Seismic Analysis of Retrofitting of RC Regular Frame with V-Braced Frame

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Abstract

Retrofitting of the existing buildings helps to reduce the serious damages under the strong ground motions. In retrofitting techniques, steel bracings are used to resist the lateral load effectively. In this study, the author aimed to investigate the four-story RC frames without and with steel bracings to understand the seismic performances of the buildings. The authors select the V bracings having 7 different thickness of steel bracings (t= 2.5, 4, 6, 8, 10, 14 and 20mm) and observed the effect in seismic behaviors of the structures in terms of maximum story displacements, inter-story drift (ISD), base shear, fundamental time period (FTP) and capacity curves. In addition, it observed the failure behaviors of the structures. To study the seismic behaviors, the response spectrum analysis and nonlinear static analysis are performed in ETABs software. The result indicates that V bracing improves the seismic performances of the RC frames as well as improves the strength capacity and stiffness of the buildings. Adding bracing in RC frames decreases the top story displacements and inter story drift of the buildings. To get the expected failure mechanism in the braced frames and suitable uniform energy dissipation behaviors, the bracings are designed in such a way that the RC columns should be the main line of defense in the dual systems. Expected failure mechanism is obtained when stronger column, weak beam and weaker bracings design philosophy is used and it is only possible when the columns are designed to resist at least 50% lateral base shear in dual systems. A suitable thickness of bracings which is economical and structurally good should be selected.

Keywords: *Capacity curves, ISD, Maximum story displacements, Pushover analysis, Retrofitting, Steel bracing*

Introduction

Strengthening of the existing structure by improving the seismic behaviors of the buildings is known as retrofitting technique. To design the existing building to resist the future strong ground motions, there are many design methods such as providing the steel jacketing in beam and columns, adding shear wall, wing walls, using fiber (FRP) in the beam-column joints and steel bracing. Nepal is the place that is seismically active and it is because of the subduction of Indian plate underneath the Eurasian plate. The past earthquake in Nepal shows the buildings are more vulnerable during earthquakes. The researchers observed that the common types of failure in RC structures are related to the construction technique and structural deficiencies (Chaulagain et al., 2015; Gautam & Chaulagain, 2016). It is important to retrofit the structure to prevent from ground shaking. There are various reasons to apply the retrofitting, such as changing the purpose of structures, updating the seismic codes, structure which is designed in past only considering gravity load, due to the application of additional load in structures. Since the global lateral displacements are the important parameter to study the seismic behaviors of the structures during the earthquakes.

Nowadays the steel bracings are used in both existing as well as new constructions of the RC buildings after the successful retrofitting process. Use of the steel bracings in the buildings is easier than other retrofitting techniques and economical than providing shear walls in structures (Badoux & Jirsa, 1990). The self-weight of the steel bracings is also less than that of shear wall which reduced the seismic weight of the structures. Generally, the bracings are divided into two parts: the ‘concentrically braced’ frames and ‘eccentrically braced’ frames. Furthers the concentric bracings are classified as X-bracings, V-bracings, inverted V-bracings, multi X bracings, and the diagonal bracings are used in the structures. there are also some advanced forms of bracings such as buckling restrained brace (BRBs), light weight BRBs, post tensioning bracings, etc. are used in buildings to improve the seismic performance of the structures. The many experimental and numerical studies suggested that the use of different types of steel bracings in RC buildings increases the seismic performance such as reduction of displacements and increases the stiffness and strength of the structures (Maheri & Sahebi, 1995; Ghaffarzadeh & Maheri, 2006). The experimental results show the substantially increases the stiffness and shear strength of structure while the bracing was used. In one of the experimental studies, the researchers observed that to get the suitable performance of the braced RC frames, the columns are designed such that, it resist at least 50% base shear (Bush et al., 1991). To reduce the buckling effect in the steel braced frames, the low slenderness ratio of the bracings (Badoux & Jirsa, 1990). It was observed that in the existing RC structures when the steel bracing is used in the buildings, its strength and stiffness increase and it decreases the drift of the structures. To understand the behaviors of the braced and unbraced frames, researchers used the pushover analysis and nonlinear time history analysis in the low rise to high rise buildings (Maheri et al., 2003). The effect of bracings in the 2D RC frames was observed and noticed that, after applying the bracings, the structures show a reduction of drift, displacements and observed other seismic parameters by using the time history analysis in the 4-16 story frame (Rahimi & Maheri, 2018, 2020). To get the suitable failure mechanisms such as stronger columns, weak beam and weaker bracings in the concentrically braced frame in moment resisting frames, columns are designed such that at least they resist the 50% base shear (Godínez-Domínguez & Tena-Colunga, 2010, 2019). Researchers observed capacity curves, failure mechanisms and over strength factors by using the pushover analysis in the low to mid-rise buildings (Eskandari et al., 2017).

In this research, the study is focused on the seismic analysis of the 4 story buildings with and without steel bracing by using the response spectrum method (RSM) and pushover analysis. Many studies only focused on the study of X, inverted V and diagonal bracings in the RC buildings. This paper focused on V shape concentrically braced frame with different thicknesses of the bracings. The effect of bracing in the RC buildings when the steel bracings choose such that, the bracings have different thickness and observed the behaviors of structures. The seismic parameter such as capacity curves, displacements, drift, base shear, fundamental time periods are observed and the effect of thickness of bracing in the base shear capacity of the moment-resisting frame is also noticed.

Objectives

The main objectives of this study are presented below.

- To understand the effect of thickness of steel bracings in RC buildings.
- To know the seismic performance of the buildings, when the column contributes the different design base shear in steel braced RC structure.
- To understand the failure mechanism and capacity of the steel braced RC buildings.

Methodology and modeling

The capacity design method is used for the design of RC with V shape steel braced frames. A similar methodology is also used by Godínez-Domínguez and Tena-Colunga (2010, 2019) in the design of low to high-rise buildings with 25%, 50% and 75% shear strength capacity in the columns. The unbraced fixed columns size four-story buildings are assumed. The steel braced with different thicknesses is applied in the assumed existing RC frames and designed. To design the RC with a steel braced frame, the response spectrum method (RSM) is applied. The Indian standard IS 1893: 2016 part 1 for seismic design and IS 456:2000 for RC design are used. The pushover analysis method is used to study the seismic behavior and strength of the structures (Abou-Elfath & Ghobarah, 2000). The capacity curves and failure patterns are observed to understand the ductility behaviors of the RC braced frame. The comparative study is made to observe the behaviors of the structures. Response spectrum analysis and pushover analysis are performed in the ETABs v18 finite element software.

Modeling of 4 story building is done in the ETABs v18 software. The materials property used in 4 story buildings is given in Table 1. The compressive strength of the concrete used in columns, beam and slab are assumed as 25 MPa and the grade of rebar is assumed as Fe 415. Other properties of the materials are used as shown in Table 1. Fig1 shows the plan and 3D view of the 4 story buildings. In four-story buildings, the 7m spans in each direction are considered. The story height of the structures is assumed as 3.2m which is generally used in Nepal. The X in Figure 1 represents that where V bracings are used as lateral load resisting systems. For seismic analysis, the zone factors is considered as 0.36 (zone factor V). The importance factors are 1 (other buildings category) and 5% damping factors is used. The response reduction for RC buildings is 4.5 (Buildings with a special braced frame having concentric braces). The live load on the floor is assumed as 5KN/m^2 and on the top floor, it is considered as 2KN/m^2. The superimposed dead load is also assumed as 2.5KN/m^2 (IS 875(part2): 1987).

The cross-sectional of the beam and columns are as shown in Table 2. The cross-sectional area of columns changes in the fourth story as shown in Table 2. The thickness of the slab is 120mm is used and the slab is considered a rigid diaphragms (Sukrawa, 2017). Hollow square cross-section steel bracings are used in this study. In all 7 models, cross-sections of the steel bracing members are changed, keeping the size of the bracing (60 mm X 60 mm) same while, the thickness of bracings changed as shown in Table 3. In the frame, the bracings are connected as a pin joint.

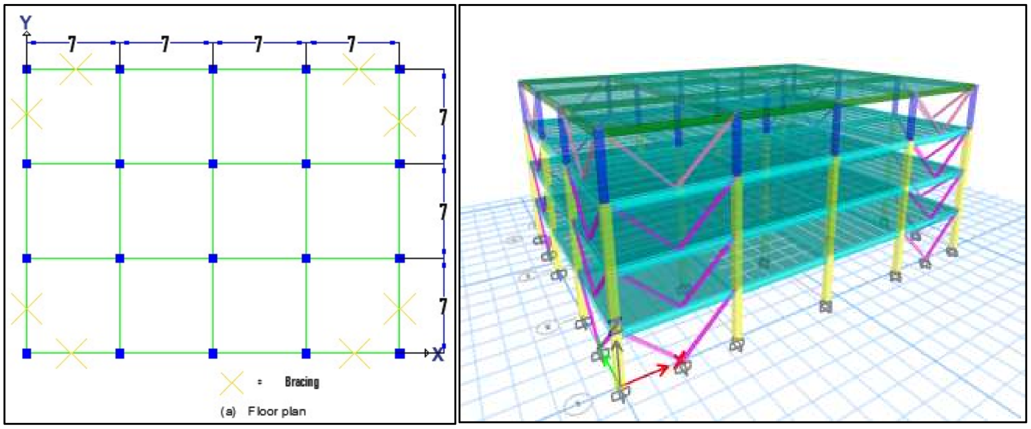
To observe the 8 models, the cryptogram is introduced: RCnVtD, where RC means reinforced concrete, n represents the models' numbers (n=1, 2, 3…), V represents the V-shape steel bracings, t represented the thickness of bracings in mm (t= 2.5,4,8,10...) and D represents the directions of models such as X directions and Y directions of the models. In each model, the RC1 is the unbraced RC frame structure and the other remaining have steel bracings with different thicknesses as shown in Table 3. Table 3 also shows the different bracings used in the models.

Table 1: Properties of the steel and concrete materials

Material properties	Concrete	Grade = M25
		Modulus of elasticity= 25000 MPa
		Density = 7850 Kg/m^3
	Steel bracing	Grade = FE250
		Minimum yield stress= 250 MPa
		Minimum tensile stress= 410MPa
		Modulus of elasticity= 21000 MPa

Table 2: Specifications of beams and columns used in the 4-story regular study buildings

	RC section	
Structures	Columns(mm)	Beam (mm)
4-storey	450X450 (1-3 story)	350X450
	350X350 (4 story)	300X350



(a) *(b)*

Figure 1: 4-story structures a) plan of the buildings (X represents the place where used V shape steel bracing (units are in m), (b) 3-D view of steel braced structures.

Results and discussion

Eight, 4 story buildings were analyzed first by using the RSA and then the further study is carried by using the nonlinear static analysis to observe the capacity of the structures. The models are having the 100% to 30% base shear contributed by the columns as shown in Table 3. The RC1 has the 100% base shear contributed by the columns, where the RC1 represents the without bracings model. When the thickness of the bracings is increased and the RC beam and columns are constants for all models. As the braced thickness increases, the base shear contribution of the columns decreases. When the 2.5mm thickness bracing is used in the RC1 models the base shear contribution in the columns decreases by 30% base shear.

Base shear and fundamental time periods (FTP)

Adding the bracing in the existing buildings, increased the lateral shear resisting capacity of the structure effectively. Applying the bracing in the RC frames also increases the demand for base shear in the overall structures. However, adding the steel bracings improve the stiffness of the structures. It is observed that without steel bracings the base shear of the RC frame is 1536 KN along with the x directions. When the steel bracing having 2.5mm thickness bracings, the base shear increases and reached 1938 KN. When the thickness of the steel bracing increases, the base shear of the structures also increases as shown in Table 3. It is observed that the base shear of the structures increases 26% when 2.5mm steel bracings are used and 42% base shear increases when 20mm base shear is used in RC frames.

The FTP of the structures is the one of important parameters to understand the seismic demands of the structures. The lateral base shear coefficient of the structures depends upon the FTP. Table 3 shows the FTP of the buildings. Without steel bracings, the RC buildings have 0.968 seconds. However, adding the steel bracing in RC frames, the FTP decreases and is recorded as 0.762 sec, when the 2.5mm thickness bracing is used. When the thickness of bracing increases, the FTP is decreased and when 20mm thick steel bracing is used, the FTP reached 0.497sec. All the given FTP represents the first mode of vibrations. In table 3, FTP along the x-axis represents the second mode of vibrations and along the y-axis represents the first mode of vibrations. A sufficient number of modes are considered in order to achieve the sum of the model mass of all modes equals to 90% of the total seismic mass as code suggested (IS 1893:2016). And also the FTP of the structures are based on the program calculated natural time period of the buildings. Study shows that time period computed from the empirical expression (code-based) are relatively shorter than those computed from the structural models

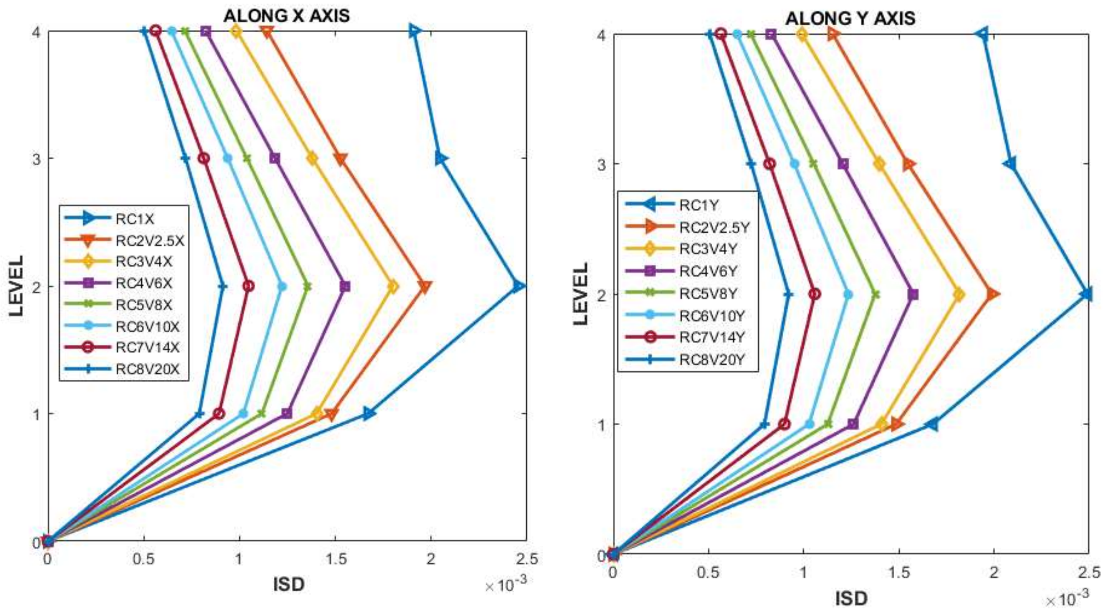
(Hoseinzadeh et al., 2011; Ehsan et al., 2013). When the base shear capacity resisted by the bracing increases, then the FTP of the structures decreases as shown in Table 3.

Maximum story displacements and inter-story drifts (ISD)

The maximum displacements and ISD are one of the important parameters to observe the seismic behaviors of the structures. The structural damage during the ground motions, it is directly related to the displacements and drifts. Hence to control the adequate damage in structures, it is necessary to provide the lateral deformations controlling devices by improving the lateral strength and stiffness of the buildings.

The ISD of the 4 story buildings is shown in Figure 2. The RC1 buildings show the maximum ISD of the structures. It is noted down the applying the steel bracing in the RC buildings, reduced the ISD. In the RC1 it is calculated as 0.002453 which is less than 0.004 as IS 1893: 2016 suggested. When the 2.5mm thick bracing is used, almost 20% reduction in ISD from RC1is observed. With increasing the thickness of the bracings, the ISD of the RC frames decreases. This shows that the thickness of the bracings is important in the reduction of ISD of the structures. The maximum ISD are: 0.001967, 0.0018, 0.001552, 0.001357 and 0.000913 for models RC2V2.5X, RC3V4X, RC4V6X, RC5V8X and RC8V20X respectively. All the drift values are less than 0.004 as the code provided. In the models RC4V6 in which columns resist the 50% base shear and observed ISD is 36% reductions that of RC1 models. When the bracing thickness is considered as 20mm which shows the ISD about 62% reduction from RC1. Similar observations are made along with the y directions. This proves that the applying the bracing in the RC frame as a retrofitting, a sufficient amount of reductions of ISD are obtained by varying the thickness of bracing without changing the size of bracing.

The story displacements of the 4 story buildings are shown in Figure 3 along with the x-directions. As same as drift, the maximum top story displacements are observed in RC1 models which is 25.4mm. When the steel bracings are used, the top story displacements of the RC1 are reduced. The maximum top story displacements are 19.34mm, 17.6mm, 15.24mm, 13.4mm and 9.278mm for models RC2V2.5X, RC3V4X, RC4V6X, RC5V8X and RC8V20X respectively along with the x directions. When the thickness of the steel bracing increases, the maximum story displacements are decreased as shown in Figure 3. For the models, RC2V2.5X which represents the model columns resist the 70% lateral base shear shows the 23% of reduction of maximum displacements is observed. Nearly 40% reduction of maximum displacements observed when the thickness of bracings are taken 6mm (RC4V6). The models having 6mm thick bracing also represent the 50% base shear contributed by the columns. The models have a 20mm thick braced model that is models represent the 30% base shear represents by the columns shows the nearly 63% reduction of maximum displacements with respect to the RC1 models along the X directions shown in Figure 3. Similar results are obtained along the y-axis. When the thickness of the bracings increasing, it reduces the maximum top story displacements effectively. Comparing the maximum displacements and drift of the RC with and without bracings as shown in Figure 2 and 3 shows that steel bracing plays a great role to reduce to maximum displacements and drift effectively (Higashi et al., 1984; Massumi, 1997).



(a) *(b)*

Figure 2: Inter story drift of the eight models (a) along the X directions, (b) along the Y directions.

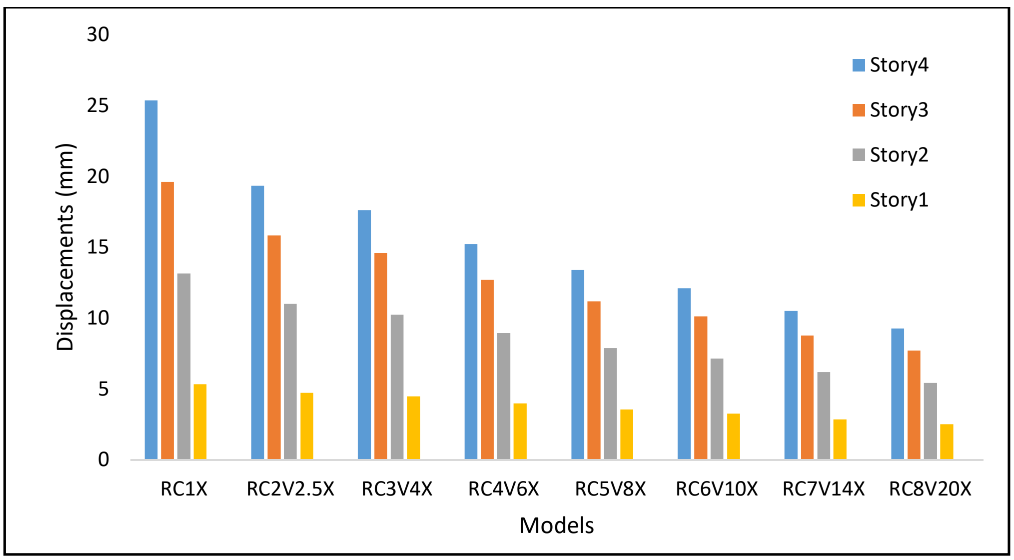


Figure 3: Maximum story displacements of the eight models along with the X directions.

Table 3: Base shear contributions in different bracings with base shear and FTP

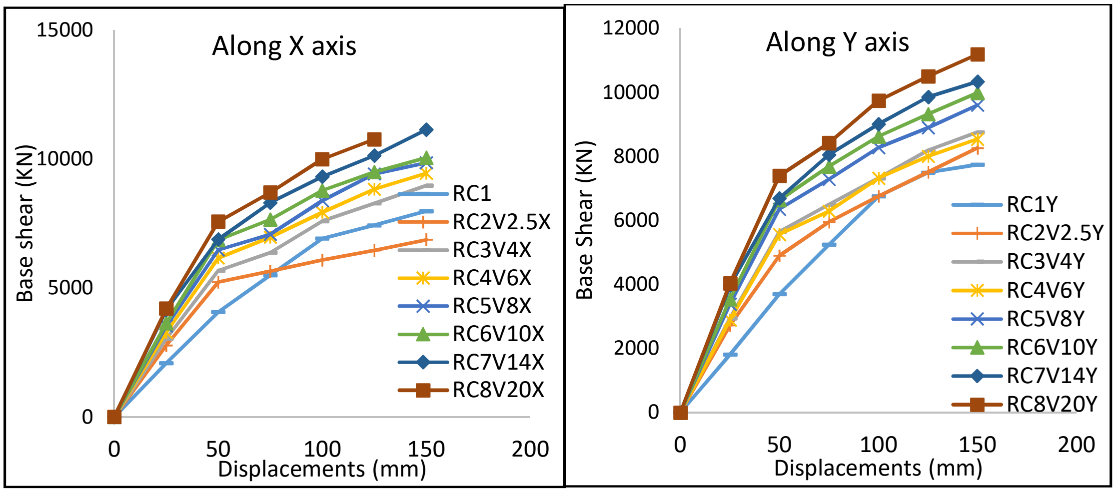
		Base shear contribution (approximately)				
models	Bracings (mm)	Columns (%)	Bracings (%)	Base shear	Fundamental time periods	Model mass (%)
RC1X	-	100	0	1536	0.951	81.6
RC1Y	-	100	0	1510	0.968	81.5
RC2V2.5X	60X60X2.5	70	30	1938	0.754	83.9
RC2V2.5Y	60X60X2.5	70	30	1918	0.762	83.8
RC3V4X	60X60X4	60	40	2113	0.692	84.5
RC3V4Y	60X60X4	60	40	2095	0.698	84.4
RC4V6X	60X60X6	50	50	2190	0.635	84.9

RC4V6Y	60X60X6	50	50	2190	0.64	84.8
RC5V8X	60X60X8	45	55	2191	0.596	85.2
RC5V8Y	60X60X8	45	55	2191	0.6	85.1
RC6V10X	60X60X10	40	60	2191	0.56	85.3
RC6V10Y	60X60X10	40	60	2191	0.57	85.2
RC7V14X	60X60X14	35	65	2192	0.528	85.4
RC7V14Y	60X60X14	35	65	2192	0.53	85.3
RC8V20X	60X60X20	30	70	2194	0.495	85.3
RC8V20Y	60X60X20	30	70	2194	0.497	85.3

Static pushover analysis

The static nonlinear analysis is performed in all models and observed the capacity curves and failure behaviors of the 4 story structures. The pushover analysis is performed in the finite element software ETABs. The displacements controlled method is used and the lateral load pattern is based on the fundamental mode shapes at each story level with corresponding story weights. The performance point or target points is obtained by using the displacements coefficients methods by using the ASCE (ASCE, 2016) codal provisions. The plastic hinges are defined in the beam and columns and bracings. The axial hinges are provided in the bracings and in the columns and beams, the flexural and shear hinges are defined. The lateral load is increased and the lateral shear force and corresponding displacements are noted and prepared the curve known as pushover curve or capacity curves. The pushover analysis help to understand the capacity of the structures, failure predictions, it predicts weak areas. The method is used mostly in retrofitting process.

Figure 4 represents the capacity curves of eight models. The four-story structure without steel bracings have the lower capacity than that of the braced frame Structures. The capacity curves show that adding the bracings improves the strength of the structures. Steel bracings significantly increase the base shear, making the building stiffer. After using the V bracings decreases the serious hinges formations in the columns. As increasing the base shear contributions in the bracings, it also increases the capacity of the structures (see figure 4). As per IS 1893:2016 code clause 7.2.7 (b), for dual systems, columns are designed for resisting at least 25% base shear of the structures. As provided in the codal provisions, it is very difficult to get the expected failure mechanism when the columns designed to resist 25% base shear in dual system. The results show that 20mm thick bracing model does not get the expected failure pattern (strong columns, weak beam and weaker bracings system). It is because of increase in the bracing thickness, the bracings become main line of defense. Hence to get uniform distributions of the energy dissipations, RC columns should be the main line of defenses. Similar observations also observed in the previous study for inverted V bracings (Godínez-Domínguez & Tena-Colunga, 2010) and X bracings (Godínez-Domínguez & Tena-Colunga, 2019). Thus, in steel bracings the thickness of the bracing is considered such that the RC frame should be the main line of defense to get better structures which shows the expected failure behaviors.



(a) *(b)*

Figure 4: Capacity curves of the 4 story buildings, (a) along the x-axis, (b) along the y-axis

Conclusion

Four-story regular RC buildings with and without V shape steel braced frames are analyzed by using the RSM and pushover analysis to understand the seismic behaviors of the buildings. The results of the analysis show that the thickness of steel bracings significantly affect the RC frames.

- This study shows that the bracings improve the seismic behaviors of the structures effectively, which implies that adding the steel bracings in the RC frame improves the strength and stiffness of the structures.
- Base shear contribution in different building with base shear and FTP indicates that increasing the thickness of the steel bracing in low-rise buildings increases the base shear, shear resisting strength and stiffness of the buildings.
- Among all the building stories considered, retrofitting of the 4-storey RC building by using the V shape steel bracings, is found to be most effective in reducing the maximum story displacement, FTP, and drift.
- For the thickness of bracings ranging from 2.5 to 6mm, columns show the main line of defense while for the thickness of bracings more than 6mm, the steel bracing becomes the main line of defense. Provided that the size of bracings is kept constant.
- From pushover analysis it can be concluded that for expected failure mechanism (strong columns, weak beams and weaker bracings), the columns should resist at least 50% lateral base shear capacity.

Further study is needed in the field of steel bracing in RC for regular and irregular buildings for higher stories. The nonlinear time history analysis is also needed for the better understanding the actual behaviors of the RC braced frame structures.

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