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Seismic Retrofit of Reinforced Concrete Frame Structures

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Abstract— One of the most effective systems in resisting the seismic force is the Moment Resisting Frame (MRF) that is used for reinforced concrete structures. Many of these structures are located in high seismic zones and have been designed based on out-dated design codes where is seismic forces are not considered or underestimated. Applying the updated seismic forces and parameters on such structures will not meet the safety requirements. Accordingly, the seismic retrofit for these structures is mandatory and cannot be avoided. Steel braces and concrete-steel composite elements are common solutions for enhancing the seismic behaviour of existing steel frame structures. In this paper, a numerical study for the seismic retrofit of RC structures that evaluates different possible techniques of existing reinforced concrete MRF structures are presented. Three multi-story buildings with different heights and located in a high seismic hazard zone have been investigated. Three retrofit techniques were introduced: (1) X-Steel braces, (2) buckling restrained composite braces, and (3) RC shear walls. The seismic performance enhancement of the studied structures was evaluated in terms of the structure's fundamental period, maximum inter-story drift and maximum base shear-to-weight ratios. Compared to the model without retrofitting, the retrofitted models showed increased stiffness, base shear and overturning moment capacities which accordingly decreased the story drift and roof displacement to the safe area. Additionally, retrofitting with buckling restrained braces resulted in the least lateral deformations and seismic forces.

Index Terms— Reinforced concrete structures, Moment resisting frames, Seismic retrofit, Seismic performance, Dynamic analysis. Base shear, RC shear walls.

1 Introduction

Earthquake is a natural hazard that may cause extensive damages especially to the built environment [1-5]. Earthquakes are random in nature and unpredictable, therefore, analysis of the structure under the action of earthquakes requires better engineering approaches and tools. Hence, several improvements are continuously takes place in the earthquake engineering methodologies during the past few decades [6-11]. Seismic risks affect a lot of important structures, such as utility systems (gas systems, telecommunication, and electric power) and transportation infrastructures (airports, ports, roads and railway systems). Although USA is considered as one of the strongest countries in terms of economic capacity, some cities were struck by severe earthquakes that left a lot of causalities and damaged structures and that resulted in a complete paralysis of these cities. Examples of these disastrous earthquakes are San Fernando (1971) and Northridge (1994) earthquakes.

In order to reduce the number of human casualties, the safety of buildings has to be ensured. A complete damage of a building is allowed after a severe ground motion as long as no collapse would occur (life safety performance level). Many of existing buildings do not meet such requirements of the current seismic codes due to several reasons, such as; (a) Design of structure according to gravity loads only (b) the updates of seismic codes and the intensity of seismic hazard, (c) any change in the occupancy of existing structures, and (d) the structure deterioration due to environmental effects. Accordingly, the seismic retrofit of these structures is an urgent need. The main objective of this study is to evaluate the seismic performance of existing nominally ductile RC frame structures with different heights when strengthened using different strengthening techniques. The structures which will be considered represents buildings that have been designed according to pre-1970 strength based code (ACI -1968) [12]. Strengthening will be conducted according to the current seismic maps and code recommendations. The existing RC frame structures represent low and medium rise buildings that are located in the city of Los Angeles, California, USA.

The considered strengthening techniques include (1) introducing RC shear walls, (3) installing steel braces, (3) installing buckling restrained braces. To evaluate the seismic performance enhancement of the studied buildings, the maximum inter-story drift, the maximum roof displacement, and the maximum story shear-to-weight ratio were obtained.

2 Numerical Modelling

A seismic force resisting system (SFRS) must be able to provide the sufficient strength, stiffness, ductility, and energy dissipation capacity to withstand the design ground motion within the code limits. The seismic analysis of a structure shall be performed according to one of the following methods; Equivalent Static Analysis, Response Spectrum Analysis (RSA), or Time History Analysis. Equivalent Static Method in all design codes has some restrictions and limitations of application, while the RSA could be conducted for any structure with an acceptable level of accuracy. Time History Analysis is more sophisticated and can be used for high importance structures or for research applications. Description for the studied buildings and the strengthening techniques suggested to upgrade their seismic performance is illustrated here. Three systems were used to strength the selected existing buildings; (a) adding a RC shear walls, (b) adding steel braces, (c) adding buckling restrained braces. Lateral forces are resisted mainly by the new strengthening system along with the existing moment resisting frames. Linear dynamic analyses were conducted for the existing and retrofitted buildings using ETABS software (Computers and Structures, 2016).

2.1 Description of the buildings under study

Three existing RC multi-story buildings with different heights were considered in this study. The buildings were designed according to a pre-1970 design code (ACI -1968) [12]. The buildings are five-story, ten-story and fifteen-story high, and that represent low, medium, and high rise buildings, respectively. The same floor plan was used for all buildings that consist of three equal bays in both directions, where the bay width equals to 6.0 m. The story height is 3.0 m and the total height of the three buildings is 15, 30 and 45 m, respectively. The columns' reinforcement and concrete dimensions varied along the height of the building according to the change of axial load acting on each group of columns. The beam concrete dimensions and steel reinforcement were assumed to be the same for the entire building. The beam dimensions were set as 350*600mm. The slab thickness in all models is set to 140 mm.

2.2 Design Parameters

2.2.1 Material Properties

The compressive strength of concrete has been assumed to be of value fc'= 25.0 MPa for existing buildings and 40.0 MPa for the new concrete used for retrofitting. The yield strength of steel reinforcement is set as fy = 400 MPa, and for steel members = 340 MPa. The value of concrete density was considered as 25 kN/m^3 and the concrete Poisson's ratio as 0.2. The modulus of elasticity for retrofit concrete was considered as 29.7 GPa, 23.5 GPa for existing concrete and 200 GPa for steel.

2.2.2 Design Loads

The structural elements of the existing buildings have been designed according to the American Concrete Institute manual (ACI 1968) [12]. The columns and beams were designed to carry a slab thickness of 140 mm, a floor cover of 1.5 kPa, an equivalent uniform load from interior partition of 1.5 kPa, a live load of 2.0 kPa, and an exterior line load due to external walls and cladding of 10 kN/m [13].

2.3 Properties of the selected site

The three existing buildings were assumed to be in the city of Los Angeles, California, USA. Los Angeles is considered to be in a high seismic hazard zone as shown in Fig. 1 (Zone 4).

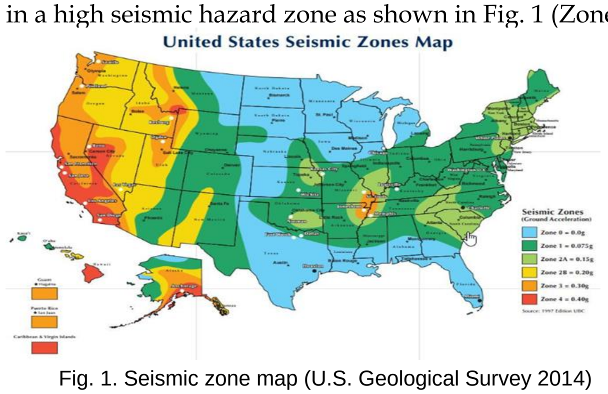

Fig. 1. Seismic zone map (U.S. Geological Survey 2014)

1.4 Properties of Response Spectrum

The response spectrum curve for Los Angeles city is shown in Fig. 2 and the properties of this spectrum are given below:
ASCE -10 Retrofit Standards, San Francisco (34.05224°N, 118.24368°W)
Site Class B – "Rock"
Section 2.4.1 – General Procedure for Hazard Due to Ground Shaking
5%/50-year maximum direction spectral response acceleration for 0.2 sec and 1.0 sec periods, respectively: Where:
S1= 0.853 g
The authority having jurisdiction (not the USGS), site-specific geotechnical data, and/or the default has classified the site as Site Class B, based on the site soil properties in according to ASEC 7-10.
The Values of Fa as a function of site classes and mapped short periods spectral response acceleration Ss =2.433g, for site Class = B and Fa=1.
The Values of Fv as a Function of Site Classes and Mapped Spectral Response Acceleration at Period S1=0.853g and Fv=1.

For Site Class = B and S1 = 0.853g, Fv = 1.
S_{MS}= Fa*Ss =1.000 x 2.433 g = 2.433 g
S_{M1}= Fv*S1=1.000 x 0.853 g = 0.853 g
S_{DS}= 2/3*SMs =2/3 x 2.433 g = 1.622 g
S_{D1}= 2/3*SM1=2/3x 0.853 g = 0.569 g

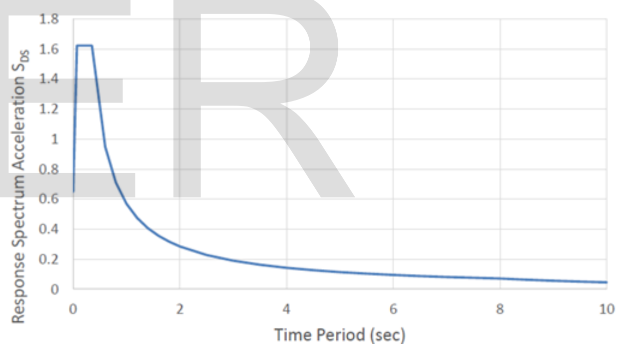

Fig. 2. The Response Spectrum Curve for Los Angeles city

1.5 Different Retrofit Techniques

In the current research, the three existing RC buildings with different heights located in Los Angeles area were strengthened using three seismic retrofit techniques: Strengthening using RC shear walls, strengthening using steel X-bracing and Strengthening using buckling restrained braces (BRB).

2.5.1 Strengthening using RC shear walls

The existing building will be strengthened by adding RC shear wall in the middle bay of the external frames on the building's four sides. The thickness of the shear walls will be considered as 300 mm. The length of the walls is considered as 3.0, 6.0 and 7.0 m long for the 5-, 10- and 15-story buildings, respectively. The wall dimensions were assumed to remain constant along the building height. The Wall dimensions and reinforcement for each building are shown in Fig. 3. These values were derived from the seismic analysis and design to satisfy the code requirements for deformations and strength,

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and to maintain the existing frame elements safe under the design ground motion. The walls were designed as ductile walls using R (Response modification factor) = 6.0 as for special reinforced concrete shear wall, Cd (Deflection Amplification Factor) = 5.0 due to the high seismicity of the building location [14-16].

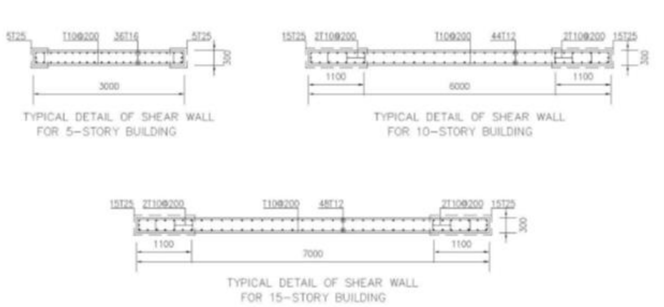

Fig. 3. Details of the shear walls for the studied buildings

2.5.2 Strengthening using steel X-bracings

Steel X-braces were installed in the external frames of the building's four sides for strengthening of existing buildings along the full height. The steel X-braces were installed in middle bay only for the 5-story building. While the braces were installed in two bays for the 10- and 15-story buildings as shown in Fig. 4. The steel braces were connected with the existing RC frame as shown in Fig. 4. Used R (Response modification factor) = 6.0 as for special steel concentrically braced Frames, Cd (Deflection Amplification Factor) = 5.0 [17].

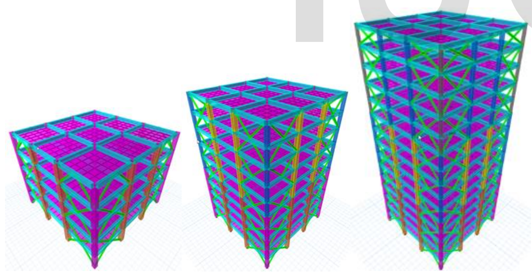

Fig. 4. Retrofitting using X-Steel braces for the studied buildings

2.5.3 Strengthening using buckling restrained braces (BRB)

Diagonal bucking restrained braces (BRBs) were installed to the existing buildings to enhance their seismic performance and reduce the buildings' deformations. The BRB is connected with the existing RC frame as shown in Fig. 5. For all retrofitted buildings, the installed BRB consists of a steel I-beam of dimensions 150 x 150 x10 mm imbedded in a square reinforced concrete section of dimensions 350 x 350 mm with steel reinforcement of 8T16. Used R (Response modification factor) = 8.0 as for steel buckling restrained braced frames (BRB), Cd (Deflection Amplification Factor) = 5.0 [18].

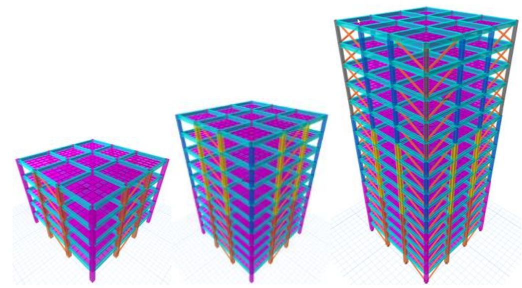

Fig. 5. The retrofit schemes by BRB braces for the studied buildings

2. Analysis Results

The dynamic analysis of existing buildings showed that the buildings collapsed at intensity levels of 44, 39, and 25% of the design response spectrum of Los Angeles city for the 5-, 10- and 15-story buildings, respectively. Table 1 shows the results for modal and dynamic analyses of the 5-, 10- and 15-story buildings for existing and retrofitted buildings.

TABLE 1

RESULTS OF EXISTING AND STRENGTHENED MODELS

	5-Stories				10- Stories				15- Stories			
	Existing	Shear Wall	Steel Bracing	Buckling Restrained braced	Existing	Shear Wall	Steel Bracing	Buckling Restrained braced	Existing	Shear Wall	Steel Bracing	Buckling Restrained braced
Time Period	1.122	0.544	0.65	0.572	2.218	1.114	1.11	1.243	3.405	1.786	1.732	1.587
Max. ID%	1.07%	0.85%	1.14%	0.64%	1.10%	1.04%	0.995	0.84%	1.13%	1.08%	1.21%	0.94%
Roof Drift %	0.70%	0.66%	0.83%	0.50%	0.71%	0.74%	0.72%	0.64%	0.72%	0.74%	0.84%	0.70%
Base Shear	1787	2979	2947	2062	1839	3562	3582	2399	1812	4029	4021	3737
$M_{overturning}$ (KN.m)	18273	32322	31245	22182	35841	58554	63896	41453	53857	78570	98197	86814

3.1 Fundamental Period

Fig. 6 shows the fundamental period for the existing structures and the retrofitted ones for the 5-, 10- and 15-story buildings. It can be noticed from the figure that the proposed retrofit techniques reduced the fundamental period of existing structures by almost 50%. This is due to the additional stiffness provided by introducing the shear walls or the braces to the existing buildings. Hence, smaller story deformations and higher seismic forces will be expected due to the seismic retrofit. The figure also shows a minor difference in the fundamental period of the retrofitted buildings, which indicates that the selected retrofit techniques provided similar additional stiffness to the existing buildings.

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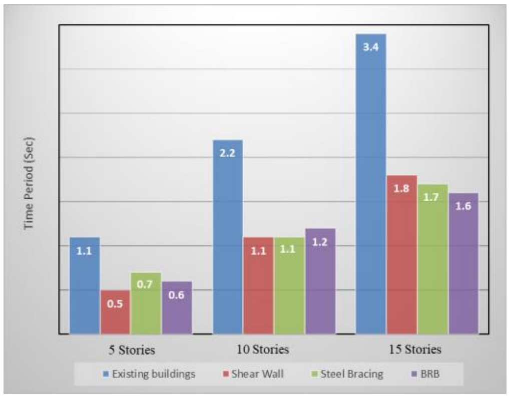

Fig. 6. Fundamental period for existing and retrofitted buildings

3.2 Inter-story drift ratio

Fig.s 7 (a), (b) and (c) presents the inter-story drift (I.D.) ratio for the 5-, 10- and 15-story existing buildings and the strengthened ones. For existing buildings, the shown I.D. values were obtained at the maximum earthquake intensity that could be resisted that was 44, 39, and 25% of the design response spectrum of Los Angeles for the 5-, 10-, and 15-story buildings, respectively. For the retrofitted buildings, the buildings were able to withstand 100% of the design intensity of Los Angeles. As shown in the figure, it is noticed that the three retrofit techniques were able to reduce the maximum I.D. ratio for the three building heights even at a 100% of the design response spectrum. Fig. 8 shows the maximum I.D. ratio for the existing buildings and the retrofitted ones. The figure shows that the buckling restrained braced buildings had the least maximum I.D. ratio compared to other retrofit systems (shear walls and steel braces) for all building heights. The figure also shows that the maximum I.D. ratio for the retrofitted structures did not exceed 1.20 percent. This value should not affect the safety of the gravity load resisting system or the non-structural elements (Adebar et. al. 2010).

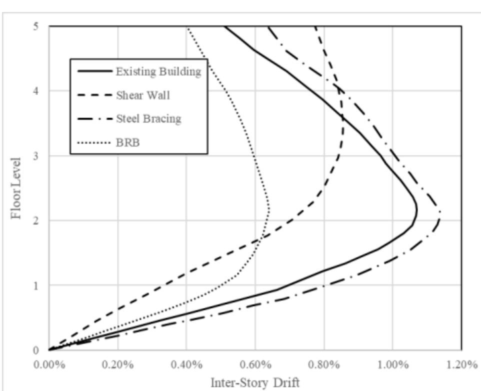

Fig. 7(a). Inter-story drift ratio for the 5-story building

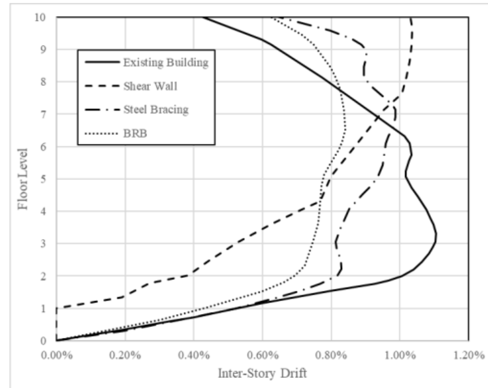

Fig. 7(b). Inter-story drift ratio for the 10-story building

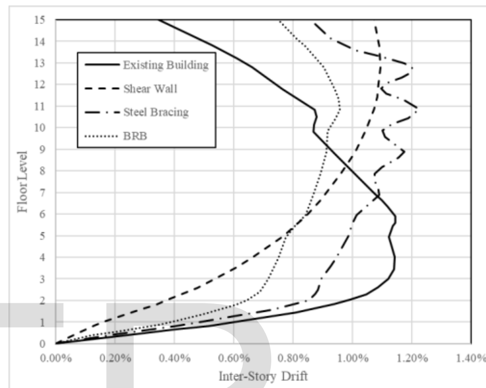

Fig. 7(c). Inter-story drift ratio for the 15-story building

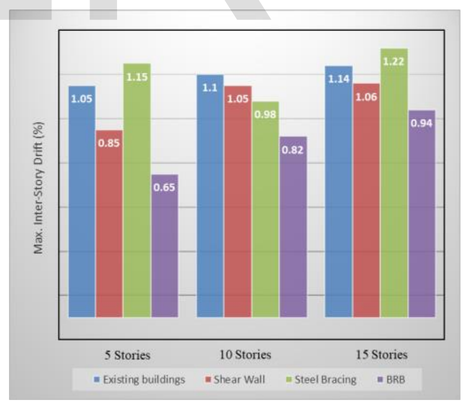

Fig. 8. Maximum I.D. ratio for the studied buildings

3.3 Story Displacement

Fig.s 9 (a), (b), and (c) show the story displacement for the 5-, 10- and 15-story buildings, respectively. The figures show the values for buildings with different retrofit schemes at the design earthquake intensity of Los Angeles (LA), and for existing buildings at the maximum earthquake intensity resisted before a collapse mechanism occurs. Similar to the I.D. ratio curves, the buckling restrained braces resulted in the least deformations compared to the other retrofit techniques. Fig. 10

shows the maximum roof drift for the existing buildings and the retrofitted ones, defined as the roof displacement divided by the building total height. It can be noted from the figure that the maximum roof drift for the retrofitted building with different heights did not exceed the value of 0.84 percent.

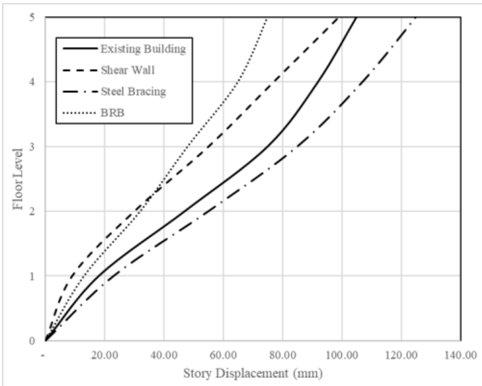

Fig. 9(a). The story displacement of the 5-story building

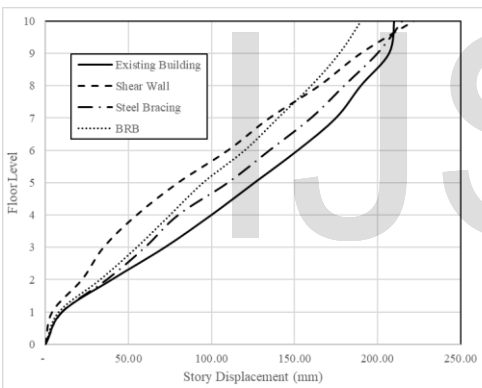

Fig. 9(b). The story displacement of the 10-story building

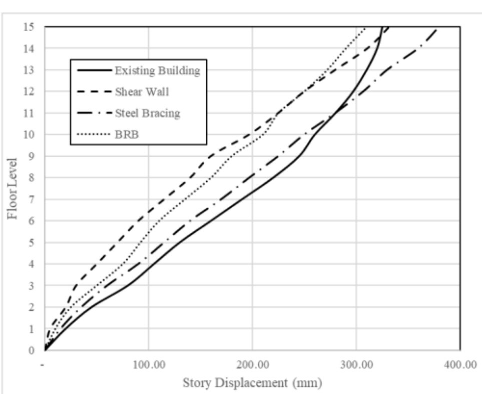

Fig. 9(c). The story displacement of the 15-story building

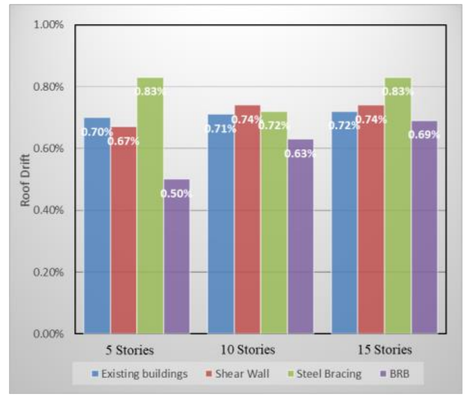

Fig.10. Maximum roof drift for the studied buildings

3.4 Base Shear

Fig. 11 shows the base shear to weight ratio for the 5-, 10- and 15-story existing buildings and the retrofitted ones with different retrofit schemes. It can be concluded that the retrofit techniques resulted in a higher base shear compared to existing structures due to the additional stiffness provided by the retrofit techniques. The figure shows that using BRB resulted in a smaller base shear compared to the use of shear walls or steel bracings for all building heights. However, similar results were obtained for the cases of shear walls and steel braces for all building heights.

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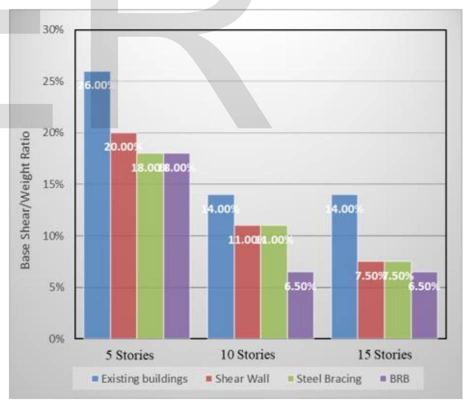

Fig.11. Base shear to weight ratio for the existing and retrofitted buildings

3.5 Overturning Moments

Fig.s 12 (a), (b) and (c) shows the story overturning moments for the 5-, 10- and 15-story buildings for different retrofit schemes at the design earthquake intensity of LA, and for existing buildings at the maximum earthquake intensity resisted before a collapse mechanism occurs. From the figures, it can be seen that the BRB resulted in the least building's base overturning moment for the 5- and 10-story buildings compared to the other techniques. On the contrary, for the 15-story building, introducing shear walls has resulted in the least base overturning moment. Fig. 13 presents the base overturning moment for existing buildings and the retrofitted ones. It can be concluded that adding shear walls or braces to existing buildings resulted in a higher seismic forces due to the additional stiffness provided by the retrofitting systems, which led to a higher base overturning moments.

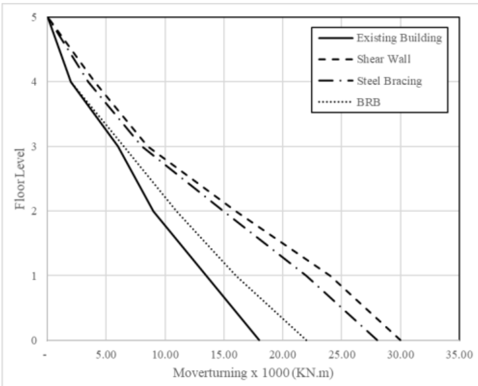

Fig.12(a). Story overturning moments of the 5-story building

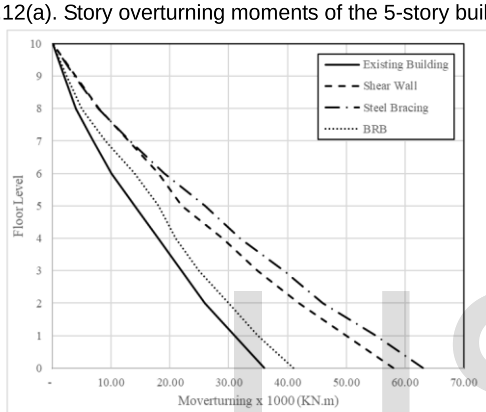

Fig.12(b). Story overturning moments of the 10-story building

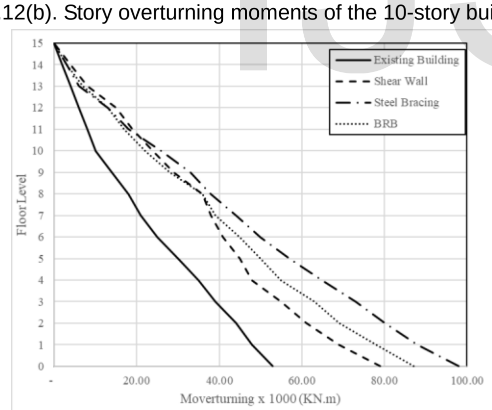

Fig.12(c). Story overturning moments of the 15-story building

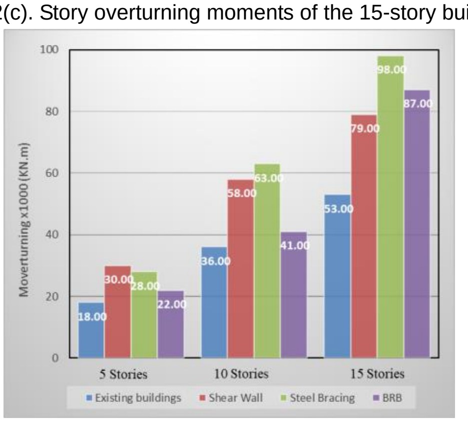

Fig.13. The base overturning moments of the studied buildings

4 CONCLUSION

In this paper, there different strengthening techniques were selected: (1) using X-steel bracing, (2) BRB and (3) RC shear wall to evaluate the effectiveness of these techniques on upgrading the seismic performance of RC frame structures. Three RC buildings with different heights were selected representing low and medium rise frames. Linear dynamic analysis has been conducted using the design response spectrum of Los Angeles city represent earthquakes with high frequency contents. The seismic performance enhancement of the analysed frames was evaluated based on the maximum inter-story drift ratio, maximum roof displacement, maximum story shear to total weight ratio. Based on this analysis, the following concluded points can be drawn:

1. Compared to the model without retrofitting, the retrofitted models showed reduced fundamental time period due to the additional stiffness provided by the retrofit schemes. Additionally, the base shear and overturning moment capacities have been increased by applying the different retrofitting techniques.
2. Due to the increased stiffness resulted from applying the retrofitting techniques, the story drift and roof displacement have been reduced to the safe margin.
3. Compared to other retrofitting techniques, the BRB technique showed the least deformations and seismic forces.
4. For all models, using RC shear wall as retrofitting technique reduced the straining actions on the columns while using X-steel bracing or BRB techniques increased the straining actions on columns.

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