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RESEARCH ARTICLE Open Access

OPTIMUM LOCATION AND BRACING SYSTEM AS ALTERNATIVE TO SHEAR WALLS FOR RETROFITTING OF RC BUILDINGS AGAINST SEISMIC LOADING

Hogr Z. Hassan [1], Najmadeen M. Saeed [1,2*], and Barham A. Haydar [2]

[1] Civil Engineering Department, Faculty of Engineering, University of Raparin, Rania- Iraq
[2] Civil Engineering Department, Faculty of Engineering, Tishk International University, Erbil- Iraq

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**Email address:*
Najmadeen_qasre@uor.edu.krd
**Corresponding Author*

Abstract:
The defective structures must be retrofitted to resist the effects of earthquakes due to the potential risks connected with reinforced concrete structures designed in many parts of the world in accordance with codes that are now proven to guarantee insufficient safety against seismic loads. Typically, shear walls or steel bracing are utilized to boost the seismic strength of framed structures. This paper discusses the possibility of using braces in two different conditions, the first one is in retrofitting already constructed structures that don't have sufficient strength against seismic loading, and the second one is the possibility of using braces instead of shear walls in designing non constructed reinforced concrete structures for economical purposes. Different bracing systems in different locations compared with reinforced concrete shear walls in affecting the structural properties of the 10-story square building. Using bracing in the interior frames of buildings was also considered. The results show that different bracing systems have different responses for structural properties such as story displacement, base shear and fundamental time period. The results are significant for detecting the best bracing system to use instead of shear walls reflecting for the two mentioned scenarios as well as considering their locations on the building.
Keywords: *Retrofitting; Seismic Loading; Steel Bracing; Story Displacement; Base Shear; Fundamental Time Period.*

1. Introduction

Seismic analysis is a branch of structural analysis, it necessitates figuring out how an earthquake might affect a building's structural performance, during the structural design, structural assessment, and retrofit processes in seismic activity zones. The cross-section of the member increases from top to bottom to stiffen and strengthen multi-story structures, which are more susceptible to seismic loads, but as a result, the buildings become costly [1]. Shear walls or steel bracing are frequently utilized to boost the seismic strength of framed structures. Shear walls are generally used in reinforced concrete structures, since steel bracing is typically used in steel-framed structures. Although, there have been recommendations for using steel bracing in reinforced concrete structures in recent years, steel bracing looks to be an appealing option to other shear walls or a rigid frame system, considering the simplicity of installation and the low effective cost [2]. Due to its outstanding ductility performance, a conventional steel brace may boost a structure's stiffness and ductility, and they are useful in minimizing the structure's deformation [3].

Reinforced concrete structures that were built in many parts of the world using codes that are now known to provide improper safety under seismic loading are potential risks; as a result, these structurally deficient buildings must be retrofitted to resist earthquake effects in accordance with modern design requirements [4]. On the other hand, since civil engineering structures may experience considerable deformation in varying situations when subjected to seismic, retrofitting the existing structures is a common proposal [5]. Different Bracing systems such as single diagonal bracing, X bracing and V bracing are used to withstand lateral stresses and transmit lateral loads, such as those produced by earthquakes, down to the ground in order to prevent the building from swaying [1].

In this study, the effectiveness of using braces in two different scenarios is examined. The first is seismic retrofitting, which involves strengthening weak structures that have already been constructed. Scientifically, it has been explained that a building reinforced with a shear wall or brace is stronger for lateral load resistance than a conventional moment resisting frame building that is not reinforced by a special method; in this study, the emphasis will be on increasing and decreasing the number of requested parameters in comparison to a conventional moment resisting frame building. As a result, the results can be used to determine the effectiveness of the method used in the retrofitting process, assuming that the moment resisting frame is the weak structure and shear wall and braced buildings are the strong models The second is the potential replacement of braces and shear walls to conventional moment resisting frame building for financial reasons when designing non-constructed reinforced concrete structures [6]. Concentrating on the structural properties such as story displacement, base shear and fundamental time period of numerical models of a 10-story square building were analyzed using the finite element method. In comparison to reinforced concrete shear walls, numerous bracing systems at various places produced a more remarkable impact on the structural characteristics of the building. The percentage change for the preceding structural characteristics is used to illustrate the consequences of various bracing systems compared to shear walls. Story displacement, base shear, and fundamental time period are the structural characteristic that is essential in building codes, so structural researchers have focused on analyzing their alterations under various forms of loading and, consequently, their implications on the overall structure.

After any earthquake and damage to buildings, there is a lot of debate about buildings that use concrete walls, especially tall buildings, which make the building very stiff and brittle and reduce ductility, so this leads to thinking about different ways to replace concrete walls or reduce its use, so one of the ways can be bracing, but it needs to come scientifically in several models to conclude the effects and changes of this replacement. The study's primary focus is on three structural characteristics: story displacement, base shear, and fundamental time period. In seismic zones, it is currently essential to limit displacement while designing reinforced concrete structures [7], this is because, in a yielding structure, the damage is often more strongly related to displacement (distortion) than to force or stress [8]. According to Mahmoudi [9] explanation of the seismic design process, calculating the maximum displacement of the buildings following strong earthquakes is regarded to be extremely vital, as well as calculating the greatest possible story drifts to prevent destruction and the lowest possible separation of joint width to prevent pounding. On the other hand, one of the most relevant characteristics influencing the seismic performance of structures of a specific ductility class is base shear [10]. Base shear refers to the greatest lateral force that could come from seismic ground motion at a structure's base, when analyzing base shear, a number of factors are taken into consideration, including the structure's fundamental period of vibration and amount of ductility [11]. This variation of the structure’s ductility could be from the bracing due to its excellent ductility performance [3]. In the process of analyzing seismic loads, researchers also pay attention to the fundamental time period of vibration. The fundamental period is one of the most significant factors included in the frame design process [12]. A reliable expression for the calculation of the basic period of vibration is crucial for both the design of new buildings and the performance evaluation of older ones in the context of seismic risk assessment and mitigation, the basic period of a structure is influenced by the stiffness and mass distribution along its height [13]. Therefore, every variation of these characteristics should be properly checked [14].

Studies on building structures that have been retrofitted with bracing [15-20] considering various structural properties, including the three properties that are the focus of this study. However, their configuration has only been for the outer bays of the buildings, ignoring using braces in the inner bays, and no comparison has been made to shear wall buildings to investigate clear data that approximately could be used in the possibility of replacing shear walls by braces. When architectural view restrictions for a certain structure preclude utilizing bracing in the exterior frame, structural engineers may consider employing bracing in the interior bays, and carefully assessing how this would influence the building's structural properties is important in resisting seismic loading.

Pushover tests were performed by Maheri, Kousari [21] on scaled-down ductile RC frame models that were directly supported by steel X and knee braces. According to test results, by immediately adding either an X- or a knee-bracing system to the frame, a ductile RC frame's yield capacity and strength capacity may be enhanced, and its global displacements may be confined to the proper values. Similarly, it is possible to accomplish a number of retrofitting ambitions, from drift control to collapse avoidance. The force path in the modified structure may be identified by the designer, who can then change the strength and stiffness as necessary. To comprehend how braced frames, especially those with weak short columns, behave under cyclic lateral loads, an analytical analysis is conducted by Badoux and Jirsa [22]. The inelastic cyclic behavior of a braced frame is adversely affected by the inelastic buckling of the braces. By utilizing bracing that gives in compression or buckles elastically at low axial stresses, instability can be avoided. However, With reference to the seismic performance of the renovated structure, the impact of distributing the steel bracing over the height of the RC frame was investigated by Ghobarah and Abou Elfath [23]. When utilizing well-designed eccentric bracing repair, the seismic performance of the nonductile building should increase more than that of the concentric bracing as long as the building deformation stays within the restrictions that create the maximum permitted link deformation angle.

Structural engineers are increasingly using numerical modeling due to the cost and impossibility of accumulating full structural performance data through experimentation [24]. Instead of using experimental methods, numerical modeling is thought to be a more cost-effective and convenient approach. Finite element techniques are used in numerical calculations to get results that are basically accurate [25]. These models are now receiving more attention from researchers because they are more effective, save time, and are less expensive [26]. Due to that, in this paper, the analysis was done using numerical models in ETABS software.

The outline of the paper is as follows. The methodology of conducting the research is illustrated in Section 2. Section 3 presents the results and discussion of all research categories, which are story displacement, base shear and fundamental time period. Finally, in Section 4, some conclusions are drawn.

2. Methodology

The 10-story of 30-meter-high residential structure was modeled using the ETABS program. In Table 1, material models used for different structural elements, the building's components, sections, lateral force-resisting elements, gravity load and seismic load properties are described. All frame members are passed the design process according to ACI 318-14 design code [27] for reinforced concrete structures. At first, a moment resisting frame model of the building is analyzed without no lateral resisting systems. Then eight different models of the building are analyzed with shear walls in different locations that are assigned with pier labels, and the shear walls in any model are replaced with different bracing systems with the same sections. The bracing systems that used in this study are X bracing, V bracing and diagonal bracing. The models were analyzed using the equivalent static method [28] and modal analysis. The comparable static lateral force approach is a streamlined method for designing structures that replaces the dynamic loading caused by a projected earthquake with a static force spread laterally. In general, the two horizontal directions corresponding to the primary axis of the building are used to assess the total applied seismic force V. It expects that the structure will react in its default lateral mode. To prevent torsional movement underground movements, the building must have a low rise and be reasonably symmetric in order for this to be true. The building must be able to withstand seismic shocks coming from either direction, but not from both directions at once [29].

Structural characteristics in the form of story displacement and base shear are analyzed using the equivalent static method, which is a static linear seismic analysis approach and it is most widely used because of its usability and applicability during the conceptual and final design phases [30]. The fundamental time period of the models is analyzed using modal analysis, also known as the mode superposition method, which is a linear dynamic response approach that evaluates and superimposes free vibration mode forms to characterize displacement patterns, mode shapes explain the configuration that a structure will inevitably reposition into the recorded behavior in all analysis procedures [31] is used in comparing mentioned systems.

The seismic load is applied from both negative and positive directions for the (X) and (Y) axis. The seismic weight was calculated by numerical procedure from the total dead load and (0.25) of live load according to UBC 97 code. A simplified approach for seismic analysis of structures is equivalent lateral force (ELF) analysis. It is predicated on the idea that an equivalent static force acting horizontally can replace the seismic forces acting on the structure. The amount of this force is derived by multiplying the seismic weight of the structure by a coefficient that relies on the seismic zone factor and the structural system utilized. The ETABS program utilizes this technique. Nonlinear deformation or P-Delta effects are not considered in the analysis process of the study.

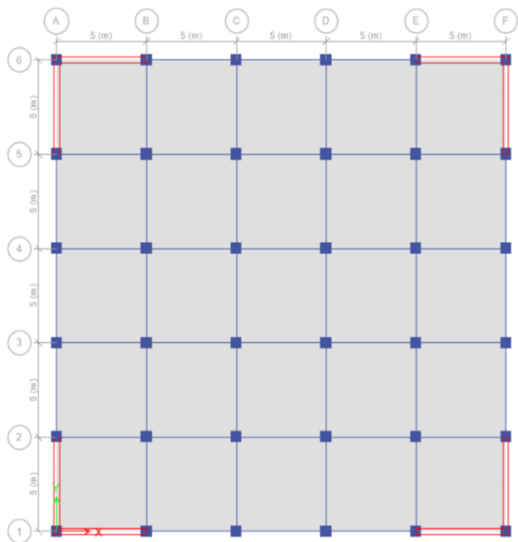
The eight numerical models of the buildings are shown in Figure 1. The figure explains the locations of the shear wall in the building that was replaced by bracing systems. The connection model between the steel bracing and the RC frame is shown in Figure 2, that is using gusset plate. This connection was studied by Maheri and Hadjipour [32] on full-scale connections for internally braced reinforced concrete frames. Their experiments are conducted to verify that the existing standards of practice for the design of the individual components of these connections to steel and concrete structures are applicable.

The building has five spans in each direction and every span is 5m. Every model contains 8 separate or connect shear walls that have 300mm thickness. The first six models consist of shear walls that are equally distributed in both directions but in different locations. In model 7 the priority of strengthening is given to one direction (Y) with 4 shear walls, the other direction (X) has only 2 shear walls. In the last model, the building strengthened in only one direction (Y), ignoring the direction of (X), to determine the effect of a strengthened direction on another one. In the 1st and 2nd cases, the study is done focusing on the exterior frames of the building. Replacing shear walls with braces in the inner bays is totally focused in the 3rd, 4th, 6th and 7th cases. While in the 5th and 8th cases, both exterior and interior frames are focused on.

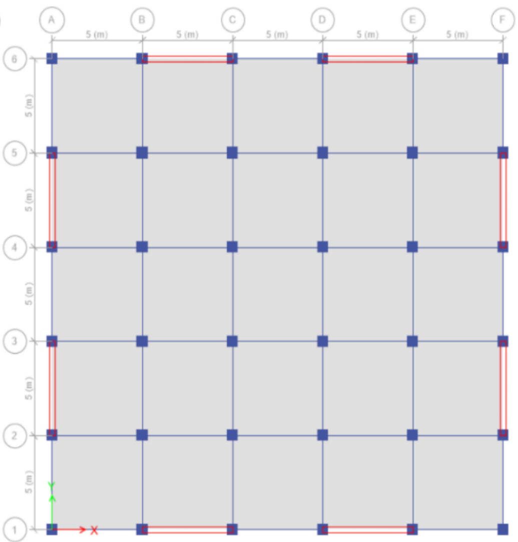
Table 1: Structural Properties that are defined for the building.

Tapes of Data	Item	Amount
Models' data	Number of stories	10
	Story height	3 m
	No. of Spans	5 x 5
	Span length	5 m
	Column size	600 x 600 mm
	Beam size	500 x 700 mm
	Slab thickness	200 mm
	Shear Wall thickness	300 mm
	X Bracing	W8 X 31, A992Fy50
	V Bracing	W8 X 31, A992Fy51
	Diagonal bracing	W8 X 31, A992Fy52
	Concrete grade	30 MPa
	Steel reinforcement grade	420 MPa
	Supports	Fixed
Gravity load data	Live load	1.92 kN/m^2
	Dead load	4.02 kN/m^2
	Beam load	11 kN/m^2
Seismic load data	Code	UBC 1997
	Importance factor	1
	R: Moment resisting frame	3.5
	R: Shear wall model	5.5
	R: Bracing models	5.6
	Seismic zone Z factor	0.2
	Soil profile type	Sc
	Cv	0.32
	Ca	0.24
	Ct	0.03

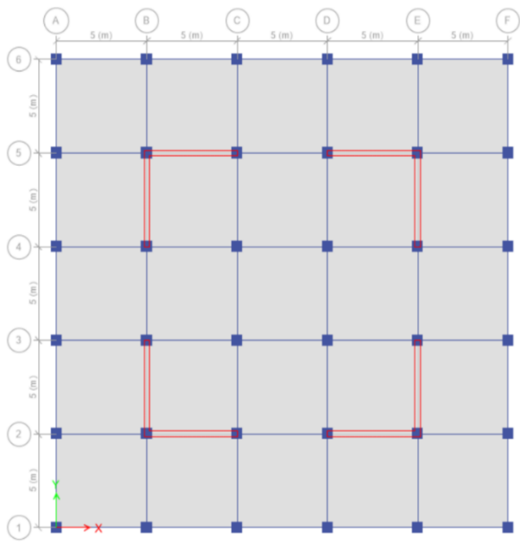
The replacement of the shear walls by bracing systems for model 7 in the Y-direction is shown in Figure 3. The systems used in this paper are X bracing, V bracing and diagonal bracing. The replacement is done for all stories from bottom to top in the same location of shear walls. it's useful to compare both systems of lateral strengthen in detail and the chance of using bracing in the case of economic benefits under acceptable structural safety.



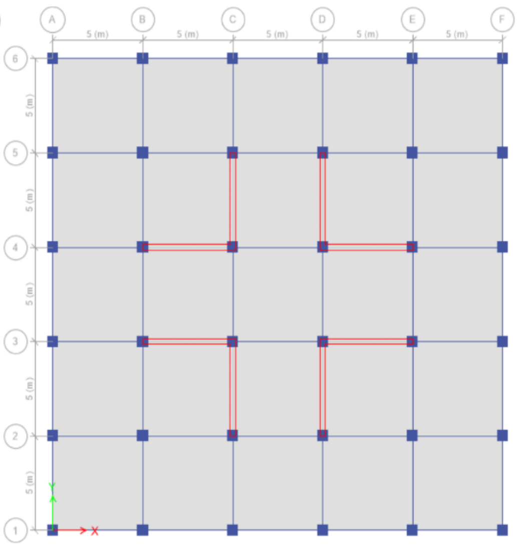
Model 1



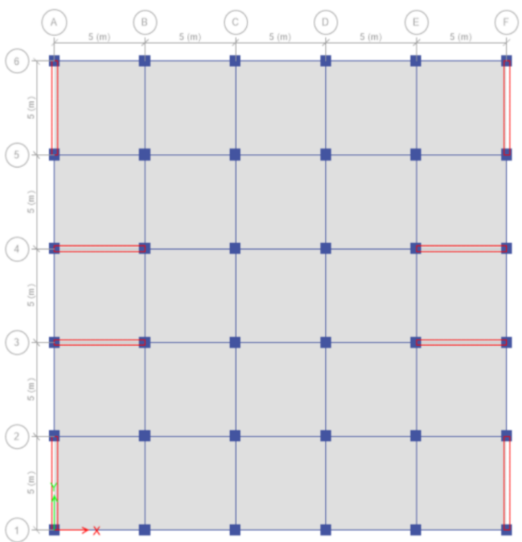
Model 2

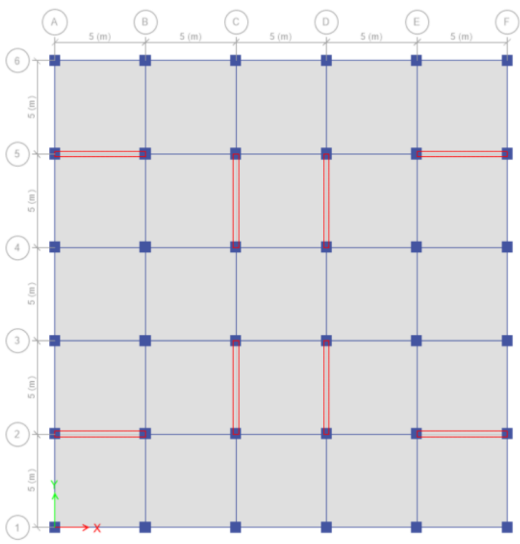


Model 3

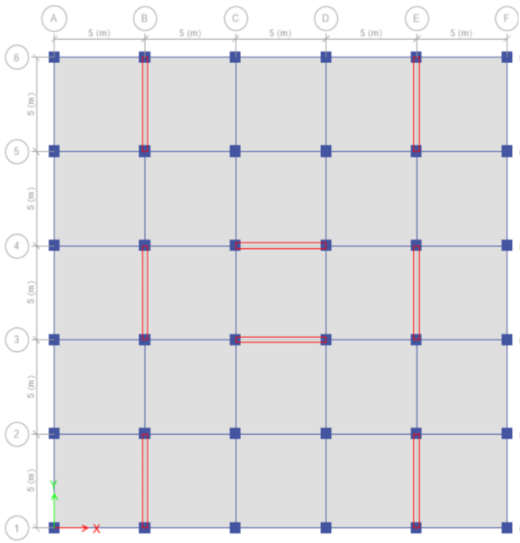


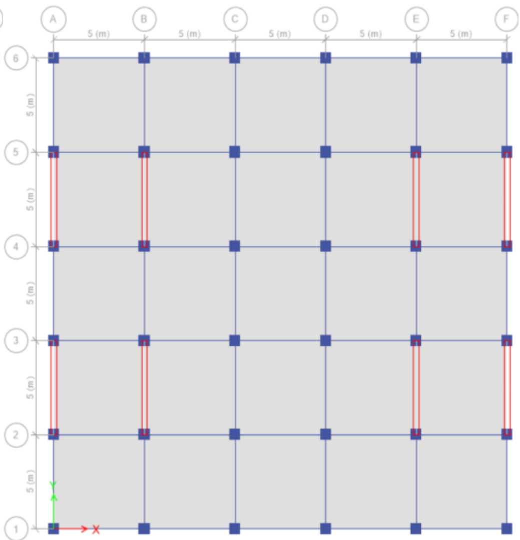
Model 4





Model 5 Model 6





Model 7 Model 8

Figure 1: Numerical models of the location of shear walls that are replaced by bracing are shown from models (1 to 8)

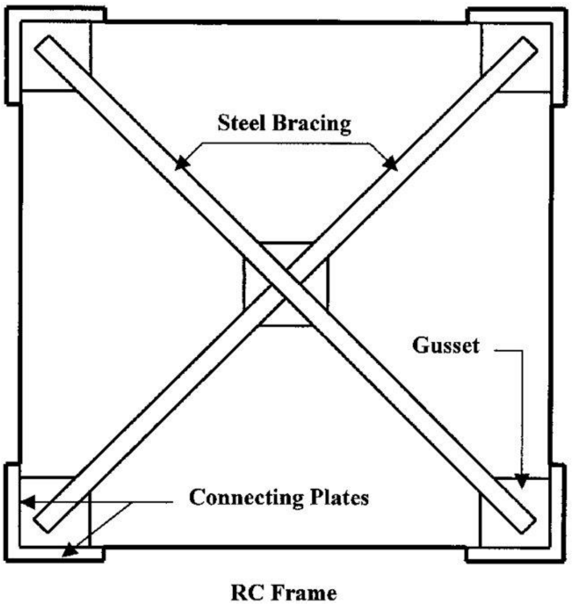
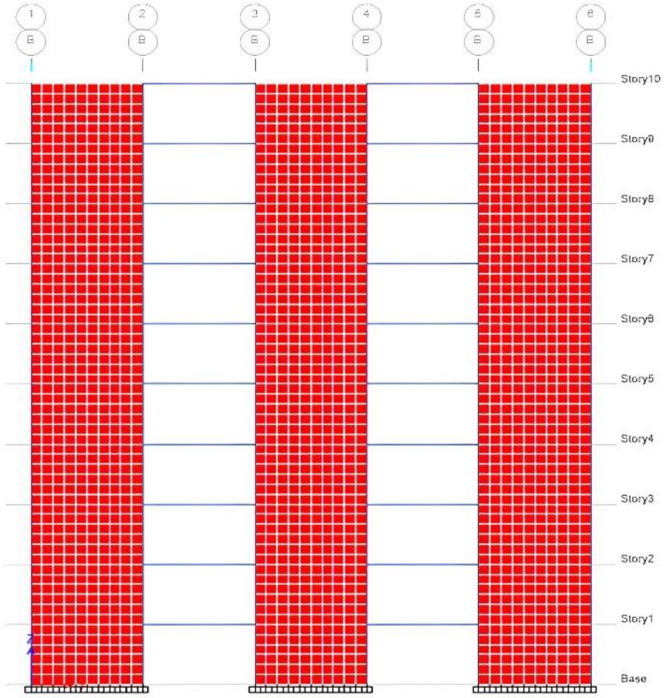
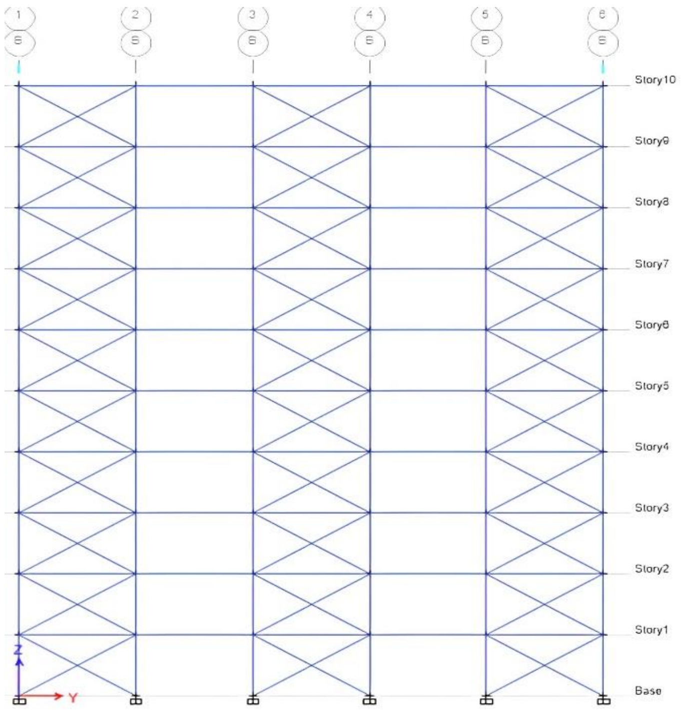


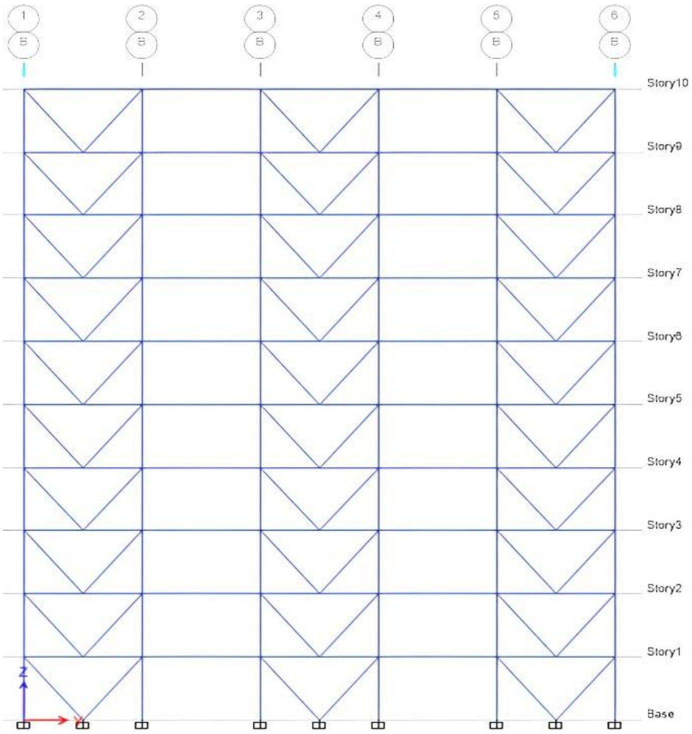
Figure 2: The model of the connection type between steel braces and RC frames using a gusset plate [32]



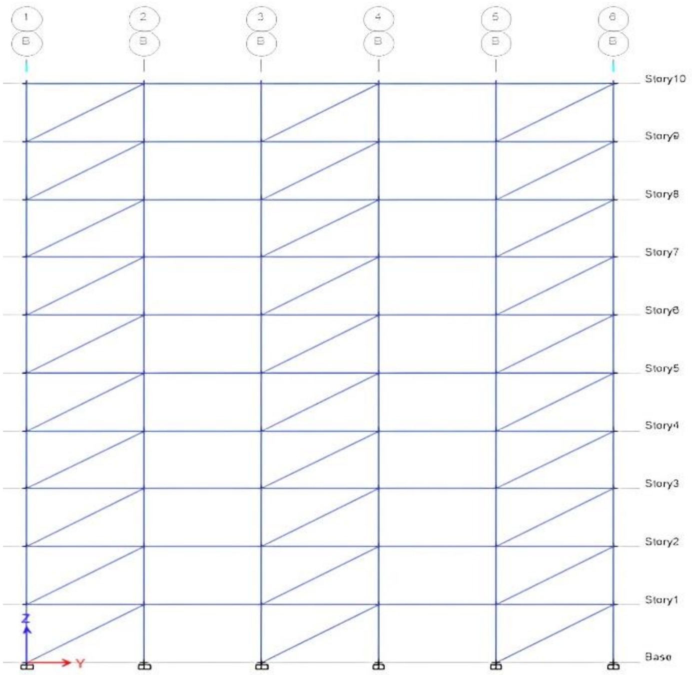
a. Shear wall



b. X Bracing



c. V bracing



d. Diagonal bracing

Figure 3: Replacement of shear walls (a) by X, V and diagonal bracing from (b to d) respectively.

3. Results

3.1 Story Displacement

According to the responses in Table 2, the top of the structure experiences the greatest story displacement in all models. The moment-resisting frame has the greatest story displacement between models, it's due to that moment-resisting frames (MRF) have no strengthening mechanism for lateral loads. Han and Jee [33] stated that the moment frame's components should be able to withstand lateral loads and gravity and the distribution of lateral loads depends on the flexibility of each component. The results show that the most displacement reduction is recorded by shear wall building, due to the fact that shear walls' considerable lateral stiffness and strength allow them to effectively control story drift and horizontal displacement [34]. On the other hand, bracing systems results show a great decrease in story displacement that presented in percentages in Figures 4 and 5, depending on Equation (1).

(1) $$\%D = \frac{d_{oi} - d_i}{d_i} * 100, i = 1:8$$

Where $\%D$ is displacement change in percentage, d_{oi} is the displacement of the case and d_i is the displacement of the moment resisting frame building.

Table 2: Story displacement of building models (mm).

Case		MRF		Shear wall		X bracing		V bracing		Diagonal bracing	
Directions		X	Y	X	Y	X	Y	X	Y	X	Y
Model	1	135.229	135.229	27.728	27.728	41.011	41.011	44.807	44.807	51.227	51.227
	2	135.229	135.229	30.947	30.947	39.816	39.816	43.433	43.433	49.46	49.46
	3	135.229	135.229	26.616	26.616	38.15	38.15	41.77	41.77	50.469	50.469
	4	135.229	135.229	32.862	32.862	42.69	42.69	46.105	46.105	53.928	53.928
	5	135.229	135.229	33.495	33.68	44.291	44.468	48.11	48.325	54.303	53.299
	6	135.229	135.229	34.516	33.36	45.298	42.211	49.048	45.812	55.234	53.015
	7	135.229	135.229	37.397	29.626	54.55	37.405	57.873	39.018	63.436	46.217
	8	135.229	135.229	67.987	25.813	79.436	32.886	79.436	32.886	80.389	39.387

The figures show that the strengthened models in both directions have a better result in decreasing story displacement in both directions. The most reduction for displacement is achieved in the location of Model 3, that the bracing systems reduced displacement by more than -71%, -69% and -62% for X, V and diagonal bracing in X- and Y-directions, respectively. The one strengthens Y-direction in Model 8 shows a displacement with 25.813, 32.886, 32.886, and 39.387 mm, and it has no great effect on the other direction (X) with 67.987, 79.436, 79.436 and 80.389 mm displacement, because the second direction is not strengthened, the percentage change for the same model shows more than -41%, % -41,% -40 in X-direction, and more than -75%, -75%, -70% in Y-direction for X, V and diagonal bracing respectively, at the same location it is about -50% and -80% in X- and Y-direction for shear wall building. The figure shows that the X bracing system has the most suitable type to replace the shear wall for reducing displacement and the best location is in Model 3. While the diagonal bracing has shown the least effect on decreasing displacement.

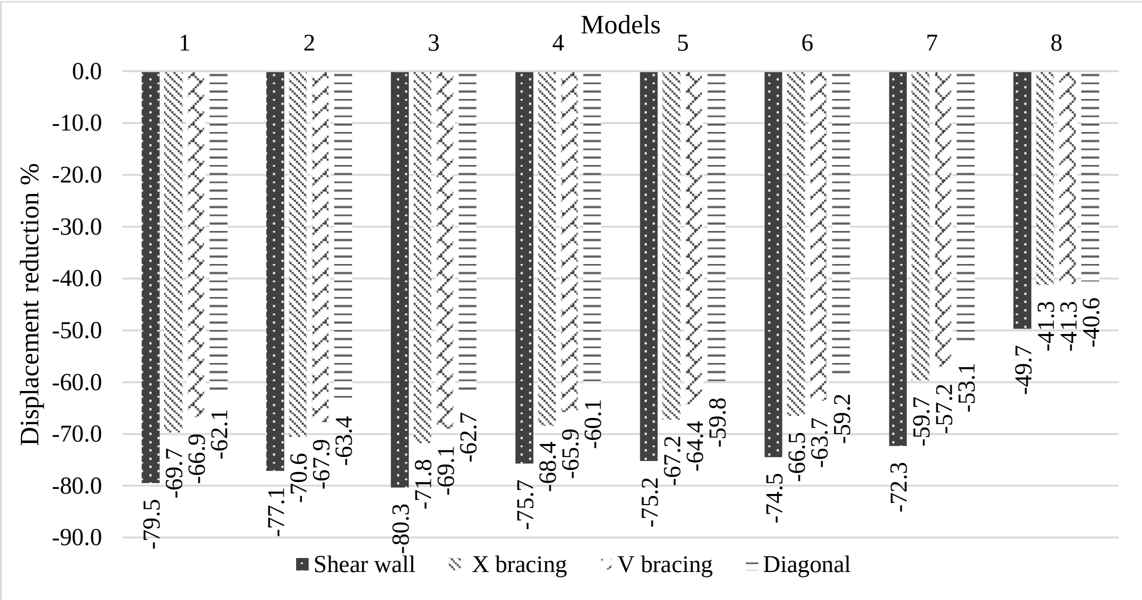


Figure 4: Percentage reduction of story displacement in X-direction of the models.

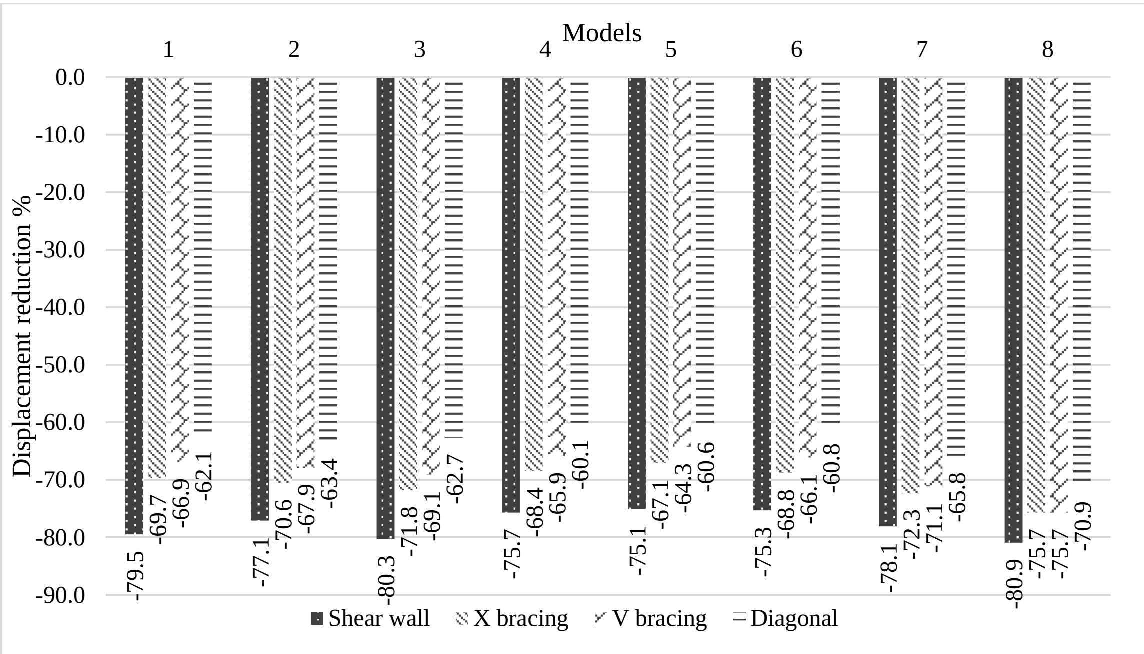


Figure 5: Percentage reduction of story displacement in Y-direction of the models.

3.2 Base Shear

According to equation (2) [28], the actual base shear capacity of a building V_{act} depends on the C_v that is numerical coefficient depends on soil condition and seismic zone (0.32) for all cases, I : importance factor is 1 for all cases, T : expected fundamental time period depends on equation (3) [28], W: seismic weight of the building and R: the factor of ductility and over strengthen of the building which is 3.5, 5.5 and 5.6 for moment resisting frame, shear wall building and braced building respectively.

(2) $$V_{act} = \frac{C_V * I}{RT} * W$$

(3) $$T = C_t * h_n^{\frac{3}{4}}$$

Depending on equation (2) the variation of the models occurs due to the variety of R, T and W, since the ordinary braced frame has the least R it produces the maximum base shear, although it has the least W it can't compensate the ratio. On the other hand, the shear wall and braced buildings have greater R so they have a smaller base shear and again their greater W cannot compensate for the ratio. Table 3 and Figure 6 clear that the base shear capacity for the three bracing models is approximately equal and about %37 fewer than the moment resisting frame model for both directions. differently in the shear wall model that produces greater base shear than bracing models, but fewer than moment resisting frame. Changing the location of the bracing models has no effective influence on the value, while in the shear wall models, it has a great impact on base shear.

Table 3: Base shear of building models (kN).

Base Shear (kN)											
Case		MRF		Shear wall		X bracing		V bracing		Diagonal bracing	
Direction		X	Y	X	Y	X	Y	X	Y	X	Y
Model	1	8510.4	8510.4	7865.1	7865.1	5336.5	5336.5	5330.7	5330.7	5327.8	5327.8
	2	8510.4	8510.4	7161.4	7161.4	5336.5	5336.5	5330.7	5330.7	5327.8	5327.8
	3	8510.4	8510.4	8492.8	8492.8	5336.5	5336.5	5330.7	5330.7	5327.8	5327.8
	4	8510.4	8510.4	8325.7	8325.7	5336.5	5336.5	5330.7	5330.7	5327.8	5327.8
	5	8510.4	8510.4	6894.9	7019.2	5336.5	5336.5	5330.7	5330.7	5327.8	5327.8
	6	8510.4	8510.4	7109.9	7384.8	5336.5	5336.5	5330.7	5330.7	5327.8	5327.8
	7	8510.4	8510.4	6033.8	8408.4	5336.5	5706.7	5330.7	5384.1	5327.8	5327.8
	8	8510.4	8510.4	5453.5	9231.3	5336.5	6290.4	5336.5	6290.4	5327.8	5465.7

(4) $$\%B = \frac{b_{oi} - b_i}{b_i} * 100, i = 1:8$$

Using equation 4 we can get Figures 6 and 7 and where $\%B$ is the percentage change for base shear, b_{oi} is the base shear of the case and b_i is the base shear of the moment resisting frame building. The only increase of base shear is more than %8 in the Y-direction by the shear wall that is in model 8.

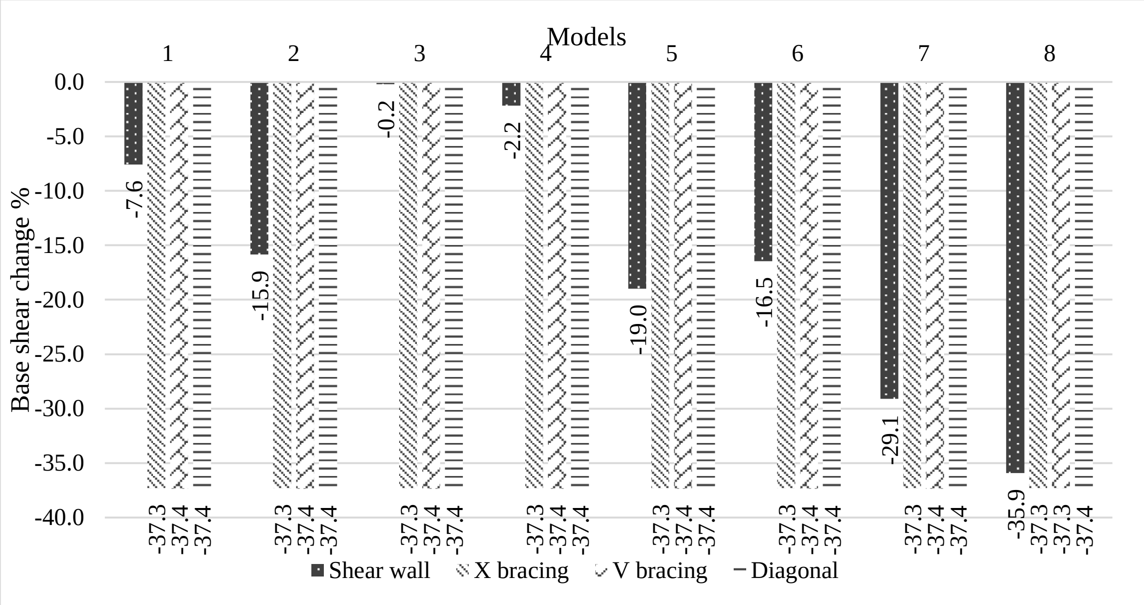


Figure 6: Percentage change of base shear in X-direction of the models.

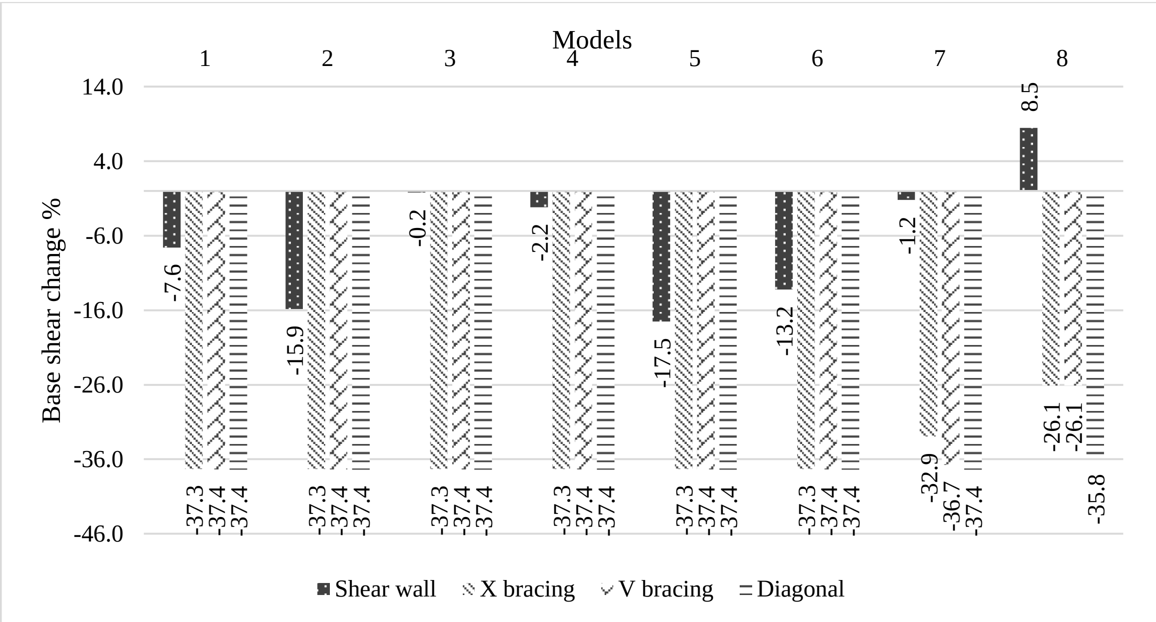


Figure 7: Percentage change of base shear in Y-direction of the models.

3.3 Fundamental Time Period

The fundamental time period is determined in modal analysis using the finite element method in ETABS software, focusing on the first mode of vibration, because the first mode of vibration of a building is critical [35]. The results are shown in Table 4. Szczepanski, Manguri [26] stated that depending on equation (5), f is inversely proportional to M and directly proportional to K. since f is the natural frequency, M and K are the mass and stiffens.

$$f = \sqrt{\frac{K}{M}} \quad (5)$$

f is the natural frequency that is inversely related to the fundamental time period T according to Equation (6)

(6) $$f = \frac{1}{T}$$

The equations clear that increasing the mass of the building will increase the fundamental time period of the building while increasing stiffness. So, if K / M of the braced building is more than that of the moment-resisting frame building, it means the fundamental time period will decrease. Depending on equation (7) the percentage change of the fundamental time period $\%T$ is compared in Figure 8, while t_{oi} is the fundamental time period of the case and t_i is the fundamental time period of the moment resisting frame building. The figure shows that generally using bracing systems decreased the fundamental time period except in model 8, which was increased at a very small range smaller than %1 for all systems while using the shear wall in the same case decreased the time period by about %7.7.

(7) $$\%T = \frac{t_{oi} - t_i}{t_i} * 100, i = 1:8$$

Table 4: The fundamental time period of building models (Sec).

Case		MRF	Shear wall	X bracing	V bracing	Diagonal bracing
Model	1	2.041	0.91	1.398	1.442	1.556
	2	2.041	0.999	1.378	1.446	1.532
	3	2.041	0.843	1.332	1.401	1.508
	4	2.041	1.406	1.763	1.783	1.814
	5	2.041	1.038	1.421	1.491	1.566
	6	2.041	1.164	1.532	1.581	1.638
	7	2.041	1.186	1.604	1.659	1.728
	8	2.041	1.884	2.044	2.044	2.042

The figure shows that the different used systems for bracing approximately have the same effect on the time period and show good results, but have less effect than shear walls. The most effective location was in model 3 where the time period decreased by more than %34, %31 and %26 in the case of X, V and diagonal bracing respectively, while in the same location, the shear walls decreased the time period by more than %58. In the case of using bracing in the inner frames, the figure shows that location 3 is the best option, whereas for the outer frames location 1 and 2 were the most effective. The results show that using bracing instead of shear walls in only one direction has not been effective in comparison with two-directional cases in the time period. The data declares that the most effective bracing system is X bracing to replace the shear wall and the best location is in model 3. While the diagonal bracing is the most unwanted scenario.

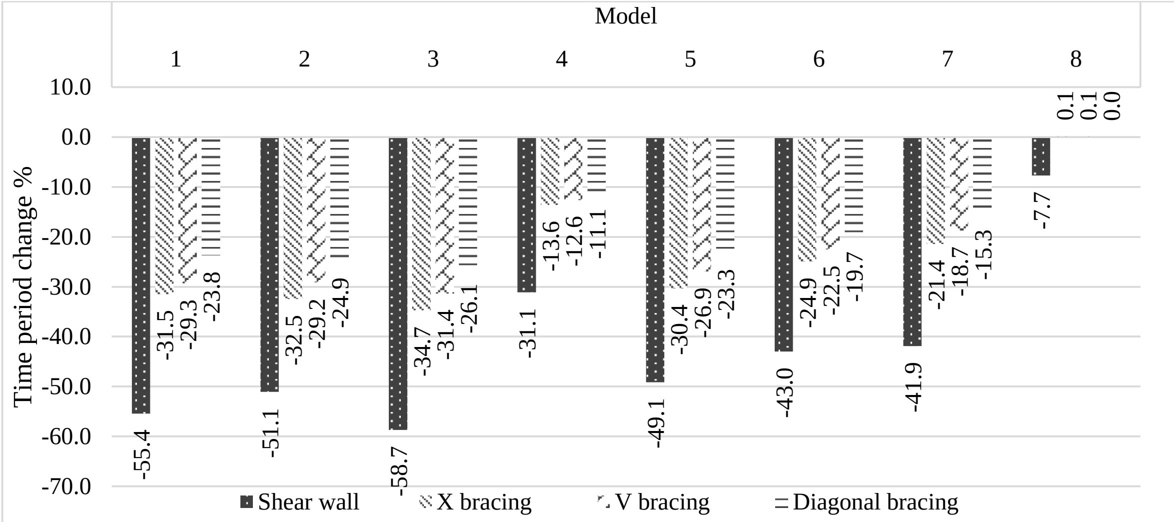


Figure 8: Percentage change of Fundamental time period of models.

4. Conclusions

The possibility of using braces in two different situations is discussed in this paper. The first is the retrofitting of already weak-built structures to make them more resilient to seismic loading. The second is the possibility of using braces in place of shear walls while designing unbuilt reinforced concrete structures for economic gain. In comparison to reinforced concrete shear walls, X, V and diagonal bracing systems at various locations were examined to determine their impact on the structural characteristics of the 10-story square structure. Bracing used in strengthening interior frames was also taken into consideration. After the analysis and presenting the results, the following conclusions are founded:

1. The best bracing system for controlling displacement is X bracing and the worst is diagonal bracing.
   - Using bracing generally in the outer frames of buildings in both directions can reduce the displacement of about %69, %67 and %62 for X, V and diagonal bracing according to the best locations, while using bracing generally in the inner frames of buildings in both directions can reduce the displacement about %71, %69 and %62 for X, V and diagonal bracing according to the best location (location 3). Bracing frames in one direction cannot affect greatly controlling displacement in the second direction. While the buildings that have both inner and outer bracing frames achieved a reduction in displacement in a good range.
   - Comparing with shear wall models, bracings can use to strengthen weak buildings in different locations to reduce story displacements and in the design, the process can be a good alternative in displacement reduction.
2. Due to its great over strengthen factor *R* the bracing systems have the smallest base shear capacity compared to moment-resisting frame and shear wall buildings.
   - Varying their location generally doesn't change the base shear capacity.
   - Comparing with moment resisting frame using bracing can give about %37 smaller base shear generally for X, V and diagonal bracing systems, while shear wall models give about %0 to %35 reductions.
3. Shear wall buildings have a greater impact to reduce the fundamental time period than bracing systems.

- Different bracing systems reduced the fundamental time period of the building by 10% to 34% approximately in the inner braced frames in locations 3 and 4, and 23% to 32% approximately in the outer braced frames in locations 1 and 2. The best system is stated to be X bracing cases.
- The bracing in one direction has approximately no impact on reducing the fundamental time period.

4. Also, the nonlinear deformation in steel frames (especially bracing buckling) is very critical during cyclic loading, but in this study, such an effect is not considered, but it can be a concern in future studies.

5. Conflict of Interest

There is no conflict of interest for this paper

6. Author's Contribution:

We confirm that the manuscript has been read and approved by all named authors. We also confirm that each author has the same contribution to the paper. We further confirm that the order of authors listed in the manuscript has been approved by all authors.

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