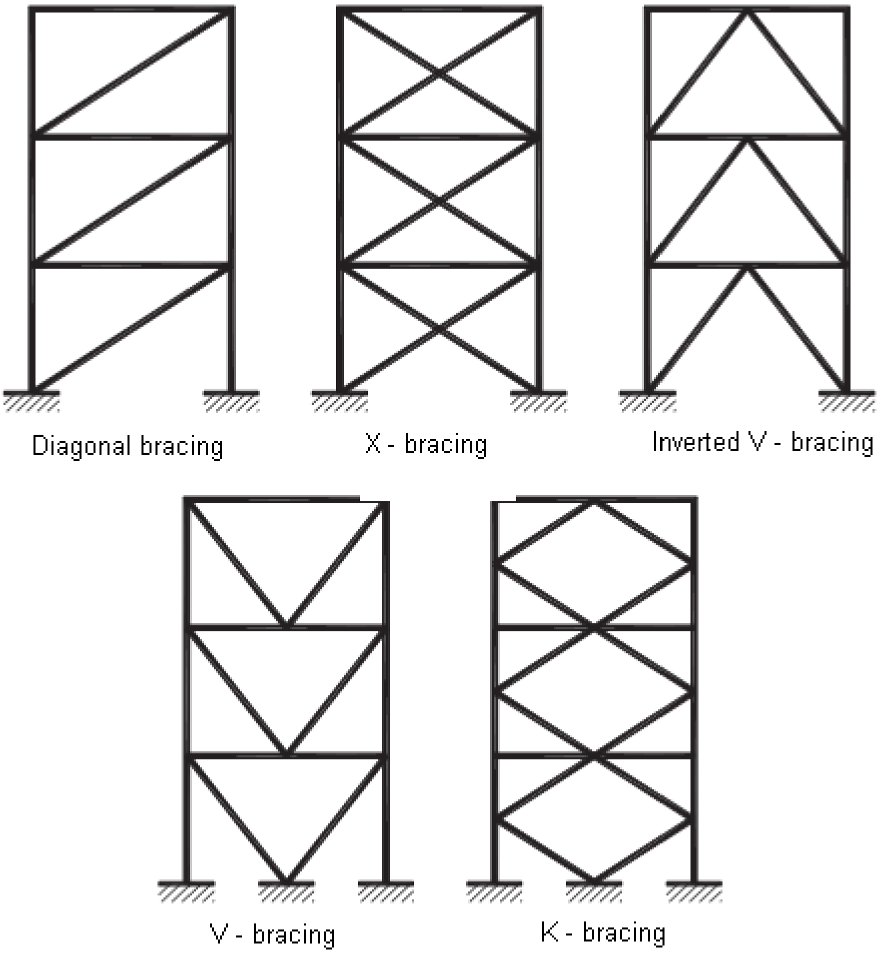

Diagonal bracing
X - bracing
Inverted V - bracing
V - bracing
K - bracing

Figure 2.13 Different configurations of concentric steel braced frames (DBYYHY, 2007)

Considering the conditions of ductile behavior under the influence of the earthquake, recently, the steel is one of the vital construction materials in our country since it is located in a major earthquake zone. However, in the design of structural steel systems, the ductility of structure and behavior against seismic forces needs to be better understood (Yazan and Uzgider, 2009). As mentioned in the introduction section, in recent years, there are various studies on the use of steel bracing for retrofitting the existing reinforced concrete structures (Goel and Masri, 1996; Maheri and Sahebi, 1997; Abou-Elfath and Ghoborah, 2000; Maheri et al., 2003; Symth et al., 2004; Güneyisi and Altay, 2004; Güneyisi and Altay, 2005; Youssef et al., 2007; Mazzolani, 2008).

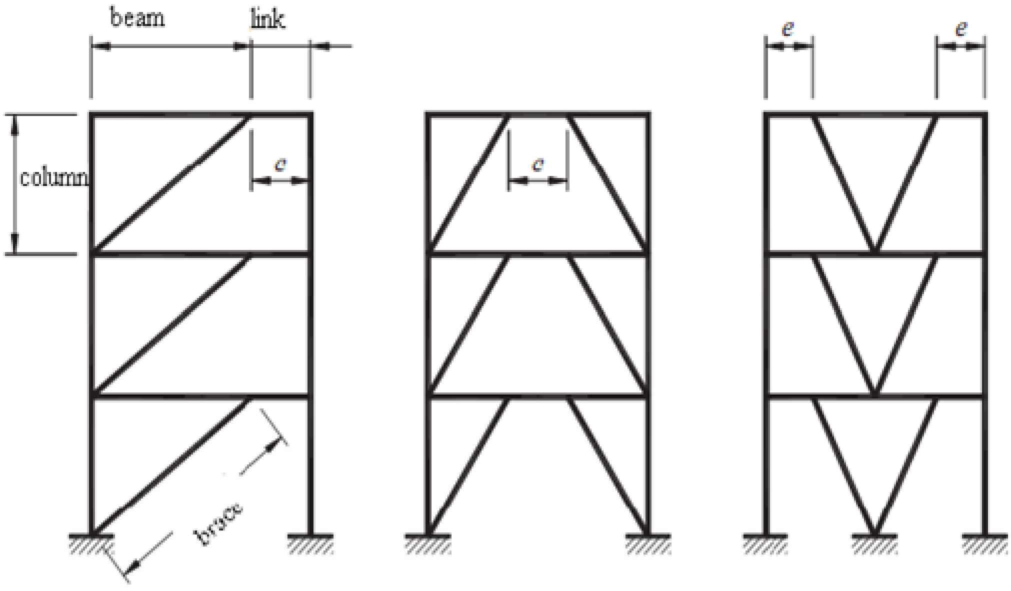
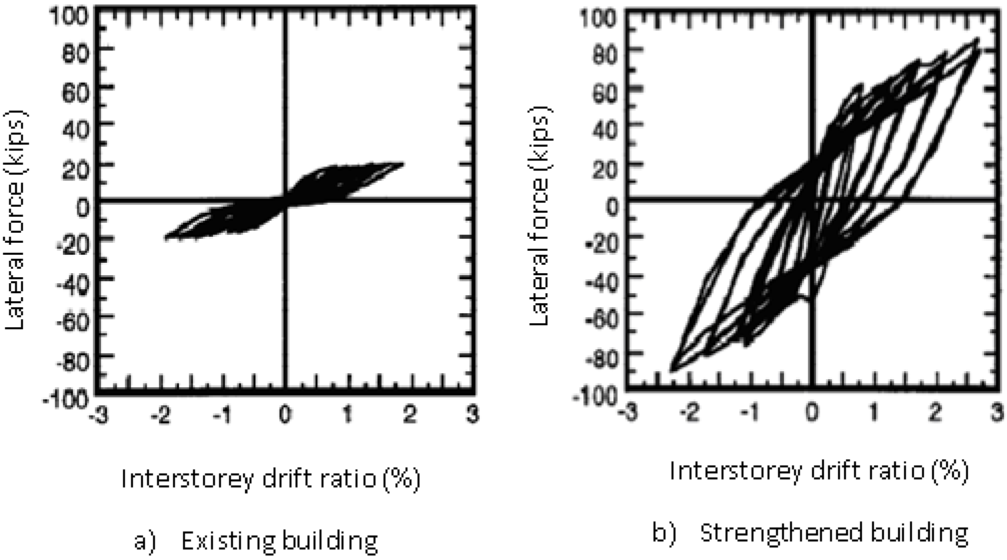


Figure 2.14 Different configurations of eccentric steel braced frames (DBYYHY, 2007)

Goel and Masri (1996) carried out an experimental investigation on retrofitting of 1/3 scale reinforced concrete building having two span and two stories by using inverted V concentric braces. The building contained column, beam, and slab systems. The concentric brace strengthening was made in outer and inner parts of the reinforced concrete building. Then, by testing existing and steel braced buildings, hysteretic cycles were obtained. In Figure 2.15, hysteresis loops for exist and retrofitted systems are shown. According to test results, it was pointed out that the retrofitted building had greater strength and stiffness due to the inclusion of steel brace. Moreover, a significant increase in energy dissipation capacity for such building was observed.

Maheri ve Sahebi (1997) investigated the utilization of steel braces in reinforced concrete framed structures. In this study, an improvement in shear resistance of reinforced concrete frames by using different diagonal braces was evaluated and the behavior of braces under tension and compression was analyzed. Based on the results, it was reported that steel braces significantly enhanced the shear strength of the case studied structures. In addition, by providing appropriate connection of concentric bracing system with reinforced concrete frame at the joint, steel brace system could be used as an alternative or addition of shear walls for reinforced concrete frame structures, especially in high seismic zones.



a) Existing building

b) Strengthened building

Figure 2.15 Hysteresis loops of the existing building and retrofitted building with inverted V braces (Goel and Masri, 1996)

Abou-Elfath and Ghoborah (2000) examined the seismic performance of non-ductile low-rise reinforced concrete structure which was strengthened by concentric steel braces. A three-storey building was analyzed by using various acceleration records. The performance of the reinforced concrete building was evaluated by consideration of roof and interstory displacements as well as damage indices. In addition, a simplified method was proposed for determining of optimum distribution of braces in structure.

Maheri et al. (2003) investigated experimentally the structural behavior of ductile reinforced concrete structure with concentric type steel braces. In their study, inelastic pushover analysis was performed on a single-storey and single-span reinforced concrete frame system with and without concentric braced frame system (X-type) which is placed in this system. Views of 1/3 scale model buildings under investigation are given in Figures 2.16 and 2.17. According to the test results, it was evident that the addition of concentric steel brace into ductile reinforced concrete frame increased the stiffness and reduced the displacement to desirable level. Moreover, it was emphasized that such concentric steel braces could be applied for new design or strengthening purposes under the earthquakes causing damages.

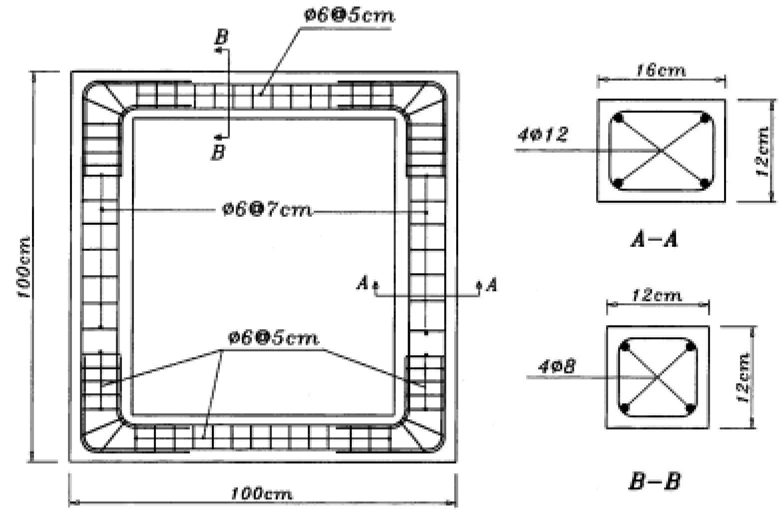


Figure 2.16 Reinforced concrete frame system (Maheri et al., 2003)

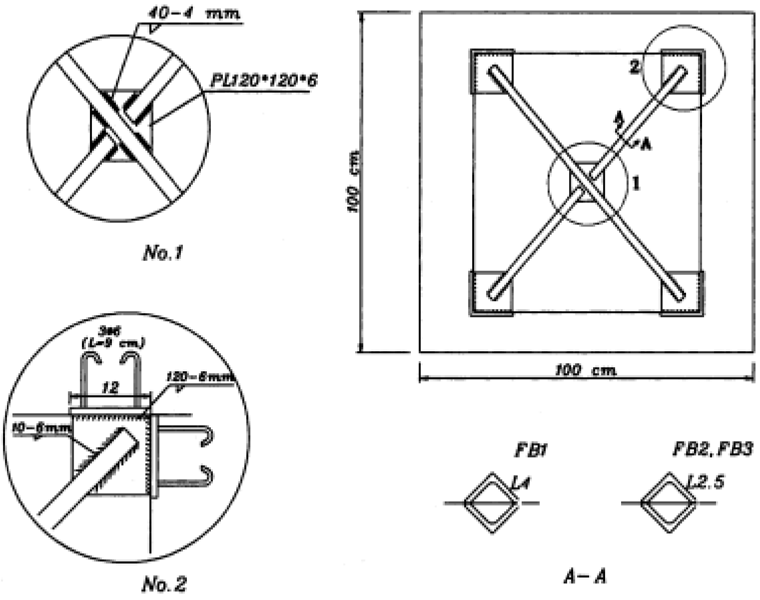
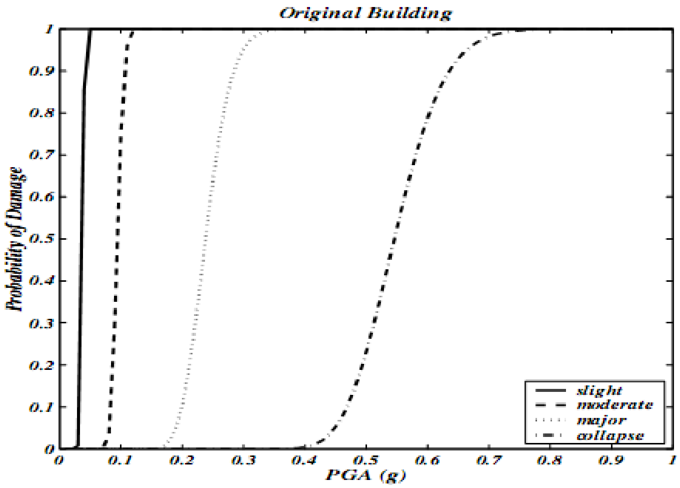


Figure 2.17 Reinforced concrete frame system with X-braces (Maheri et al., 2003)

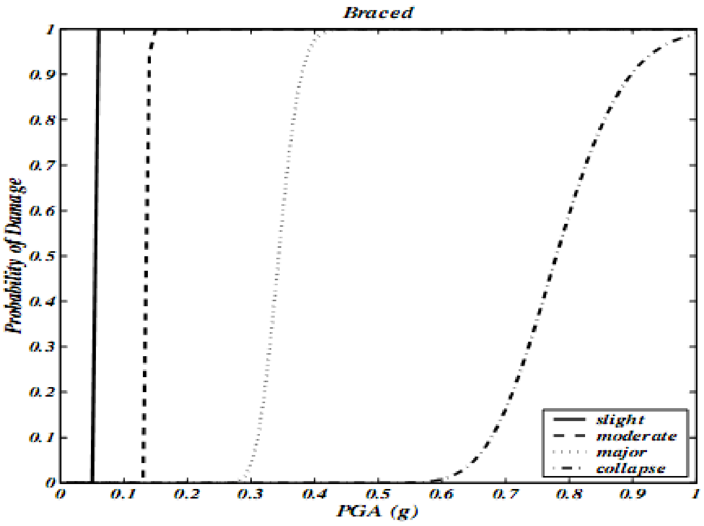
Maheri and Hadjipour (2003) performed an experimental research and design of steel brace connection to reinforced concrete frame. Three types of brace to reinforced concrete frame connections were examined. The connections were designed in full scale. It was observed that the steel brace to reinforced concrete frame connections could be designed effectively by using the appropriate current provisions

In the study of Symth et al. (2004), the utilization of concentric steel brace systems in strengthening the reinforced concrete building was investigated in comparison with another widely used retrofit technique of the shear wall. A residential reinforced concrete building located in Istanbul was selected. The following cases were under investigation: i) the original structure, ii) the structure retrofitted with a bracing system, iii) the structure retrofitted with a partial shear wall, and iv) the structure retrofitted with a full shear wall. In the analysis, 3D finite element models of the case studied buildings were carried out. The fragility analysis of the structure in its different retrofitted configurations was performed. Figure 2.18 indicates the fragility plots for different levels of the damage for the original and retrofitted buildings.

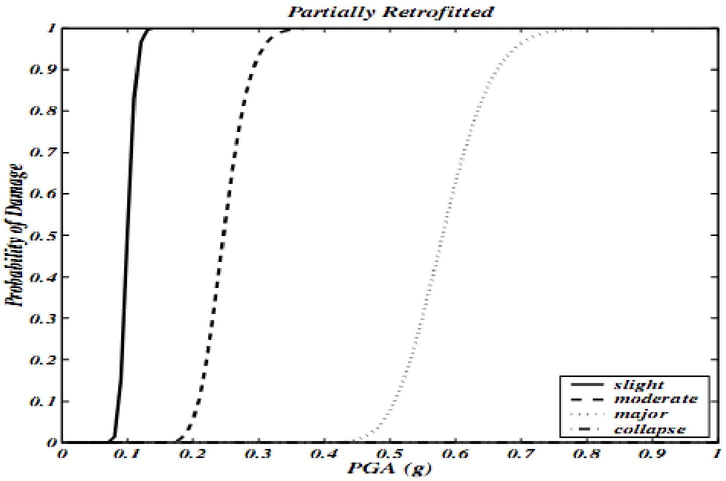
From the results of the fragility cures, it was highlighted that the curve related to a given damage level had a tendency to shift from left to the right. In their study, the results of the analysis were also examined by considering the probabilistic benefit-cost analysis. Moreover, it was reported that the proposed methodology in this study could be enlarged to a whole region by taking into account different type of the structures, soil class, retrofitting techniques, etc.


Original Building

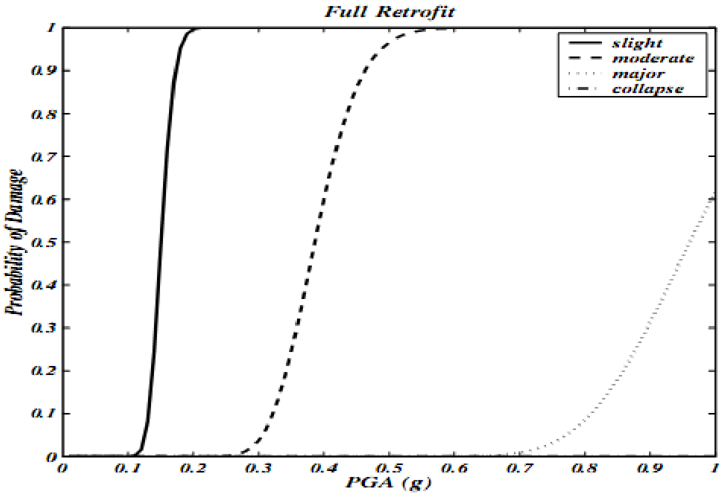
a)


Braced

b)



c)



d)

Figure 2.18 Fragility curves as a function of slight, moderate, major, and collapse different levels for the original and retrofitted buildings (Symth et al., 2004)

Youssef et al. (2007) performed an experimental study on the earthquake performance of RC frames with concentric steel braces. Two cyclic loading tests were carried out on a bare and braced RC frames. Figure 2.19 shows the forces acting on the scaled model RC frames while Figure 2.20 reveals the experimental set-up and test specimens. It was observed that the braced reinforced concrete frame would behave adequately under a given earthquake event in comparison to bare moment frame.

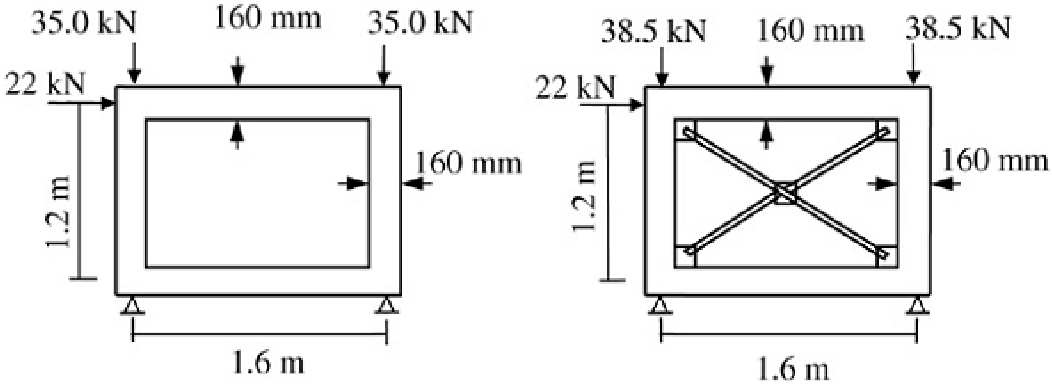


Figure 2.19 View of the scaled RC frames (Youssef et al., 2007)

Figure 2.20 View of test set-up and the frame system (Youssef et al., 2007)

Mazzolani (2008) gave the detailed explanation on the outcomes of full-scale experimental tests conducted on various innovative earthquake upgrading methods considering the utilization of yielding steel components. The cyclic experimental tests were performed on actual reinforced concrete structures installed with the different types of braces and shear walls. Figures 2.21 and 2.22 illustrate various retrofitting techniques for the reinforced concrete structures.

Figure 2.21 Photographic view of original building and typology of brace retrofitting method (Mazzolani, 2008)

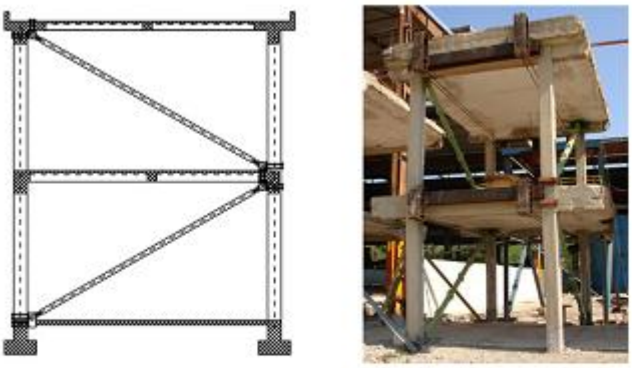


Figure 2.22 Reinforced concrete structure with structural braces in diagonal configuration (Mazzolani, 2008)

Godínez-Domínguez and Tena-Colunga (2008) performed a numerical study on behavior of moment resisting reinforced concrete concentric braced frames in earthquake zone. In their study, twenty-seven regular reinforced concrete moment resisting concentric braced frames with steel bracing were designed in accordance with the seismic, concrete and steel guidelines of Mexico’s Federal District Code. The structure models varied between 4 and 16 stories. Inverted-V braces were utilized in such reinforced concrete frames. Nonlinear static analysis was carried out for all frames. Figure 2.23 shows the frame layout configurations. The collapse mechanism of the model where the columns resisted near 50 % of the total earthquake shear load is illustrated in Figure 2.24. It was concluded that the optimal strength balance between the reinforced concrete frame and the steel bracing system seemed to vary, depending mainly on the height of the structures. A correlation of the assessed over-strength factors with the shear strength contribution for the columns to resist lateral earthquake loads was also observed.

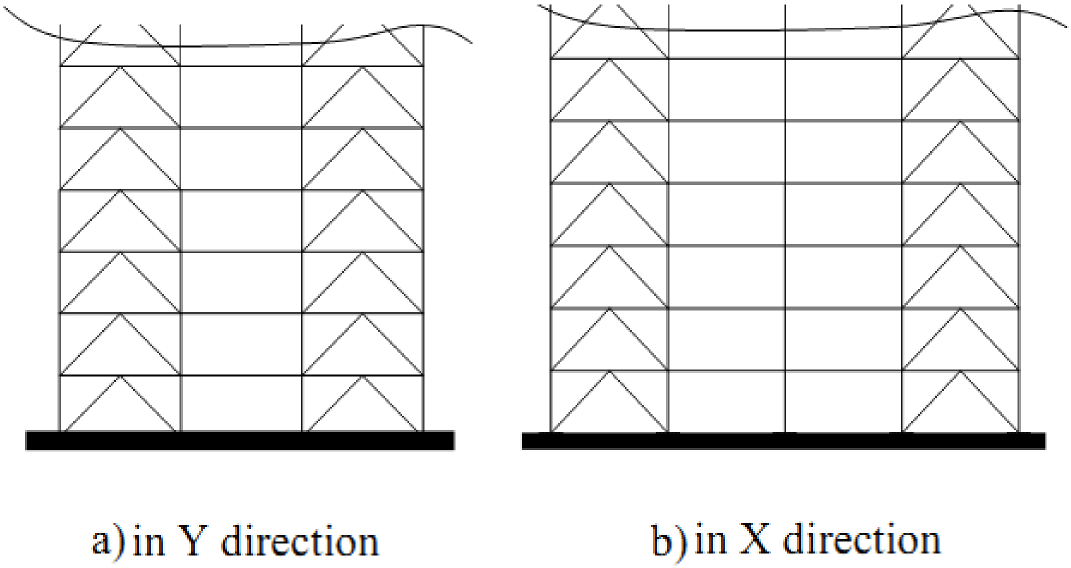


Figure 2.23 Elevation views of the frames with concentric brace (Godínez-Domínguez and Tena-Colunga, 2008)

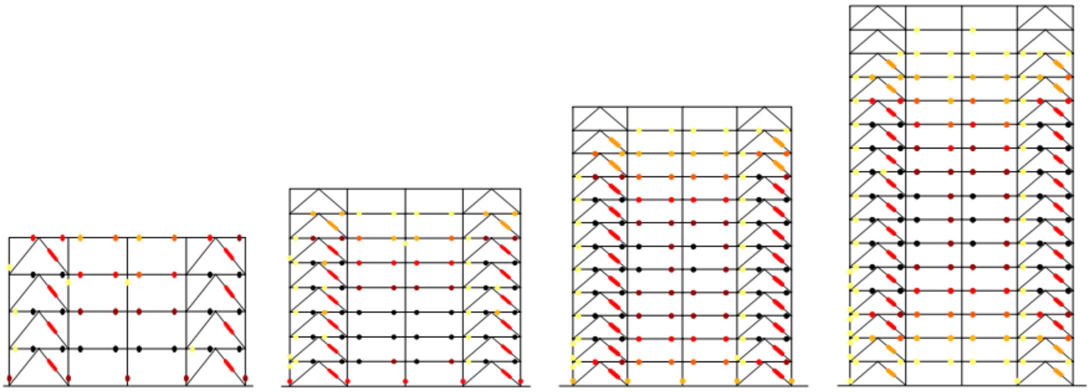
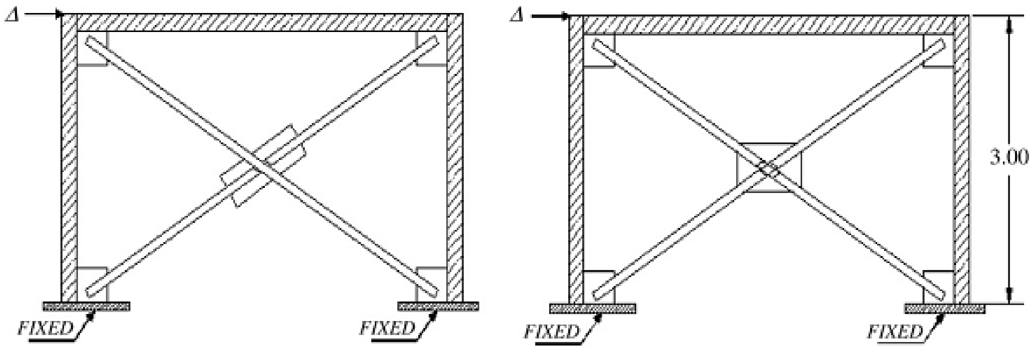


Figure 2.24 Collapse mechanisms for the models (Godínez-Domínguez and Tena-Colunga, 2008)

The influence of mid-connection detail of X-bracings containing build-up sections on the elastic-plastic behavior of braced systems was studied by Davaran and Hoveidae (2009). Figure 2.25 demonstrates the structural models used in the analysis while the types of connections are given in Figure 2.26. The buckled shapes of the braces in the frame system are also illustrated Figure 2.27. Their results indicated that the suggested mid-connection configuration could enhance both strength and ductility of cross braced frames. Moreover, it was observed that the use of two cover plates on discontinuous diagonal members in mid-connection could moderately enhance the overall behavior of the braced frames.



a) b)

Figure 2.25 Structural models of braced system with a) ordinary mid-connection and b) proposed mid-connection (Davaran and Hoveidae, 2009)

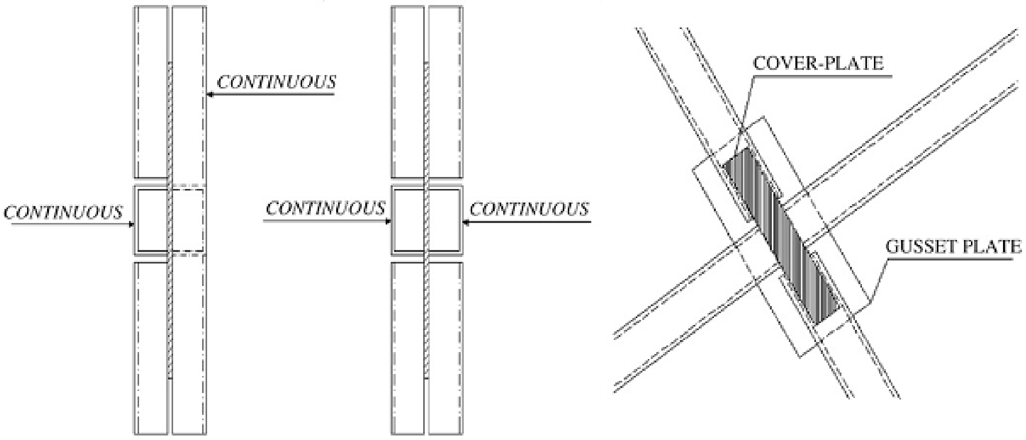


Figure 2.26 Mid-connection details (Davaran and Hoveidae, 2009)

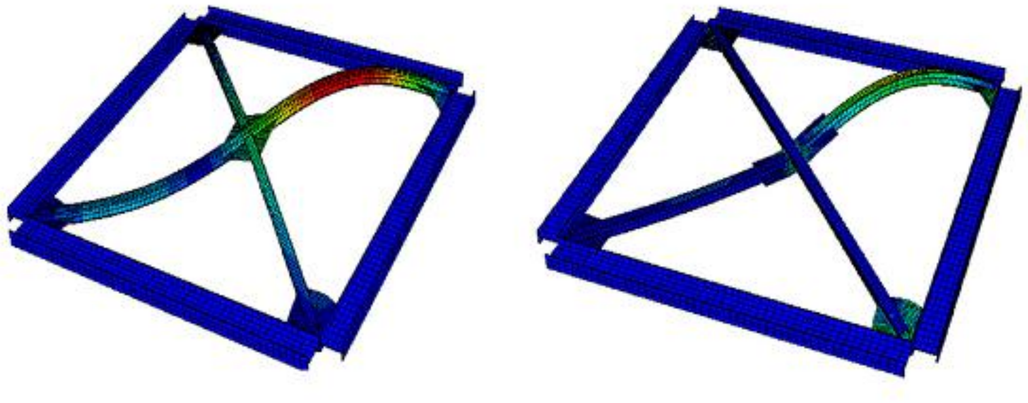


Figure 2.27 Buckling of brace systems (Davaran and Hoveidae, 2009)

In the experimental study of Paul and Agarwal (2012), the pushover test was conducted on the following 1/4 scale reinforced concrete frame models: i) bare frame (BF), b) infilled frame (INF) and a steel braced frame (SBF) under quasi-static condition. The steel braced frame model contained a reinforced concrete frame with concentric steel bracing of X-pattern. Figure 2.28 shows the RC bare frame while Figure 2.29 reveals the experimental set-up. The analysis of the different frames showed that there was an significant improvement in stiffness, yield load, and ultimate load of approximately 3.4, 2.9, and 2.7 times, respectively owing to inclusion of infill wall while the above three parameters raised approximately 17, 11.6 and 14.7 times, respectively because of the use of the steel bracing.

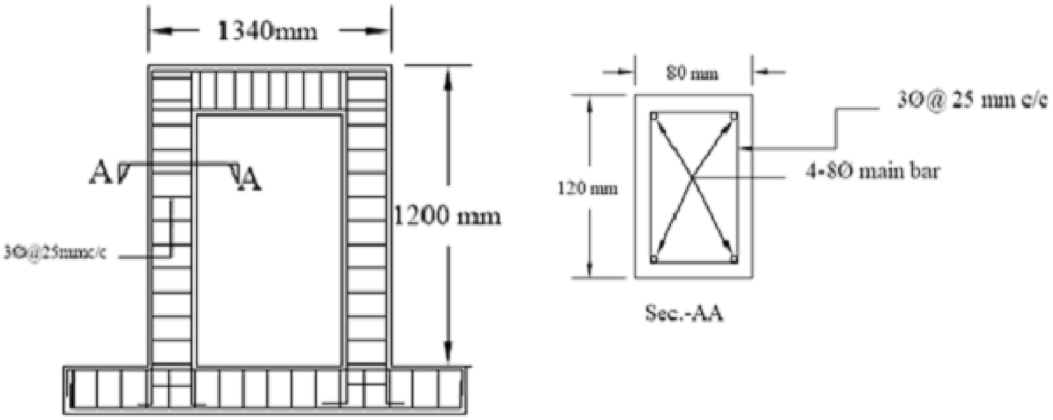


Figure 2.28 Details of the reinforced concrete bare frame (Paul and Agarwal, 2012)

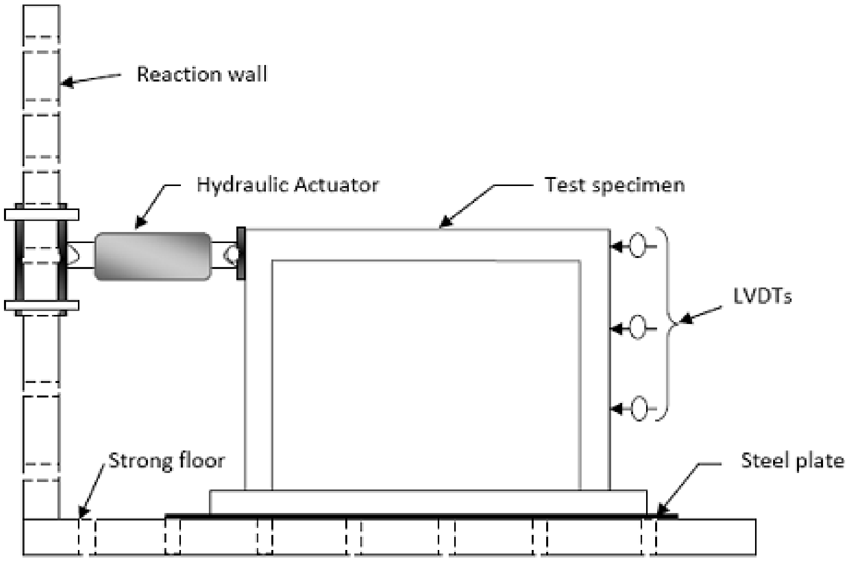


Figure 2.29 The pushover test set-up for the reinforced concrete frame (Paul and Agarwal, 2012)

Furthermore, it was reported that in strengthening non-ductile reinforced concrete structures, the use of the eccentric steel brace system left behind that of the concentric steel brace owing to insufficient studies on the design, model, and behaviour of eccentric steel brace (Ghobarah and Abou-Elfath, 2001). This highlights the needs of further researches on this issue.

In the eccentric bracing systems, the forces are transferred to the braces by means of the bending and shear forces occurred in link elements. The eccentrically braced frame systems have excellent ductility and energy dissipation capacity due to the link elements. Well designed link elements provide a stable energy absorption capacity in the structure. Different configurations for the eccentric bracing system such as V-brace, K-brace, X-brace, and inverted Y-brace are utilized. In Figure 2.30, commonly used eccentric steel braces for the purpose of strengthening of the reinforced concrete structures are given as an example. In the reinforced concrete structures, it is more difficult to provide an adequate ductile link element at the mid span of the frame. For this reason, Y-brace type which has vertical link element is recommended for strengthening of the reinforced concrete structures as an eccentric steel bracing system (Fehling et al., 1992; Ghobarah and Abou-Elfath, 2001). In such case, a vertical link element is connected to a reinforced concrete beam. In addition, the connection of vertical link element to reinforced concrete beam and connections of braces to reinforced concrete members have to be designed carefully.

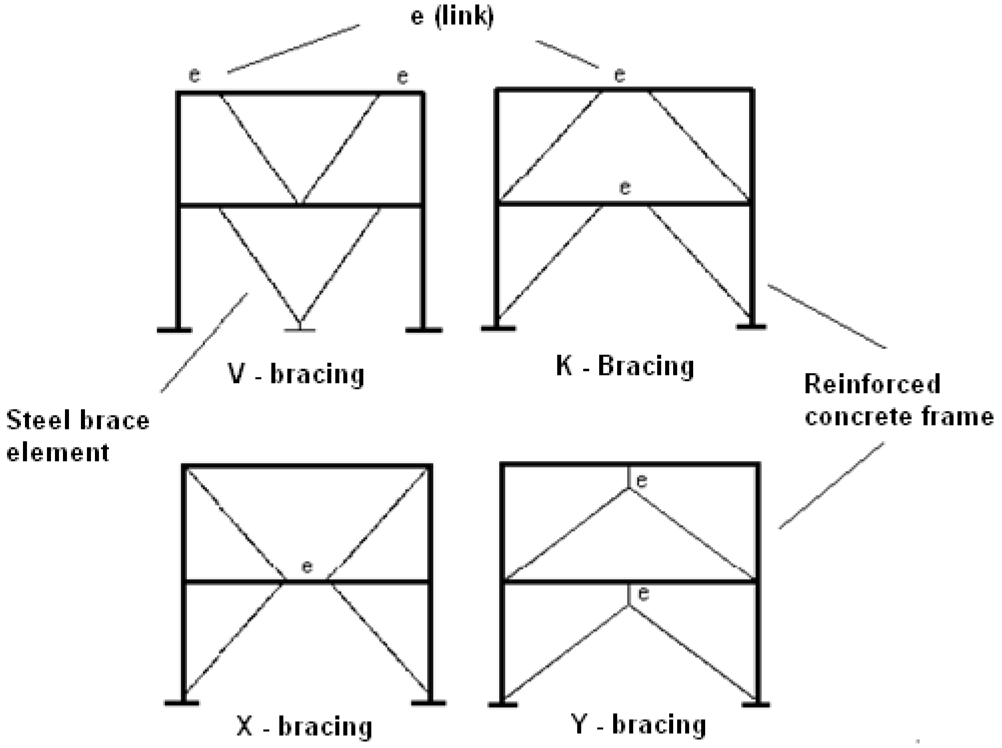


Figure 2.30 Eccentric bracing systems for retrofitting RC structures

Güneyisi and Altay (2005) performed a numerical study on strengthening the existing five storey reinforced concrete structure which had inadequate earthquake safety by using reinforced concrete shear wall as well as eccentric steel braces. The existing and strengthened structures were evaluated comparatively by virtue of nonlinear static and dynamic analyses. As a retrofit strategy, three different types of strengthening technique including the use of shear walls and structural steel braces. Nonlinear behavior of structural elements was modeled according to FEMA 356. Moreover, the performance point and level of the existing and retrofitted buildings were computed using the capacity-spectrum method defined in ATC-40. The buildings were also evaluated by the dynamic analysis. In the dynamic analysis, İzmit (PGA=0.23g), Kobe (PGA=0.76g), and Hachinohe (PGA=0.20g) earthquake acceleration records were employed. According to data gathered in their study, the retrofitted buildings underwent less displacement and more capable of energy dissipation capacity, depending on the earthquake and chosen strategy of strengthening.

Korkmaz (2007) examined the seismic response of reinforced concrete structures retrofitted with eccentric steel bracing. The existing and the retrofitted frames are analyzed by nonlinear static pushover analysis. A 10 story frame was used and this structure was retrofitted eccentric braces. Figure 2.31 shows the existing frame and frames with eccentric braces. It was reported that the retrofit of the frame system with eccentric braces resulted in at least two times better performance than the existing one.

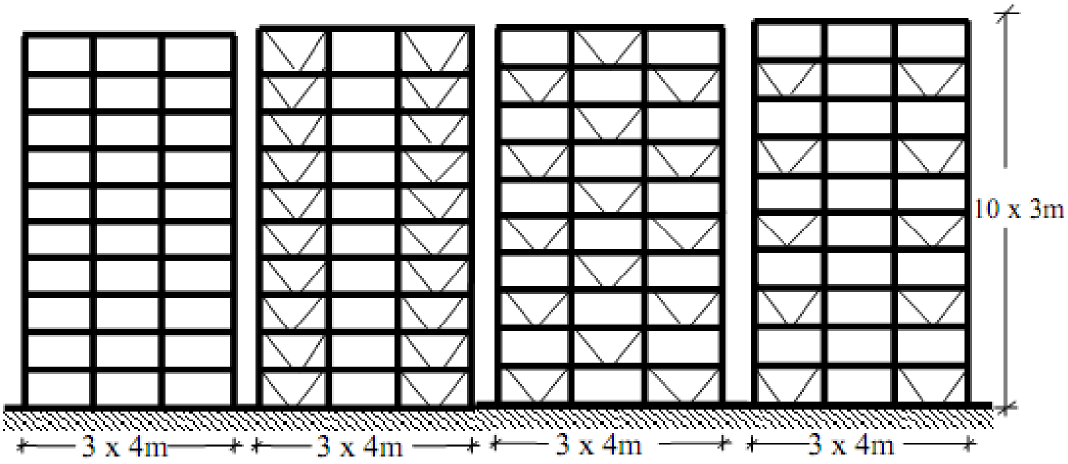


Figure 2.31 Elevation views of the frames (Korkmaz, 2007)

In the study of Özel and Güneyisi (2011), the earthquake performance of a mid-rise reinforced concrete building strengthening with eccentric steel braces was examined by virtue of the fragility analysis. They used different configurations of eccentric steel braces such as D, K, and V shapes as a retrofit strategy. Nonlinear dynamic analysis was performed on the structures before or after retrofit using a set of ground motion records. Various limit states, namely, slight, moderate, major, and collapse were taken into account. The analysis of the results showed that the generated fragility curves after strengthening with steel braces proved enhancement in comparison to those before strengthening. Figure 2.32 illustrates the fragility reduction over the existing reinforced concrete structure for different strengthening cases as a function of various damage levels.

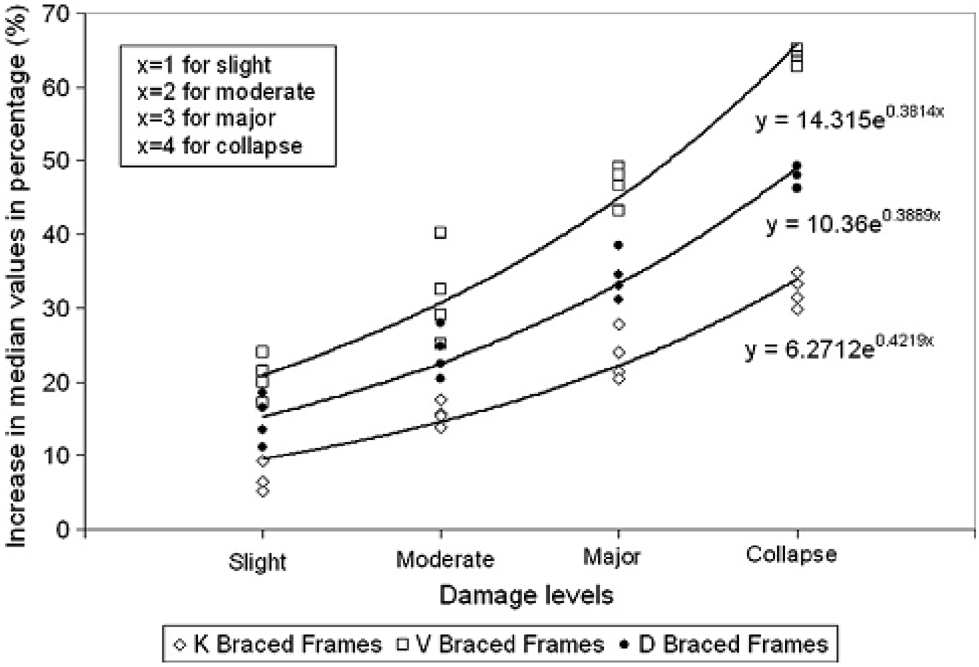


Figure 2.32 Fragility reductions due to the use of different eccentric braces in retrofitting (Özel and Güneyisi, 2011)

Da-pen et al. (2012) conducted an experimental investigation on seismic performance of reinforcement concrete frames with eccentric braces. To this aim, they constructed two single-story single-pan reinforcement concrete (RC) frame structures in a 1/3 scale in laboratory. A pseudo-dynamic testing technique was utilized to work the mechanical properties and the earthquake response under El-Centro ground motion regulated based on China earthquake design provision. Figure 2.33 shows the dimension of test specimen. A concrete class of C30 was considered in constructing RC frame. The axial compressive strength of concrete was measured as 23.6 N/mm². An energy dissipation element having section of H 100x100x6x8 and a length of 250 mm were used in bracing system. Moreover, the eccentric steel brace consisted of diagonal braces having a section of H 100x100x6x8. Figure 2.34 indicates the failure of the test specimens. The results obtained from the experimental study showed that the eccentrically steel braced RC structures had perfect earthquake performance under seismic action due to the superior ductility, strong bearing and fine energy absorbing capability supplied by a dissipation member and high lateral stiffness supplied by diagonal bracings.

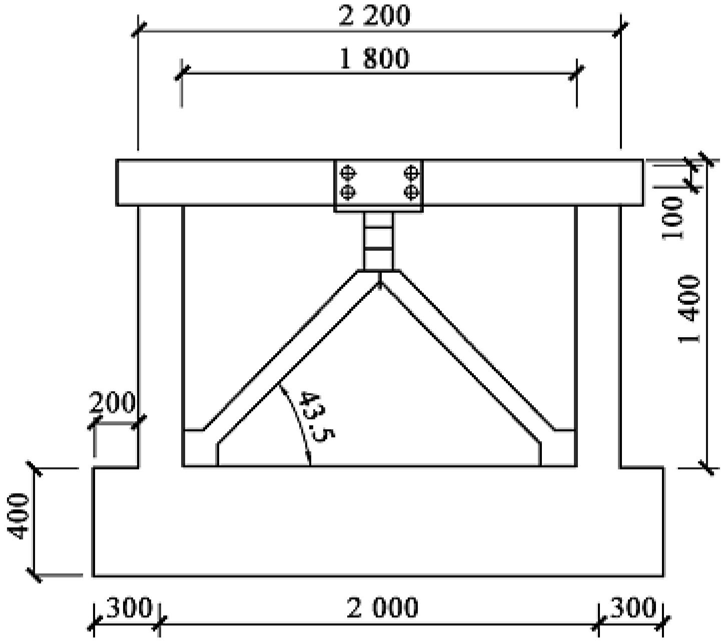


Figure 2.33 RC test specimen with eccentric bracing (in mm) (Da-peng et al., 2012)

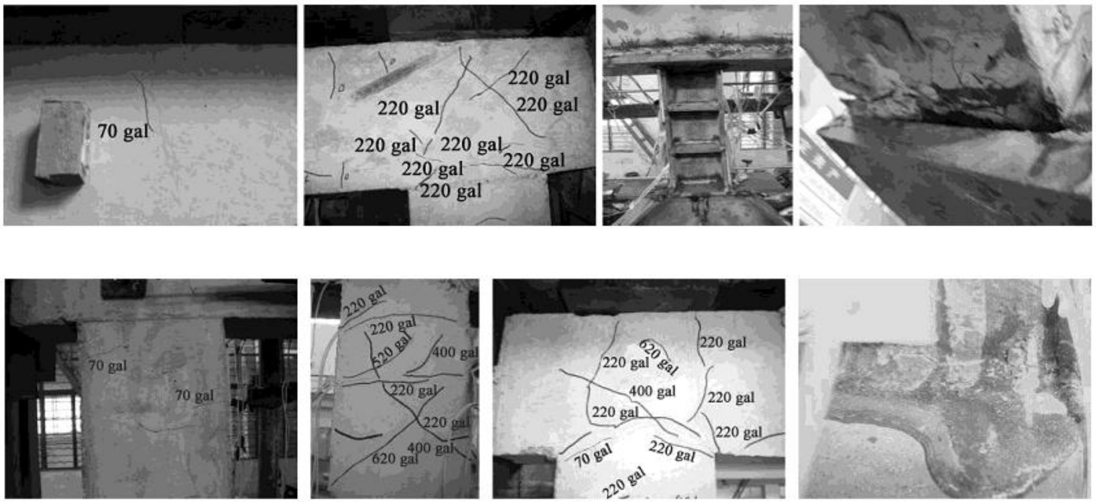


Figure 2.34 View of the failure of the test specimens (Da-peng et al., 2012)

Varum et al. (2013) conducted a study on seismic evaluation of retrofitting strategies for non-seismically designed reinforced concrete buildings using eccentric steel braces. The effectiveness of ductile steel eccentric brace systems in the seismic strengthening of existing reinforced concrete structure was assessed. Both of the ductile bracing system and the vertical device were modeled with the steel fiber model. The braces were designed by bar elements in the bracing system. Figure 2.35 illustrates the total energy dissipation for the bare frame and retrofitted frame. It was concluded that the effectiveness of the strengthening in the enhancement of the earthquake response was observed. The adoption of the strengthening approach studied confirmed to raise considerably the hysteretic dissipated energy, and might avoid the building structures to occurrence rigorous damages or collapse, for moderate to high earthquake events.

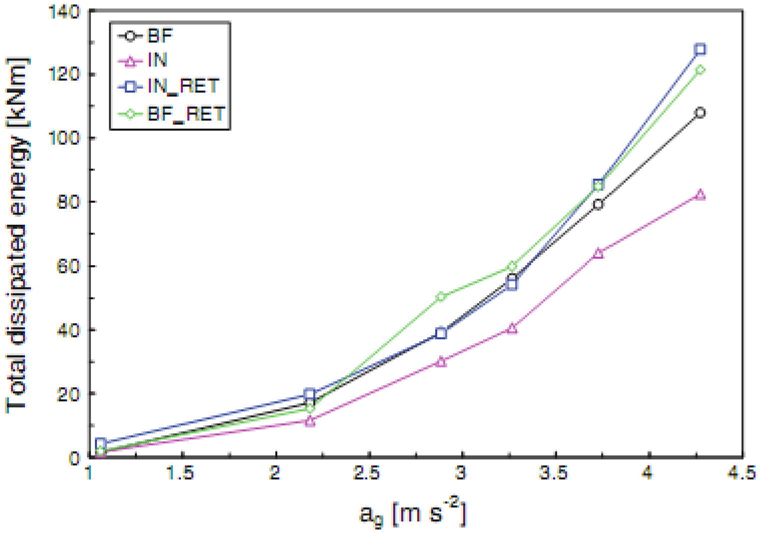


Figure 2.35 Total energy dissipation curves of the bare and retrofitted frames (Varum et al., 2013)

CHAPTER 3

ANALYTICAL STUDY

3.1. Description of Existing Reinforced Concrete Building

In this study, an existing 3 story reinforced concrete hospital building located in Gaziantep was examined. The building consists of basement, ground floor, and first floor. The dimension of the structure is 14.3 m in x-direction and 29.8 m in y-direction in the plan. The total living area is approximately 427 m² at each storey level. The height of the building at each floor is 3.5 m. In addition, the model building has seven spans in long direction and three spans in short direction. The slab thickness is 15 cm on basement and ground floor, 12 cm on normal floor. The column dimensions are 30x70 cm on basement floor, 30x60 cm on ground floor, and 30x50 cm in normal floor. The beam dimensions are varied as 30x60 cm and 30x70 cm in the structure.

In the existing structure, the concrete class of C16 and steel type of S220 were used. Thus, the characteristic compressive strength of concrete (f_{ck}) is 16 MPa and the corresponding modulus of elasticity (E) is 27 000 MPa. The yield stress of the reinforcing steel bars (f_y) is determined as 220 MPa. The case studied building is located in a soil class of Z3. The typical building floor plan is given in Figure 3.1. The three dimensional view of the building is shown in Figure 3.2.

The sample building presents the characteristics of the buildings designed according to the 1975 Earthquake Code (ABYYHY, 1975). For example, lack of shear walls in structural system, inadequate confinement in beam-column connections, insufficient concrete class, use of plain steel bars, etc.

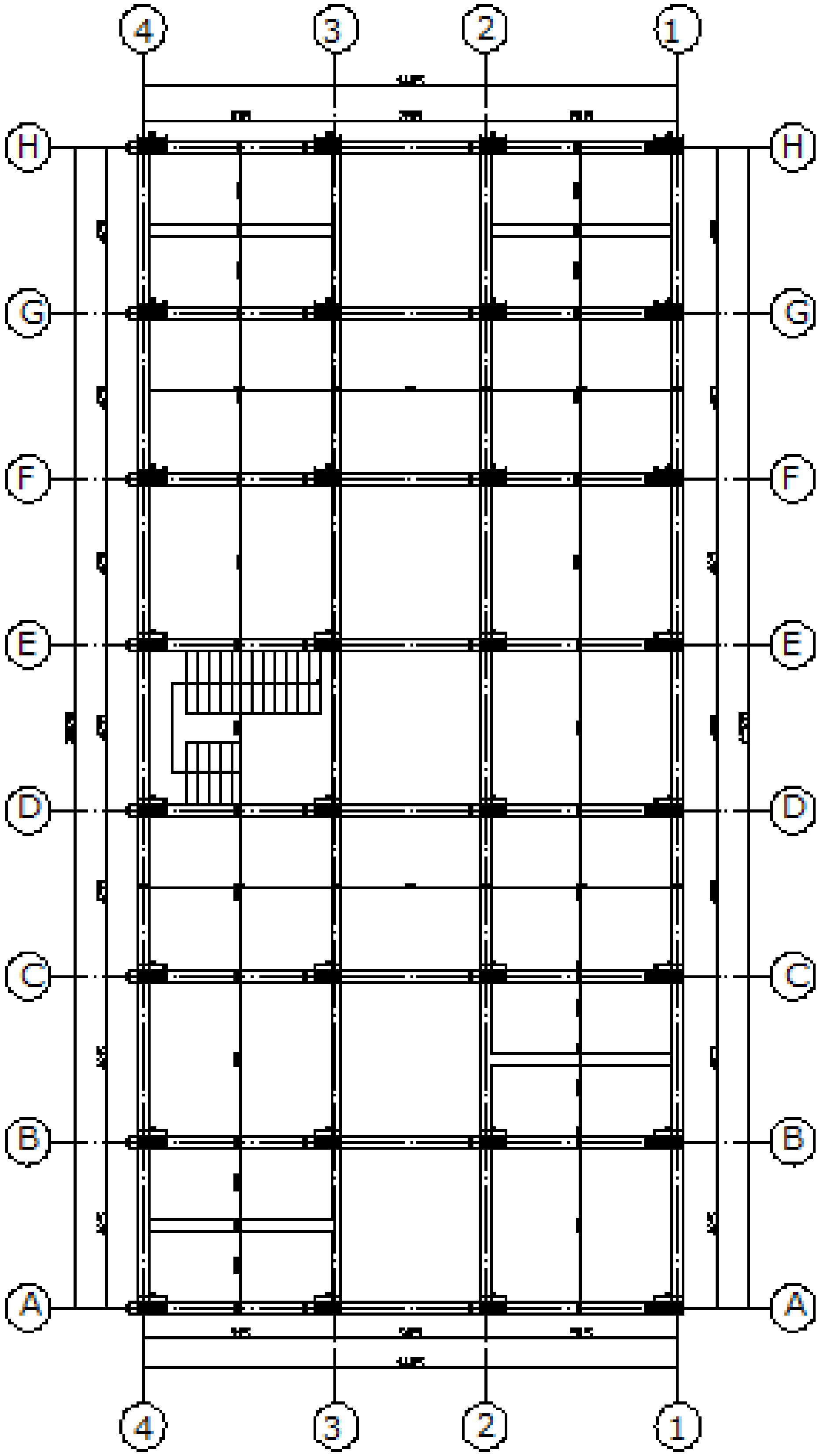


Figure 3.1 The ground floor plan of the RC building

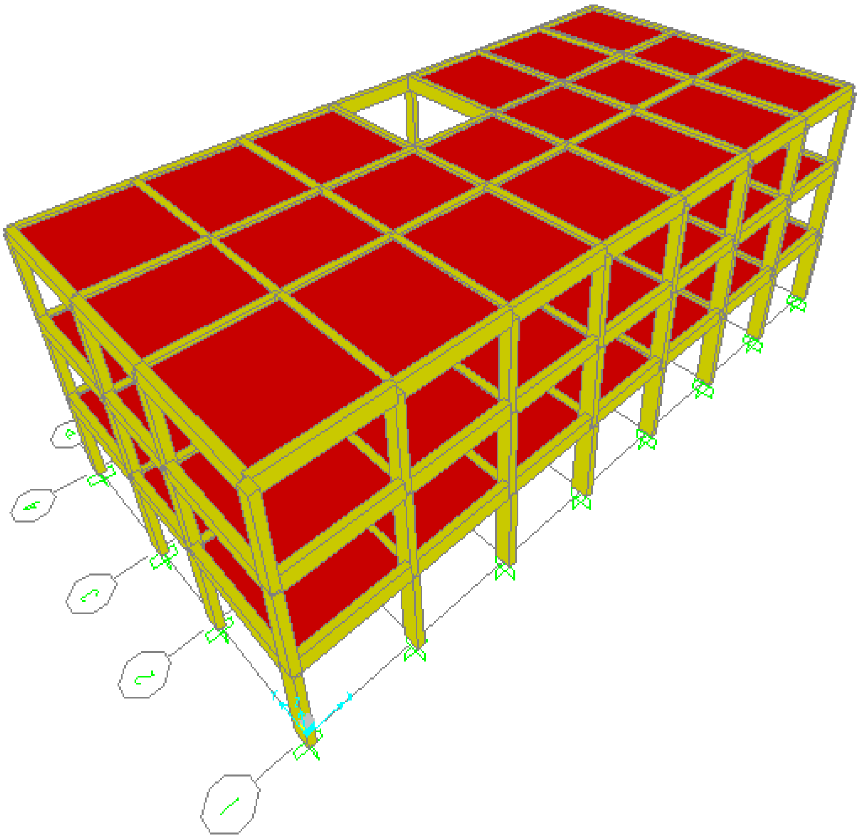


Figure 3.2 3D view of the RC building

3.2. Description of the retrofit strategy

In strengthening the existing reinforced concrete building, inverted Y-shaped steel bracing which is one of the configurations of the eccentric steel brace systems were used as a retrofit strategy. Inverted Y-type braces were inserted into the exterior bays of the structure in both directions. The model views of the existing RC frames for x and y directions are shown in Figures 3.3 and 3.4, respectively. Moreover, those of the retrofitted frames with inverted Y-type structural steel braces for x and y directions are provided in Figures 3.5 and 3.6. In Figure 3.7, the application of the inverted Y-type bracing is given as an example.

In the eccentric steel bracing systems, loads are transferred to the braces by means of the bending and shear forces occurred in link elements. While this connection provides the energy dissipation, it is designed to prevent the buckling of brace members.

Following relationship (Eqn. 3.1) was used for the determination of the critical length of link element (e) (Ghobarah ve Abou-Elfath, 2001). In this equation, M_u shows the ultimate end moment while V_u shows the shear force. Considering the experimental study results on the eccentrically steel braced frames by Kasai and Popov (1986), the ultimate moment (M_u) is equal to $1.2M_p$ and the shear force is equal to $1.5V_p$. Here, M_p and V_p show the plastic moment and shear force of link element, respectively. Moreover, by substituting these relationships into Eqn. (3.1) Eqn (3.2) is obtained.

$$e = \frac{M_u}{V_u} \tag{3.1}$$

$$e = 0.8\frac{M_p}{V_p} \tag{3.2}$$

Popov ve Malley (1983) recommended the use of the following equation (Eqn. 3.3) to calculate the critical length of the link element. This formula was obtained from the experimental study on link element and beam-column connection of eccentrically braced frames. The formula for evaluating the length of a link ensures that the link yields mainly in shear. In Eqn. 3.3, b_f and t_f show the flange width and flange thickness, respectively while t_w shows the web thickness of a flange section link.

$$e = \frac{2b_f t_f}{t_w} \tag{3.3}$$

In this study, for the Y-braces to be used for retrofitting of the structure, three different link lengths were selected based on the equations above. Thus, the link lengths under investigation are varied from 35 to 75 cm. For all link elements, HLS280 profile was used. In diagonal elements, pipe profile was used which has a diameter of 152.4 mm and thickness of 4 mm. The modulus of elasticity is E=200 GPa and the yield strength is f_y=240 MPa for the steel used. In strengthening the structure, all bracing elements have the same length, cross-section, and material properties on each floor. Thus, the effect of link length of inverted Y-bracing on the strengthening of the RC structure was examined for both of the directions.

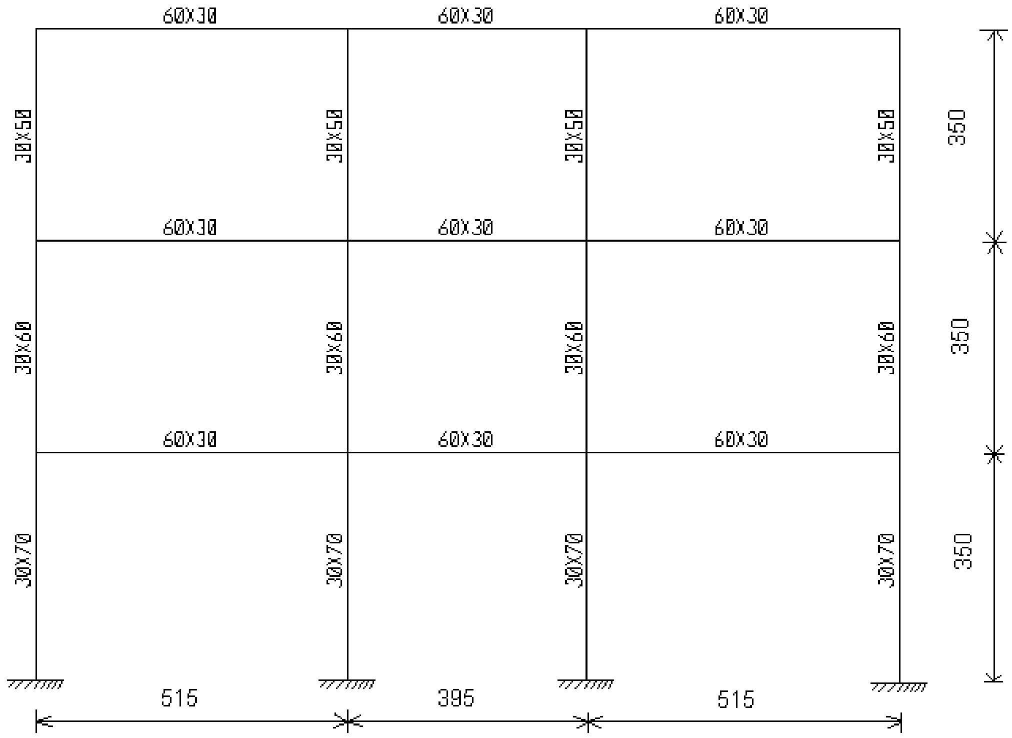


Figure 3.3 View of the existing RC frame in x-direction

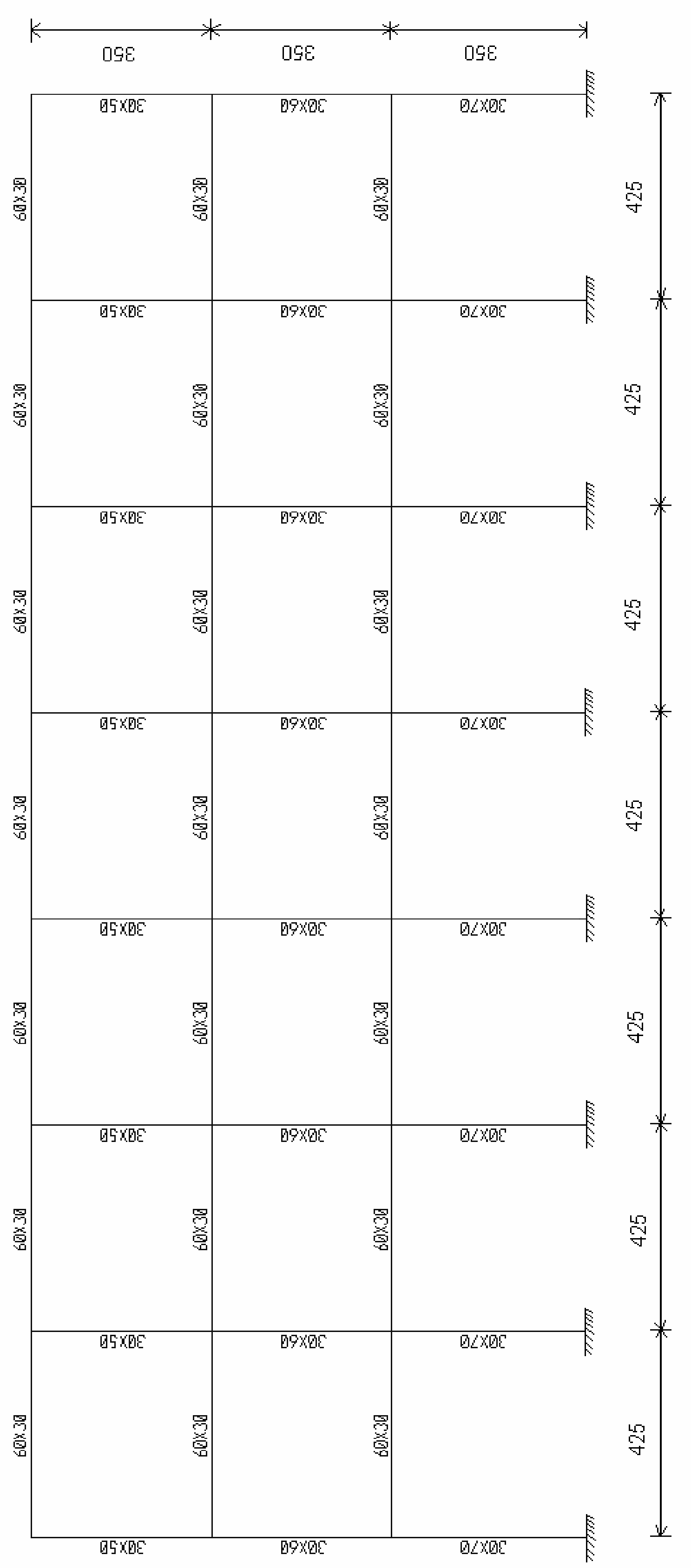


Figure 3.4 View of the existing RC frame in y-direction

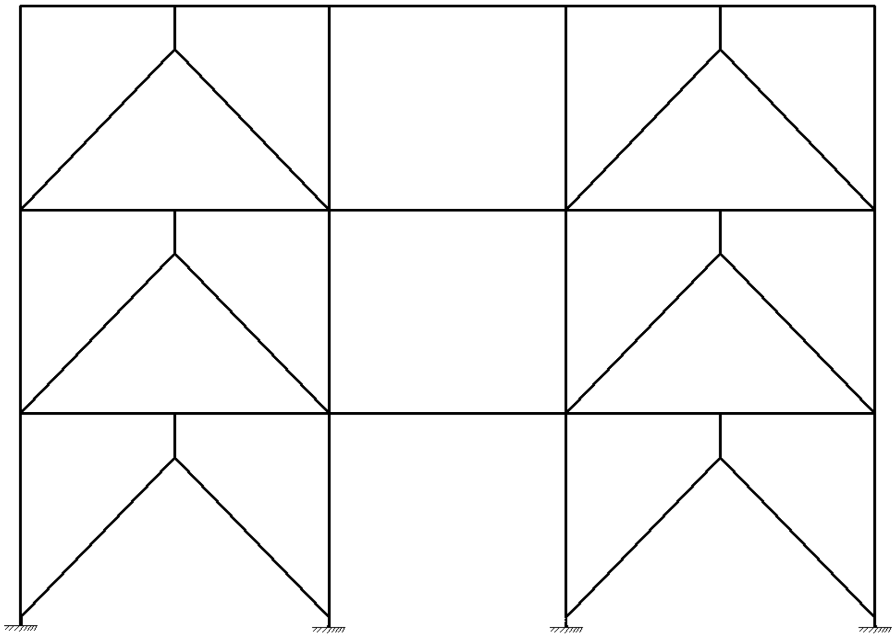


Figure 3.5 The retrofitted RC frame in x-direction

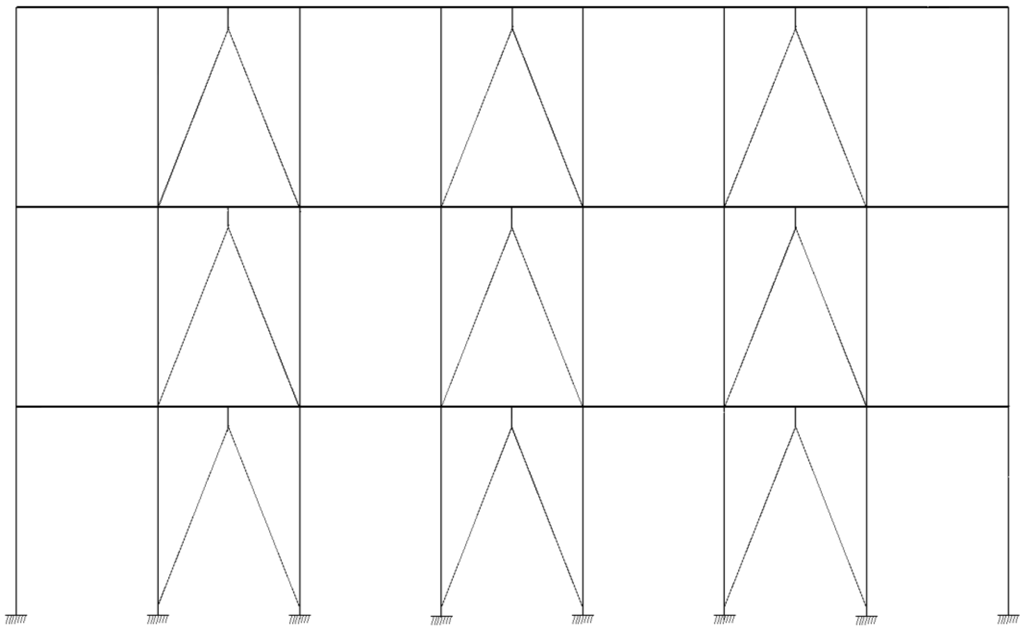
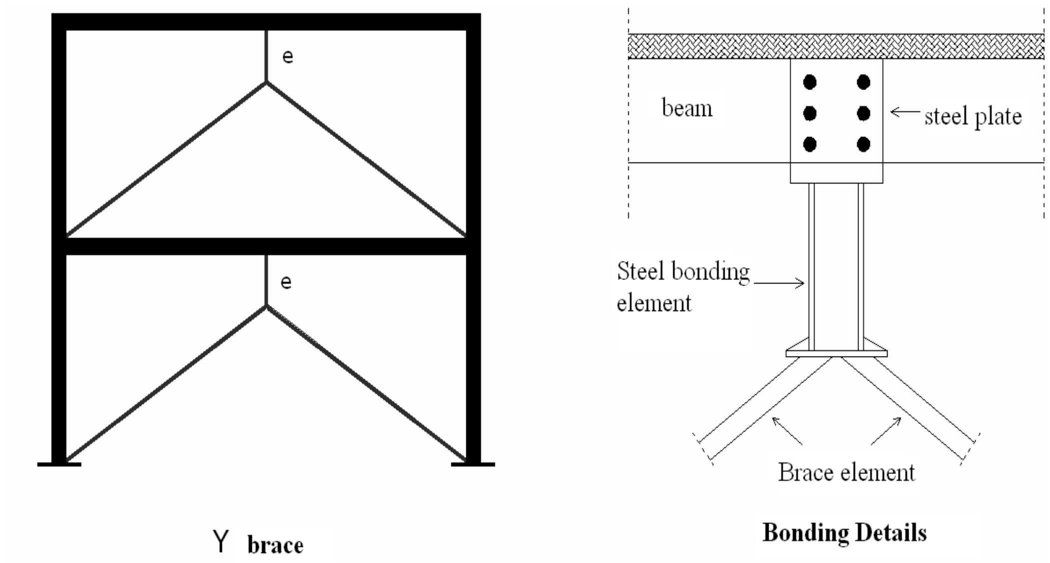


Figure 3.6 The retrofitted RC frame in y-direction



a) b)

Figure 3.7 a) RC frame retrofitted with inverted Y-steel bracing and b) Connection details (Ghobarah and Abou-Elfath, 2001)

3.3. Modeling and Analysis

In the finite element modeling and analysis of the existing and retrofitted RC structures, the DRAIN-2D computer program (Prakash et al., 1993) was used. The seismic performance of the structures was investigated using nonlinear static analysis and dynamic time history analysis. In the nonlinear static analysis, the capacity curves of each frame system were obtained and evaluated comparatively. Moreover, in the dynamic analysis, a ground motion record of 1999 Chi-Chi was used to compute the story displacement and time history of story displacement for the case study structure with and without inverted Y-bracing. In Figure 3.8, the ground motion record of 1999 Chi-Chi earthquake used in this study is given.

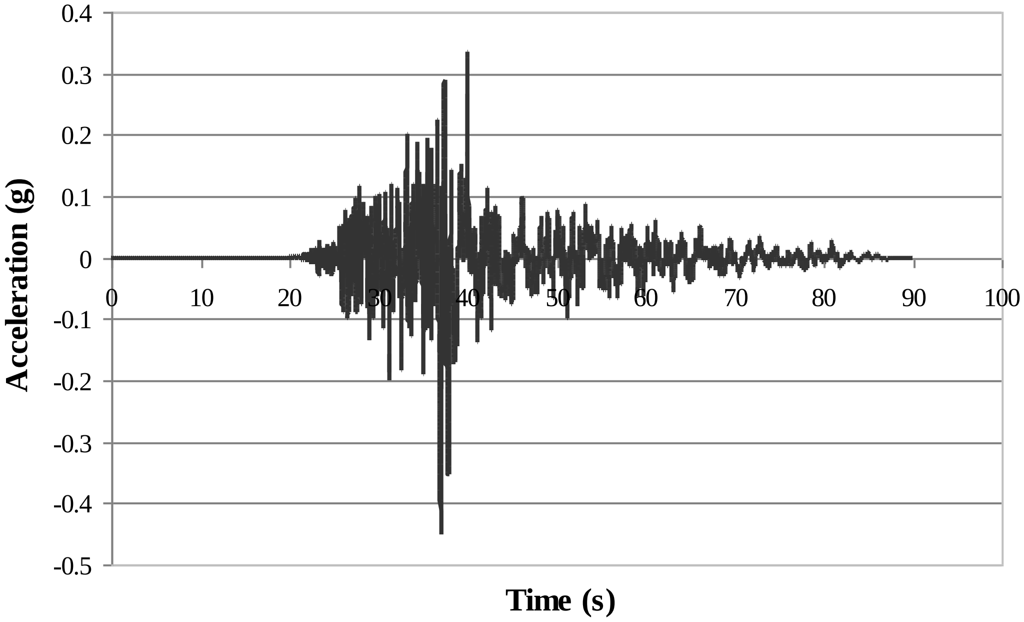


Figure 3.8 The ground motion of 1999 Chi-Chi earthquake used in this study

CHAPTER 4

RESULTS AND DISCUSSION

The first three periods of the existing and retrofitted RC structures were determined and summarized in Table 4.1. As seen from the table, the existing frame had first fundamental periods of 0.514 s in x-direction and 0.347 s in y-direction while the retrofitted frames possessed the periods from 0.286 to 0.310 s in x-direction and from 0.214 to 0.232 s in y-direction, depending mainly on the length of link element used in retrofitting. This indicated that the retrofitted frames were stiffer compared with the existing ones.

Table 4.1 Periods of vibration for the existing and retrofitted structures

Frames	Period (s)		
	T_1	T_2	T_3
X-direction			
Existing frame	0.514	0.186	0.122
Retrofitted frame: Case I-e1=35 cm	0.286	0.104	0.070
Retrofitted frame: Case II-e2=55 cm	0.293	0.107	0.072
Retrofitted frame: Case III-e3=75 cm	0.310	0.113	0.076
Y-direction			
Existing frame	0.347	0.118	0.066
Retrofitted frame: Case I-e1=35 cm	0.214	0.076	0.048
Retrofitted frame: Case II-e2=55 cm	0.220	0.078	0.050
Retrofitted frame: Case III-e3=75 cm	0.232	0.082	0.052

Figures 4.1-4.4 show the capacity curves of the existing and retrofitted frames in x-direction while Figures 4.5-4.8 demonstrate the capacity curves of the existing and retrofitted frames in y-direction. In Figures 4.9 and 4.10, the comparison of capacity curves for the existing and retrofitted frames in x-and y-directions, respectively. As observed from the figures, in x-direction, the maximum base shear of the existing frame was 351 kN while that of the retrofitted frames varied from 1342 to 1444 kN, depending mainly on the length of link element used in retrofitting. This revealed that the retrofitting cases yielded approximately 3.8-4.1 times higher lateral load carrying capacity than the existing frame. Moreover, in y-direction, the maximum base shear of the existing frame was obtained as 434 kN whereas this value was in the range of 1797 to 1883 kN in the case of the retrofitted frames. Thus, the lateral load carrying capacity of the existing structure was improved about 4.1-4.4 times after strengthening.

As a result, it was pointed out that in both of the directions all retrofitted cases had higher strength and stiffness in comparison to the existing RC frame. Decreasing the length of link element in inverted Y-bracing system resulted in greater lateral load carrying capacity in x- and y-directions of the RC structure. In addition, among the retrofitted cases, the selection of link length as 35 cm in Y-bracing (case-I) provided the highest capacity while the use of 75 cm link length (case-III) gave the lowest capacity for the case study reinforced concrete structure.

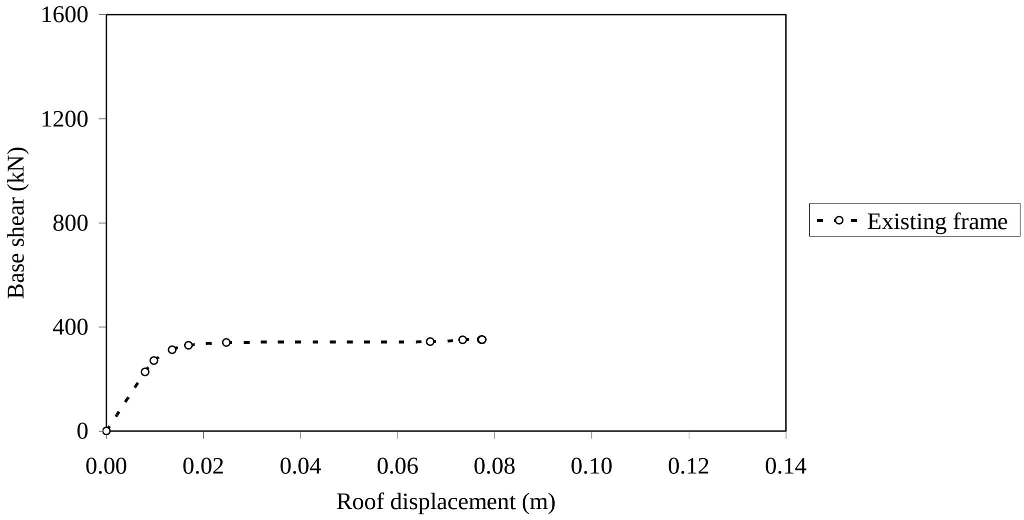


Figure 4.1 Capacity curve for the existing RC frame in X direction

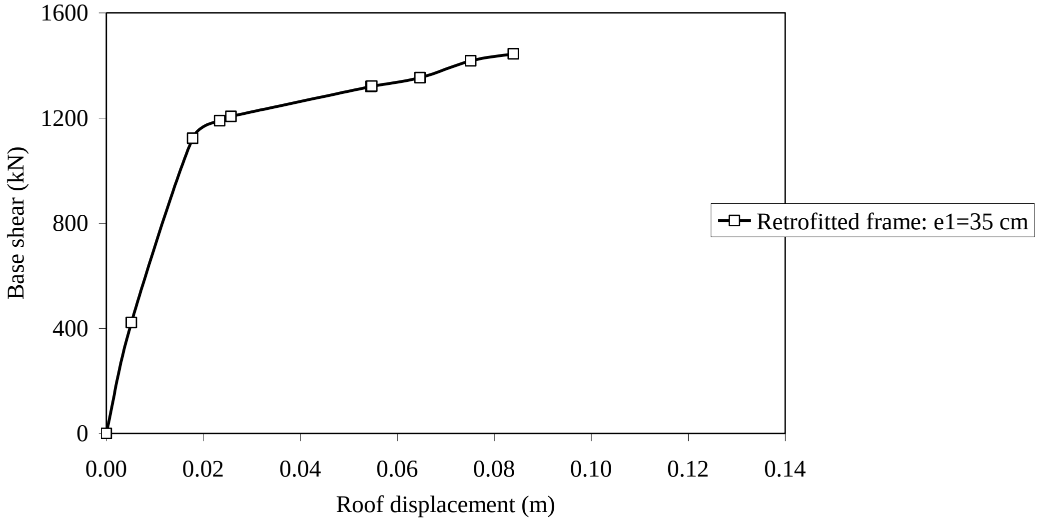


Figure 4.2 Capacity curve for the retrofitted RC frame (Case-I) in X direction

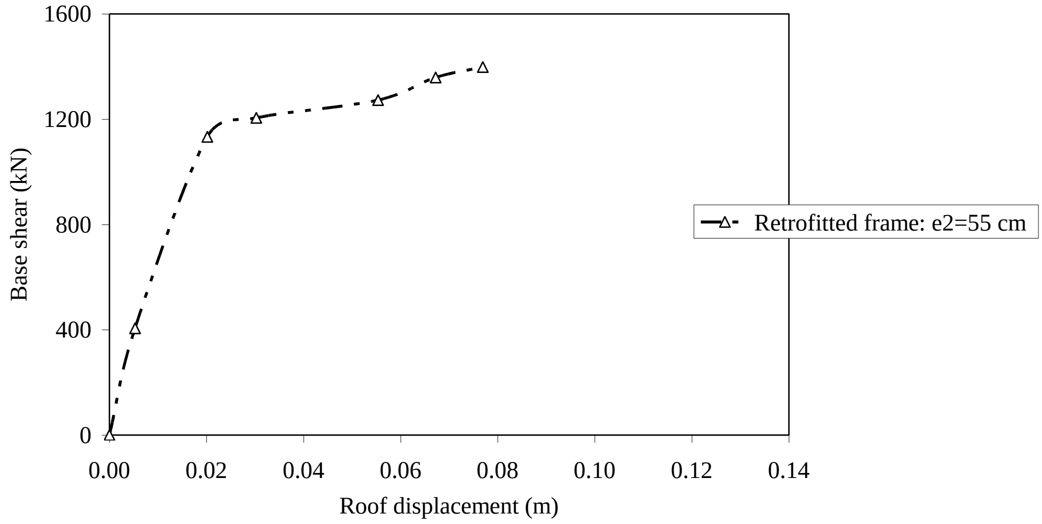


Figure 4.3 Capacity curve for the retrofitted RC frame (Case-II) in X direction

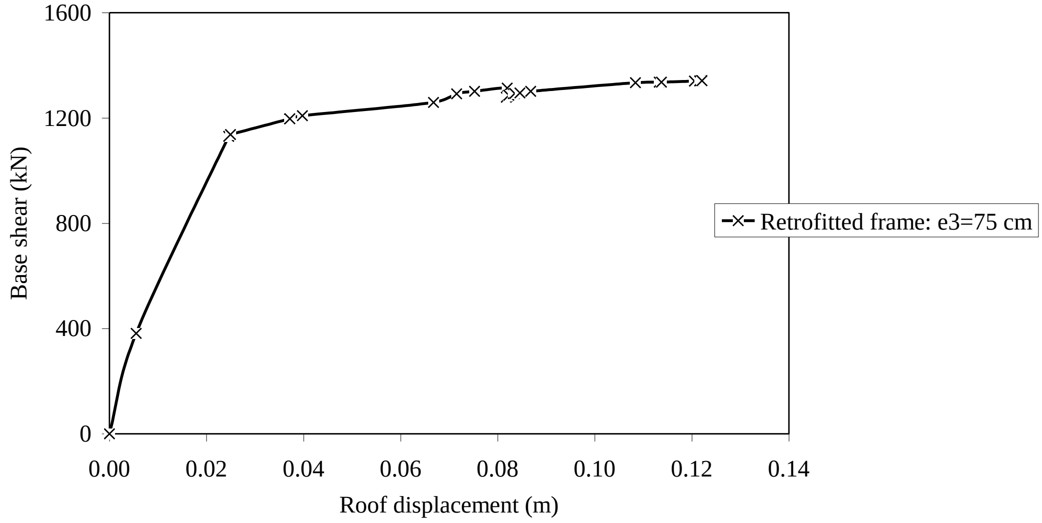


Figure 4.4 Capacity curve for the retrofitted RC frame (Case-III) in X direction

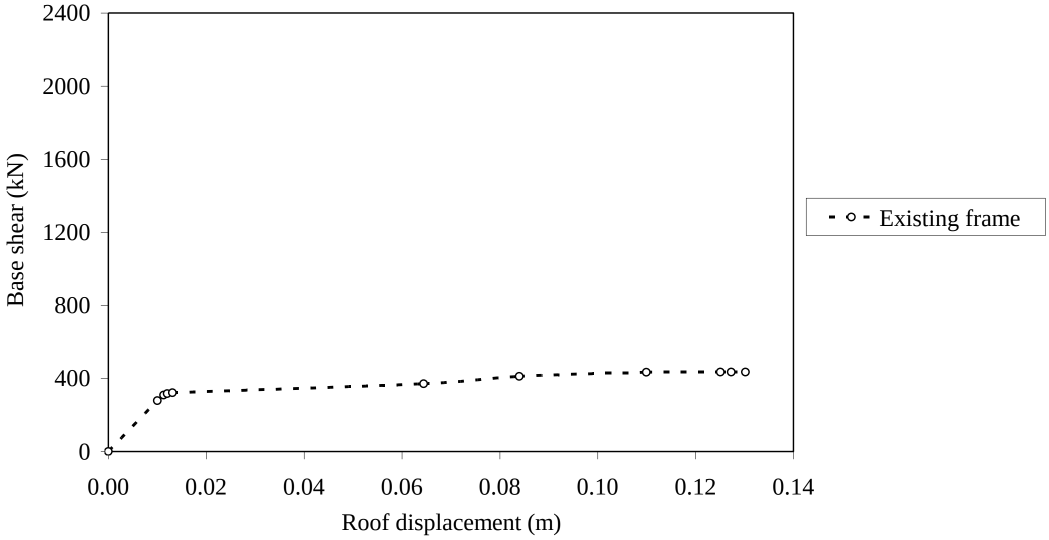


Figure 4.5 Capacity curve for the existing RC frame in Y direction

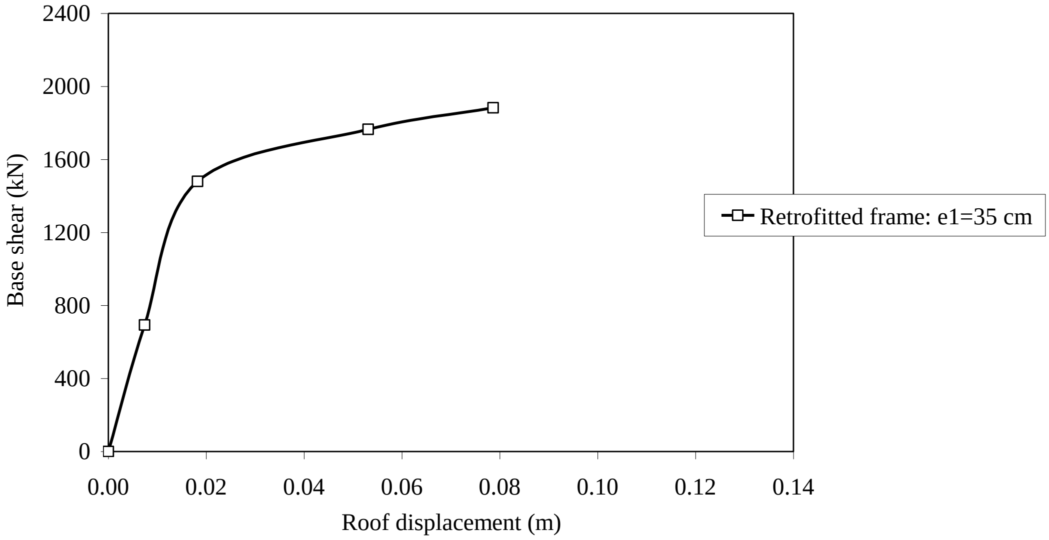


Figure 4.6 Capacity curve for the retrofitted RC frame (Case-I) in Y direction

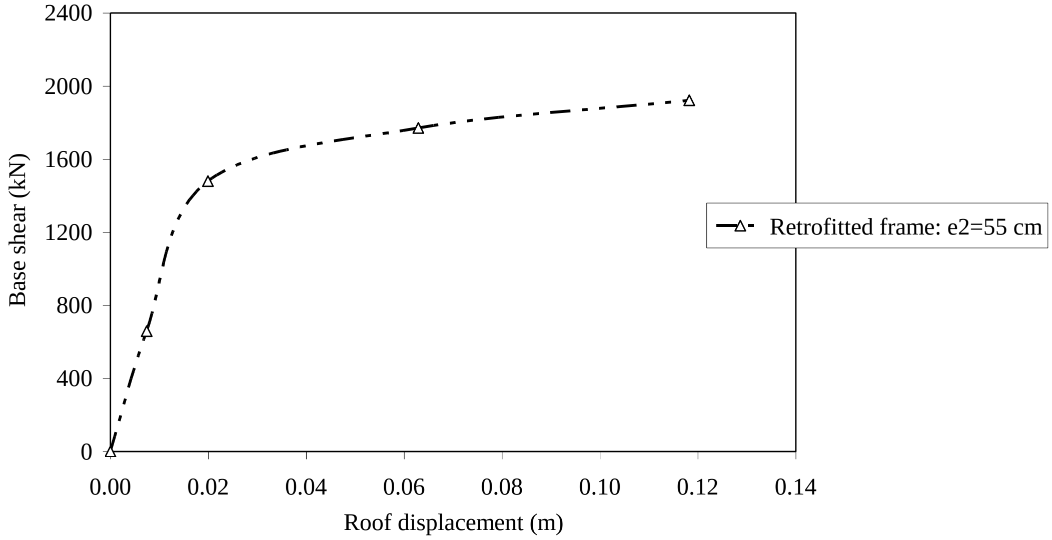


Figure 4.7 Capacity curve for the retrofitted RC frame (Case-II) in Y direction

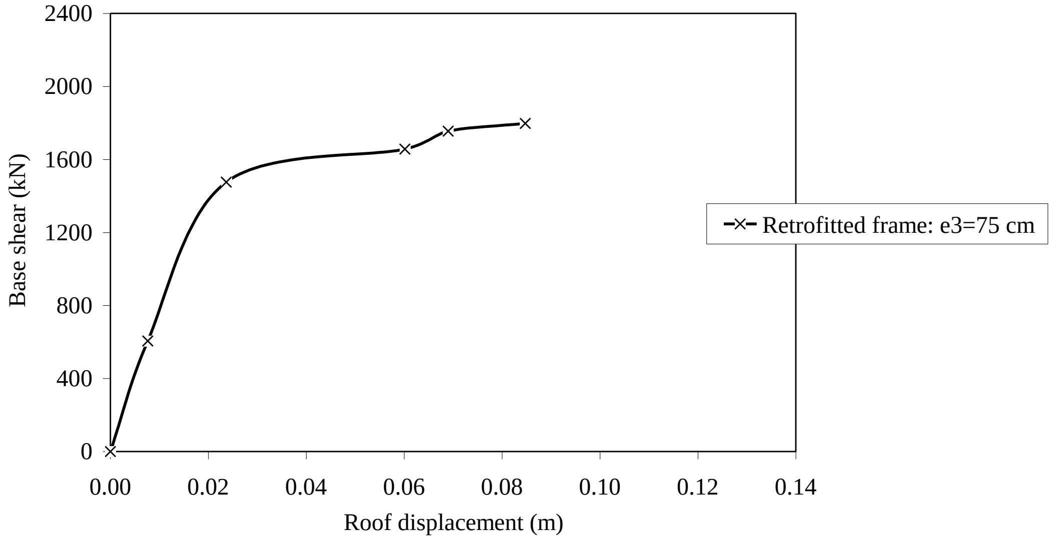


Figure 4.8 Capacity curve for the retrofitted RC frame (Case-III) in Y direction

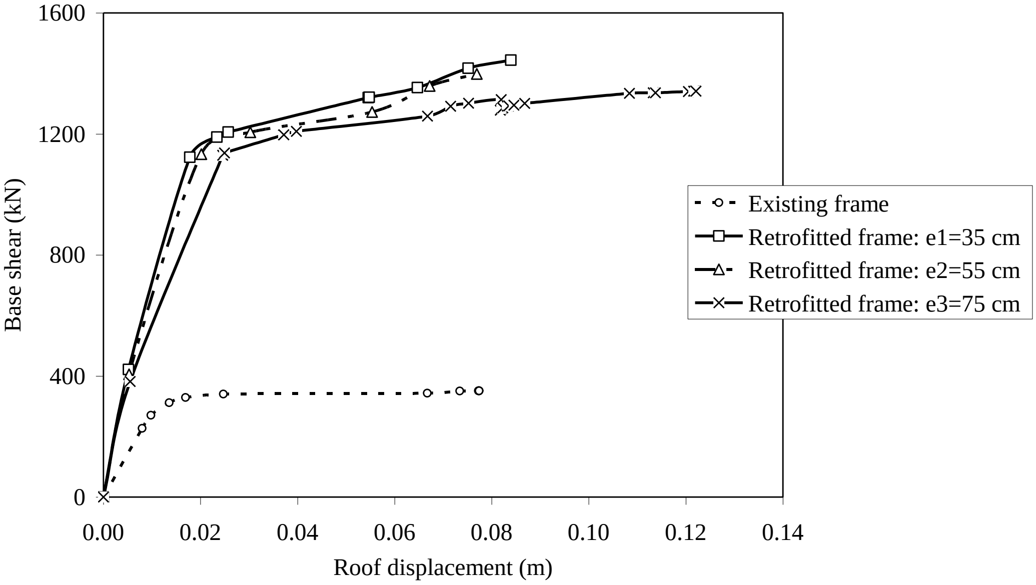


Figure 4.9 Comparison of capacity curves for the existing and retrofitted RC frames in X direction

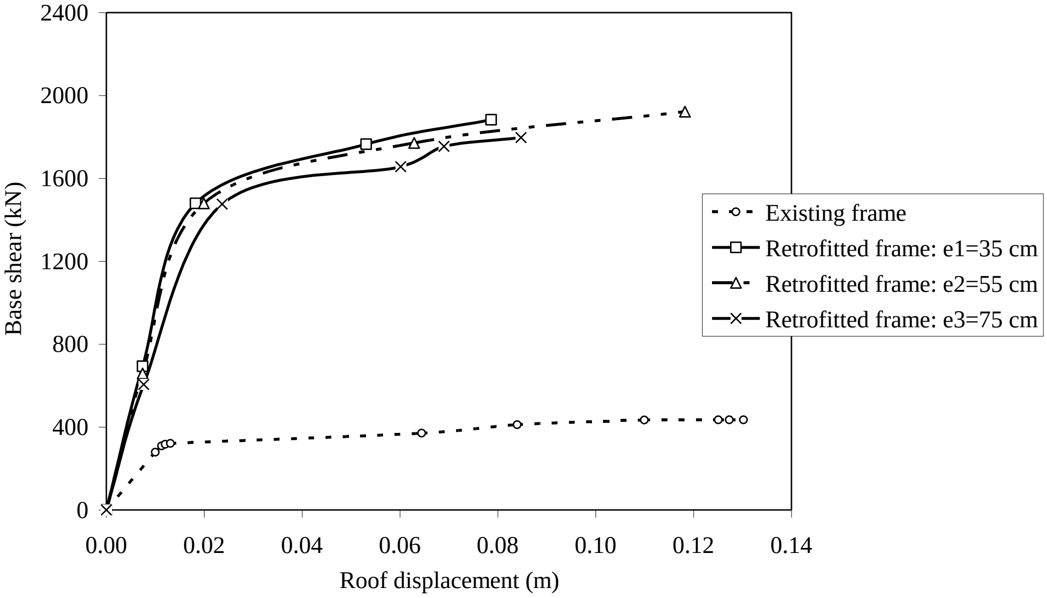
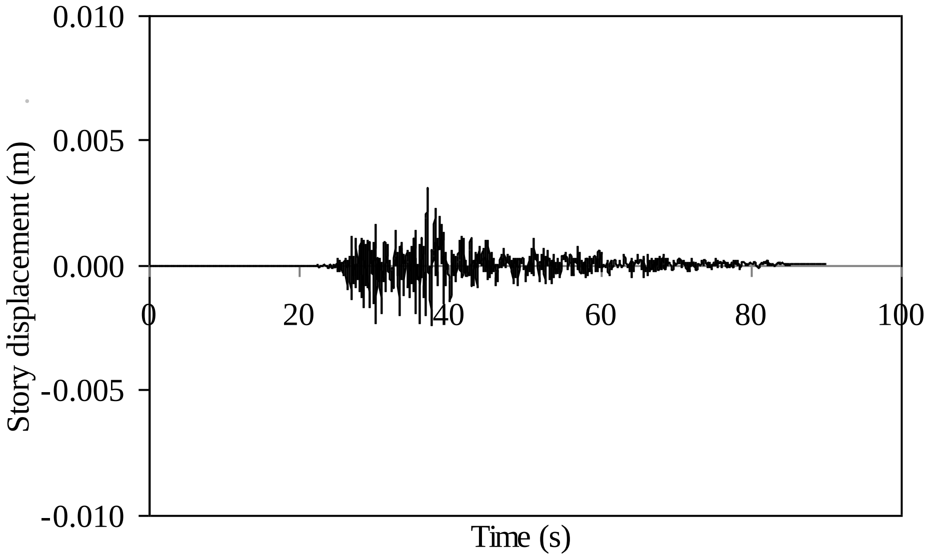
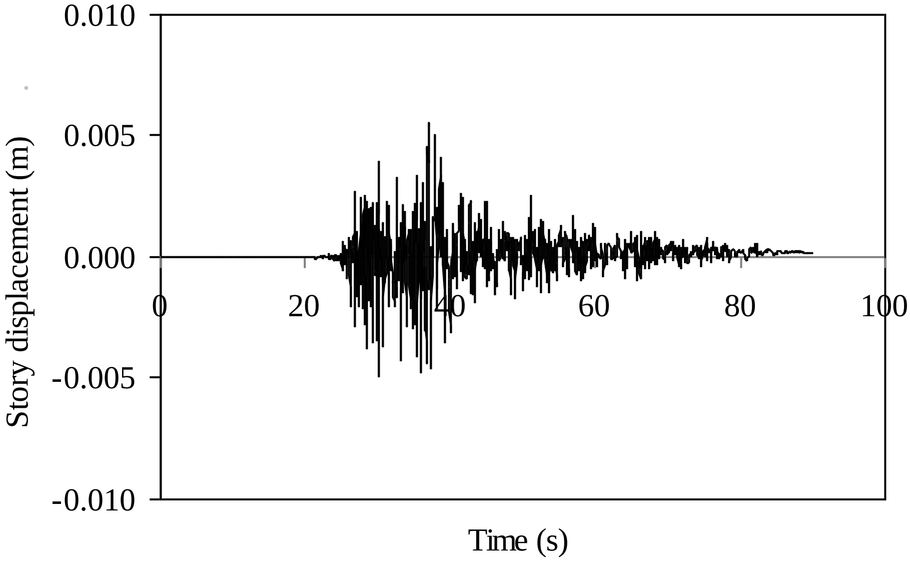


Figure 4.10 Comparison of capacity curves for the existing and retrofitted RC frames in Y direction

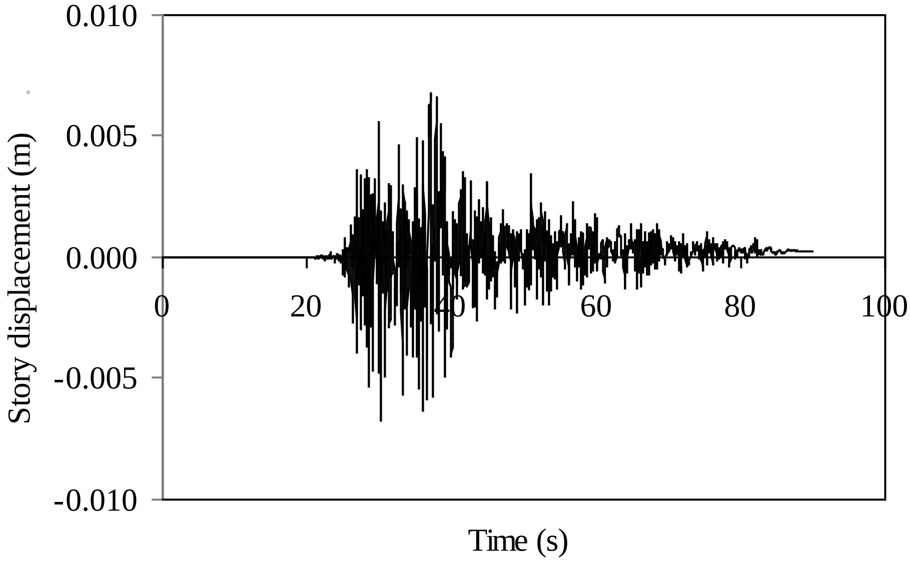
In evaluating the dynamic behavior of the existing and retrofitted structures, 1999 Chi-Chi earthquake record was used in the analysis. Figure 4.11 illustrates the time history of the story displacement of the retrofitted frame (Case-I: e1=35 cm) for different story levels. The variation in story displacement with story level for the existing and retrofitted frames in x-direction are given in Figures 4.12 and 4.13, respectively while that for the existing and retrofitted frames in y-direction are presented in Figures 4.14 and 4.15, respectively. As seen from the figures, the story displacement of the structure after retrofitting was considerably reduced for both of the direction of the structure. For example, in x-direction and in first story, the retrofitted frames had about 4.6-5.1 times lower story displacement than the existing frame. In the same way, in y-direction of the structure, this value was approximately obtained between 2.1 and 2.6. Similar to the observation in lateral load carrying capacity of the frame system studied, decreasing link element length in inverted Y-bracing resulted in lower displacement values.



a)



b)



c)

Figure 4.11 Time history of story displacement of the retrofitted frame (Case-I: e1=35 cm) in x-direction: a) 1. story b) 2. story, and c) 3. story

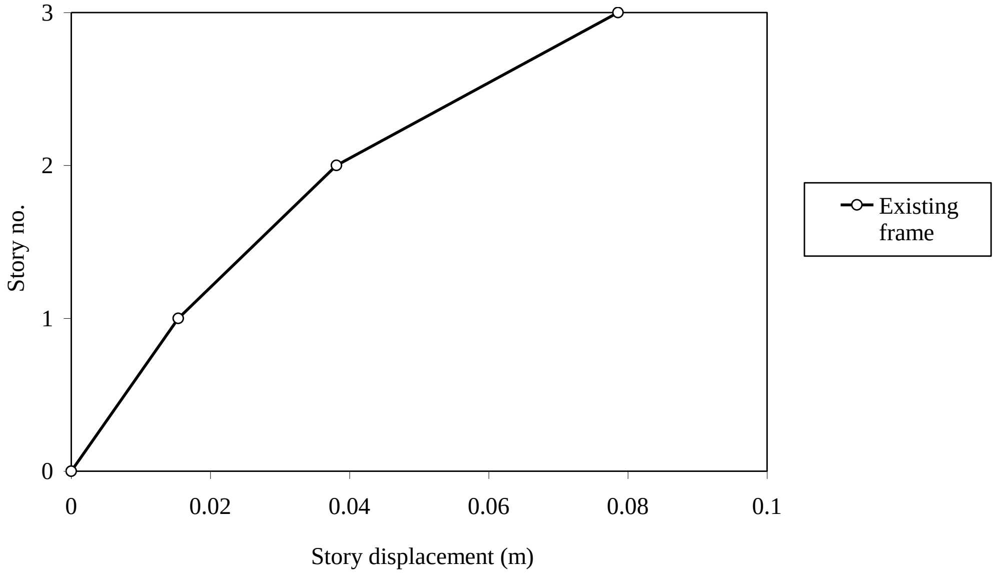


Figure 4.12 Story displacement vs. story no for the existing frame in x-direction

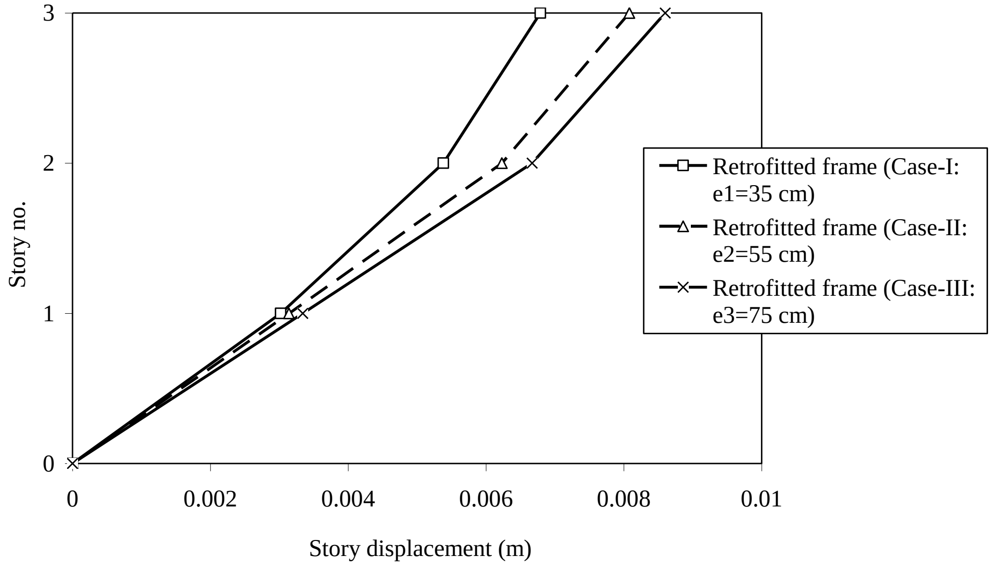


Figure 4.13 Story displacement vs. story no for the retrofitted frames in x-direction

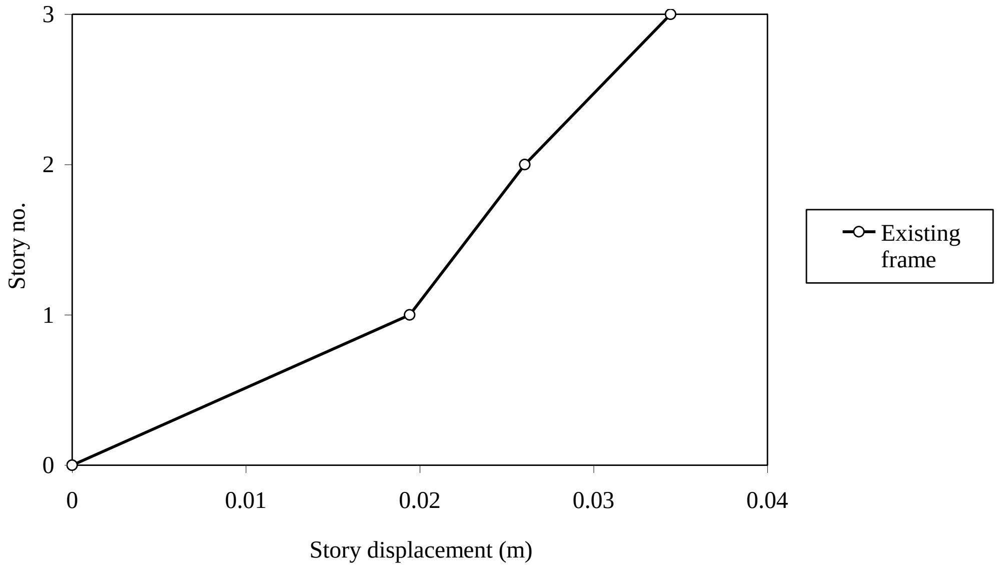


Figure 4.14 Story displacement vs. story no for the existing frame in y-direction

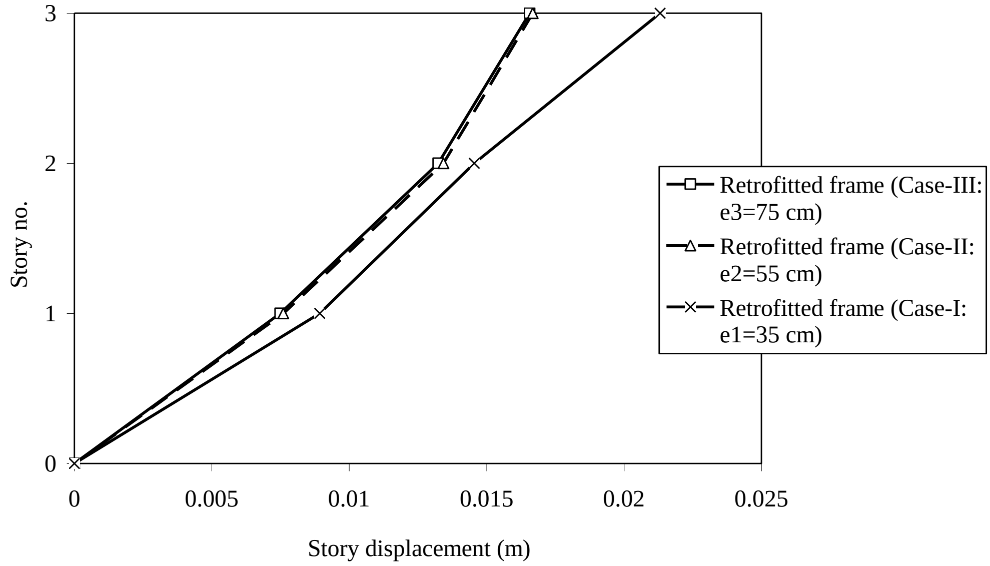


Figure 4.15 Story displacement vs. story no for the retrofitted frames in y-direction

CHAPTER 5

CONCLUSIONS

In this study, the seismic performance of an existing reinforced concrete (RC) structure before and after retrofitting with inverted Y-bracing was evaluated based on nonlinear static and dynamic analyses. Based on the results of the analysis carried out in this study, the following conclusions can be drawn:

- It was observed that the strength and stiffness of the existing RC structure were significantly increased after retrofitting. The fundamental period of the retrofitted structures were also reduced.

- The RC frame had maximum base shear values of 351 kN and 434 kN in short and long directions, respectively. After strengthening with Y-bracing, the load carrying capacity of the structure was enhanced. For example, about 3.8-4.4 times higher capacity was evaluated for the retrofitted cases in comparison to the existing one, depending mainly on the length of link element used.

- Similarly, the retrofitted frames had lower story displacements than the existing frame for both of the directions. It was pointed out that the roof displacement of the retrofitted structures was approximately 1.6-11.6 times less than that of the existing one, depending on direction of earthquake and type of retrofitting.

- The results of the analysis also indicated that reducing the length of the link element in the application of the inverted Y-bracing as a retrofit strategy gave greater load carrying capacity for the structure, on the other hand, provided lower story displacement value.

- Moreover, among the retrofitted cases considered in this study, inverted Y-bracing with 35 cm link length (Case-I) resulted in the highest capacity for the structure while that with 75 cm link length (Case-III) caused the lowest capacity.

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