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Comparison and Evaluate of Seismic Behavior of Concrete Moment Frames Structures with Buckling Resistance Bracing and Shear Walls

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Abstract

The vulnerability of buildings and reinforcing them is one of the important issues for earthquake prone countries. In recent decades, studies on improving and strengthening different structures have led to innovation of new and different methods in this field. Most of these method require a break in utilization, so that the reinforcement operation can be finished. Various methods such as adding structural components (steel and concrete shear wall, steel cross braces and buckling restrained braces), strengthening weak component parts and structure use change can be used to improve the structure's seismic performance. In response to many scientific issues and economic considerations, engineers usually use converge buckling restrained braced frames as a resistant system against lateral loads during an earthquake. These cross braces will lead to increased rigidity and resistance in concrete structures. In this research, a method is presented to create a simple model of buckling restrained braces. After introducing the components of buckling restrained braces, a sample of this type of cross brace will be modelled in component-restricted Abaqus Software considering all the used items. The goal of this research is to numerically analyze the behavior of buckling restrained braces (BRB) in terms of resistance, ductility and energy absorbability. The results indicate the higher influence of shear wall on strengthening concrete structures compared to a building braced with one BRB opening.

1. Introduction

Iran is amongst the countries which has suffered from casualties and damages of earthquakes, thus earthquake-resistant systems seem completely necessary. The power of earthquake and its estimation is one of the most important forces influencing the building designs. The impact of an earthquake depends on various factors such as the behavior of materials and the structure, earthquake characteristics and geological conditions of the building site. UBC97 regulations explicitly states that buildings should remain stable after a design-limit earthquake. This regulation defines "design-limit earthquake" as an earthquake whose occurrence probability is less than 10% in 50 years. Nowadays, in order to achieve a stable and economic structure in earthquake prone areas, a desired mixture of resistance, rigidity and ductility is created in the structure [1-3]. Common structural systems have both advantages and disadvantages in confronting lateral forces in linear and non-linear area. One of the systems that solved these problems was BRB, which was considered in this research. This system, due to prevention of buckling, has the same non-elastic behavior in tension and pressure and both parts absorb the same energy and become worn out. Also, the structure's behavior improves in terms of stability and absorbability [4, 5].

By studying the behavior of buildings in recent earthquakes, researchers have come to the conclusion that increasing rigidity and more energy dissipation with maintaining the structure's stability is an appropriate solution for reducing the

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amount of location change and hence, the reduction of damages. Nowadays, energy dampers are used in structures in order to dissipate the earthquake's energy. The main advantage of using dampers is absorption of the earthquake's energy in components separated from the structure's frame. Amongst different types of dampers, hysteresis dampers have a special place due to their low cost, high reliability and lack of mechanical parts. BRBs are considered as a specific type of hysteresis dampers [6].

Numerous researches have attempted to improve these cross braces in order to reach an ideal elastoplastic behavior. The idea of buckling restrained braces were first analyzed in Japan by Yashino in 1971. He experimented flat steel plates in flat concrete panels. This system was in fact a shear walls in which the cross brace was used. The difference is that there was a distance created between steel plates and the shear wall's concrete. Yashino concluded that this system has a higher energy depreciation compared to when there is no distance between the steel plate and shear wall's concrete [7]. In 1973, Wakabayashi conducted experiments on these steel plates and demonstrated that in order to increase the energy depreciation, a deboning material should be used between the steel plates and the shear wall's concrete. By reviewing the history of studies on yielding braces without buckling, the need for this brace was created when we want to increase the pressure resistance of the brace component, without affecting its tension resistance and eventually see a different hysteresis response in the behavior of this brace component [8]. In Iran and in 2015, Hosseini worked on presenting a component-limited computational model, in order to review the cyclic behavior of buckling restrained braces. In this study and in order to analyze the performance of buckling restrained braces, Ansari presented a component-limited model of this element using ANSYS software [9]. According to the results from analysis of this brace which is under axial cyclic load considering the off-axis effects arising from the frame, it can be seen that confining the brace's metal core with a metal sheath and enclosing concrete could prevent the buckling of the core and the brace has the same behavior in tension, pressure and also providing the regulations' requirements. In this study, a method is presented to create a simple model of buckling restrained braces. After introducing the BRB components, a sample of this brace will be modeled in component-limited Abaqus software, considering all the used items. After confirming the real sample model using available lab results by non-linear dynamic analysis, the simple model will be created. The goal of this research is to compare the seismic performance and strengthening the concrete structure using buckling restrained brace and shear wall and to numerically analyze the behavior of BRBs in terms of resistance, ductility and energy absorbability.

2. Materials and Methods:

2.1. Design foundations of buckling restrained brace

2.1.1. Lateral bearer system

Lateral bearer system is a part of the whole structure which is used to endure the lateral loads arising from wind and earthquake. In high buildings, the metal skeleton is consisted of beams and columns and their resistance against lateral forces (wind or earthquake) depends on degree of restraint of their beams and columns connections. Types of lateral bearer systems include: bending frame, shear wall and brace frame [10].

2.1.2. Bending frame

Bending frame is a frame in which the connections of beams to the columns are restrained. In this system, the lateral forces on the structure are inhibited using the rigidity of connection between beam and column [11].

2.1.3. Shear Wall

The shear wall is a wall usually made of concrete which is used for resistance against lateral forces (applied on the wall's plate). These walls are also known as right diaphragm [11].

2.1.4. Braced Frames

Braced frames consist of right components (columns), horizontal components (beams) and diagonal components which are included to confront lateral forces and prevent the tilting of building's skeleton when a lateral force is applied. The locating of braces in a building's plan should be symmetric; braces can be converging or divergent. In converge brace, the axis of diagonal components is symmetric at one point of their beam or column or their intersection; but in divergent braces, diameters don't have to cross at one point [12].

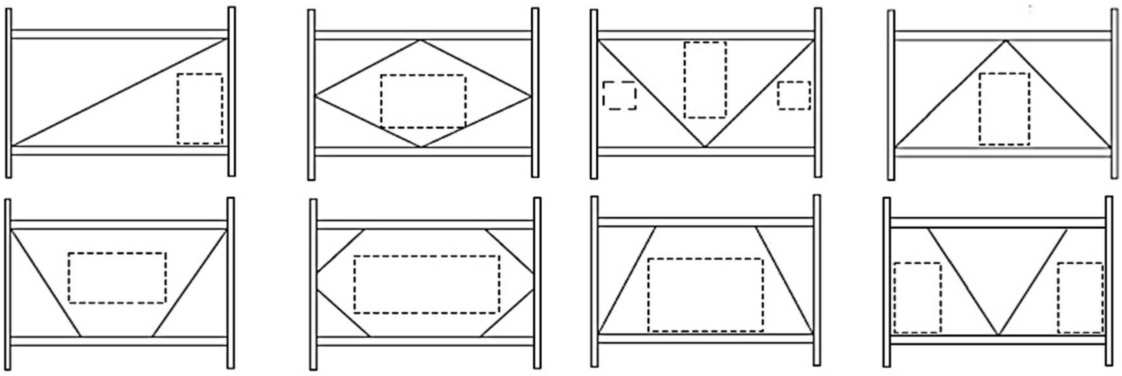


Figure 1. Examples of converge and divergent braces [12]

2.2. Buckling Restrained Brace

The most general form of BRB consists of a steel core embedded in a steel sheath. The void between the core and sheath is filled with an appropriate filler material such as mortar. Before pouring the mortar, a bonding material with a small air gap between the steel core and mortar is provided. This material and also the air gap are used to prevent the transfer of axial force from the brace's core to the sheath and mortar. In fact, the steel sheath and mortar only prevent the buckling of the brace and the steel core is responsible for enduring the axial force [5].

Many of behavioral defects of common converge braces is the result of difference between the tension and compressive capacity of the braces and deterioration in resistance of these braces under cyclic loading. Therefore, numerous researches have attempted to improve these braces to reach an ideal elastoplastic behavior. In order to reach this goal, we had to use an appropriate mechanism to prevent the compressive buckling of the brace and to make the compressive yielding of steel possible. The desired method consisted of enclosing a ductile metal core amongst a mass of concrete which is itself surrounded by a metal membrane. The main foundations of this brace's performance is prevention of the buckling of steel core due to the possibility of compressive yielding and thus the possibility of energy absorption in this component [13, 14]. This will be possible by covering the whole length of the steel core in the steel pipe filled with concrete and mortar. In this system, there is a need for provision of a slip surface or a discontinuity layer between the metal core and the enclosing concrete. The purpose of this is to make the metal core bear the brace force alone. Materials and geometry of the slip layer should be in a way that makes the relative movement between the steel core and concrete possible; a movement that is due to shear and Poisson effect. As a result, this prevent the local buckling of the core and also makes its yielding during compressive loading possible. Concrete and steel tube-like chamber provide the rigidity and bending resistance required to prevent the total buckling of the brace and also makes possible the load tolerance by the metal core to the extent of yielding without reduced rigidity or compressive resistance of the brace during the loading cycles. Also, concrete and steel chamber prevent the local buckling of the core. Non-elastic cyclic behavior of these braces has been analyzed by numerous experiments. These experiments which matched the component-limited studies demonstrated that in contrast to common braces, stable hysteresis cycles are achieved in tension and compression and thus a high capacity for earthquake's energy absorption is created in the structure [12].

Behavior of frames with buckling restrained braces, despite of similar appearances, are very different with common brace frames. In buckling restrained brace systems, hysteresis loops are stable and there is no decline in resistance and rigidity in system after frequent loading cycles. While the studies in the last two decades show that in co-axial braces, these braces will experience total buckling in the compression mode and thus the system will deteriorate in resistance and rigidity and will in fact lead to downfall of the hysteresis curve. Also in the stretching mode, the connections details of the brace face a critical situation. In other words, by using BRBs ductility increases and the fragile mode in the co-axial brace system will turn into a ductile mode. The amount of designing force resulting from the static method in this moderate co-axial system is significantly more than BRB system; which makes it un-economic compared to buckling restrained brace. Compared to braces 7 & 8, it should be stated that the unbalanced force on the beam in systems of braces 7 & 8 does not exist in the buckling restrained system [15].

Since the basis of hysteresis dampers' performance is shape changes in steel, the designing basis of structure with BRB system is similar to designing basis of frames with off-axis braces. Therefore, we can use the equivalent static method in estimation of designing force of frames with off-axis braces which are presented in Standard 2800 to also estimate the designing force of frames with this system [13]. After determining the loads on the structure and analysis of the frame under them, the amount of force create in braces P_{br} is determined. Therefore, the cross section required for the brace's yielding area equals:

$$A'_{br} = \frac{P'_{br}}{1.25 \times 0.6F_y}\,\alpha \tag{1}$$

Here, α can be considered between one and the ratio of ultimate resistance to maximum load arising from analysis in components which receive the brace's load (such as columns). Bigger amounts of this coefficient increase system's rigidity and absorbability. F_y equals the yielding resistance of steel core of the brace. Coefficient of 1.25 is because of inclusion of strain hardening in steel. In other words, other frame components should be designed in a way to remain in the elastic range in the final state. Because, due to increased BRB force resulting from steel's strain hardening, the amount of force created in braces in the final state will be more than their yielding resistance. Thus, by considering this coefficient, we make sure that other frame components don't fail until the end of the earthquake [11].

Because the cross section of the central core is significantly smaller than the cross section of the connection's distal area, most of the elastic and plastic location changes occur in this area; considering this, axial rigidity of each buckling restrained brace equals:

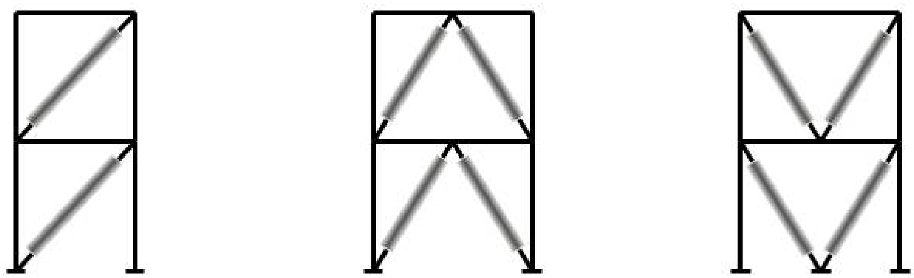
$$K_{br} = \frac{EA'_{br}}{L'_{br}} \tag{2}$$

L'_{br} is the length of the central core and E is the elasticity module of the steel materials. Also, the axial strain of the yielding area equals [11]:

$$\varepsilon_{br} = \frac{\delta_{br}}{L'_{br}} \tag{3}$$

Here, δ_{br} is the axial shape change of the brace.

We can increase the rigidity of the brace by reducing L'_{br} and also therefore reduce the relative location change. As the above equation shows, this occurs independently from the brace resistance. This characteristic is quite significant, in terms that it gives the designer freedom of action. Also, selecting the steel's resistance and brace's cross section enhance this freedom. Shapes of buckling restrained braces are illustrated in figure 2.



Diagonal **Contrast V-type** **V-type**

Figure 2. buckling restrained braces [6]

2.3. The components of buckling restrained brace

The components of buckling restrained brace include these 5 segments:

1. Enclosed flowing segment: This segment can be rectangular or cross-shaped. Also, one or multiple steel sheets are used enclosed. Because this segment is designed to flow under cyclic load, mild steel is more applicable due to its higher ductility. As another alternative, high-resistance low-alloy steel or steel materials with specific flow resistance and without high swings can be used. This type of materials is crucial for a reliable capacity design in BRB frames [9].

2. Enclosed elastic segment: This segment usually has a bigger area than the central core to ensure its elastic response. This could be done by broadening the steel core (transfer in width should be done slowly to prevent the tension concentration in the steel core). Also, using the hardener welded to the steel core to increase the area is all right.

3. Not-enclosed elastic segment: This segment is the continuation of the enclosed elastic segment which connects the brace to the Gusset Plate junction. In designing this segment, we should pay attention to its local buckling and facilitating the installing and uninstalling of this brace.

4. Separating and expanding materials: slippery materials that efficiently eliminate or minimize the shear transfer between the steel core and mortar. Materials such as rubber, polyethylene, silicon oil, mastic tape are some examples. Due to the enclosure mechanism, the buckling of the steel core is possible in higher modes. That's why the void needs to be large enough to let the steel expand in the compression mode. In estimating the empty distance between mortar and steel core, the Poisson coefficient of 0.3 in elastic mode and 0.5 in flowing mode should be taken into consideration. Designing the empty space needs to be considered based on the maximum strain. If the sectional area changes between the enclosed elastic segment and enclosed flowing segment, an empty space should be provided along the front of the broadened area to prevent contact between the steel plate and mortar. Such contact could unexpectedly increase the compressive resistance of the brace which will exceed the designing force and hence will not be desirable in terms of capacity designing. Also, it increases the possibility of an unbalanced force on chevron frame's equipment. Figure 3 also shows an exterior empty space which prevents contact between patch sheets and enclosure mechanism.

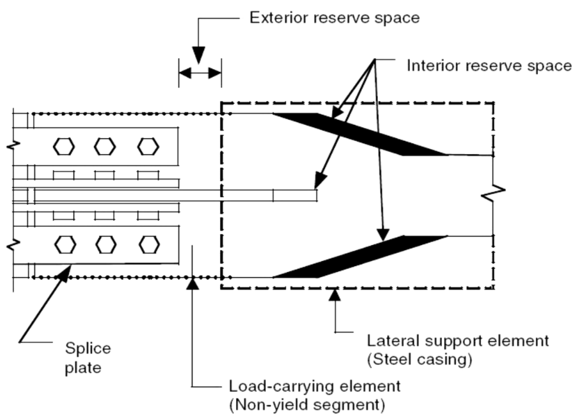


Figure 3. Empty space to prevent the contact between steel plate and mortar [10]

5. Enclosure mechanism: This mechanism usually consists of mortar and metal sheath (Figure 4). But some of BRBs that have not used mortar are shown in Figure 5:

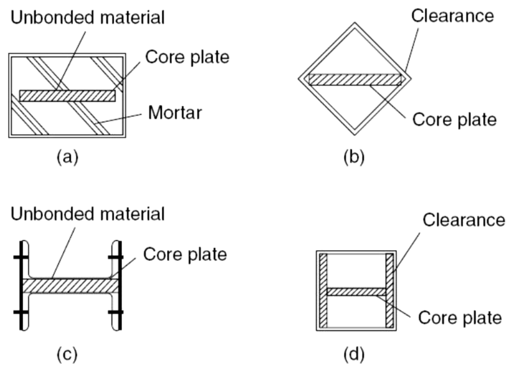


Figure 4. Enclosure mechanism of the core with mortar [10]

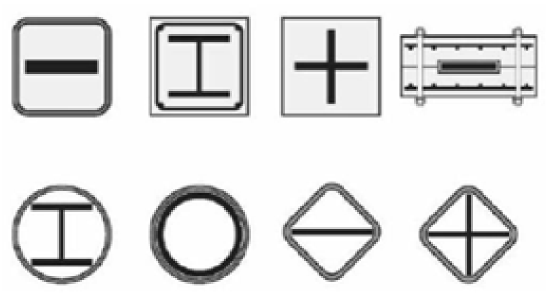


Figure 5. Enclosure mechanism of the core [10]

3. Modelling and analysis of the models

In order to review the characteristic of concrete structures braced with concrete shear wall and BRB, number of models were reviewed and modelled. The created models were analyzed under static and dynamic loads. For this, concrete buildings with 6, 10 and 15 stories with three 5-meter openings were designed in ETABS software and all the wall's peripheral initial sections were extracted from it (Figure 6); then these sections were modelled in Abaqus software using finite element method (FEM). FEM is a numerical method for solving problems of engineering and mathematical physics. The analytical solution of these problems generally require the solution to boundary value problems for partial differential equations. The finite element method formulation of the problem results in a system of algebraic equations. The method approximates the unknown function over the domain. To solve the problem, it subdivides a large system into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function. The employed method to solve our partial differential equation, is the finite element method (FEM). The primitive variables, eigenfrequencies, and the wave functions are computed. In this method, each domain is divided into a collection of subdomains. Each subdomain is represented by a set of element equations to the original problem. The domains type to perform the (FEM) solution is free tetrahedral [16]. Considering that in this study, we tried to enter the plastic area by static and dynamic loading in all the models that were modeled by the regulatory hypotheses and review all the possible failures; we also compared the static and dynamic states to achieve an optimal design and to analyze the results by available regulations. Considering that the modeling and analysis were carried out for each of the 3 buildings and to avoid repetition and similarities, we only mention the results and findings for the 6-story buildings. The models under study are based on Table 1. The final measurements are shown in Table 2.

Table 1. Models under study

Model	Brace type	Number of stories	Description
M6	-	6	-
M6B	BRB	6	Brace in the middle frame
M6B2	BRB	6	Two braces in lateral frames
M6B3	BRB	6	One brace in each opening
M6SW	Shear wall	6	Shear wall in the middle frame
M10	-	10	-
M10B	BRB	10	Brace in the middle frame
M10SW	Shear wall	10	Shear wall in the middle frame
M15	-	15	-
M15B	BRB	15	Brace in the middle frame
M15SW	Shear wall	15	Shear wall in the middle frame

Table 2. Measurements obtained from ETABS (meter)

Steel shell's thickness	BRB measurements	Shear wall's thickness	Column measurements	Beam measurements
0.005	0.4×0.4×5.9	0.4	0.4×1.4×3.2	0.4×0.4×5.0

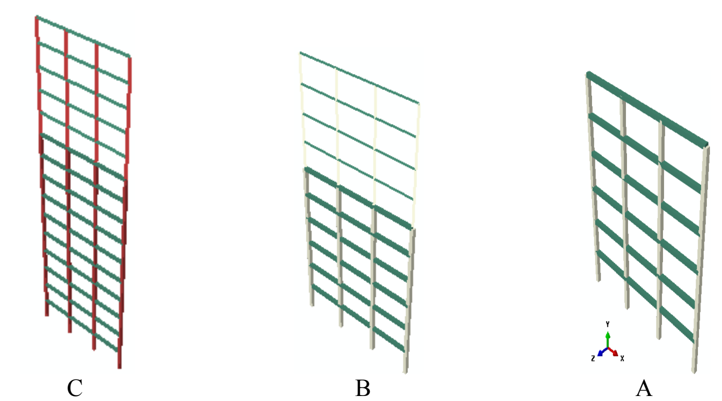


Figure 6. Models under study. A) 6 stories B) 10 stories C) 15 stories

4. Modeling in Abaqus Software

Modeling in Abaqus is based on the element method. In this section, aforementioned models are analyzed using pushover and non-linear dynamic methods. Wire is used to model the beams; although we could also use solid and shell, but because wire has two nodes, modeling and orientation of beams and columns should be carefully done, but the software's calculations and analysis costs decrease substantially and results accuracy increase considerably; and in solid modeling due to increase of elements and nodes and consequently the increase of node forces created in the structure and complexity of equations, costs will rise significantly and accuracy drops. To model the shear wall, we use SHELL elements which is a rectangular page element of S4R type. In order to perform a non-linear static analysis according to the following figure, all the models were put under lateral displacement and the end connected to the ground is closed in all the degrees of freedom.

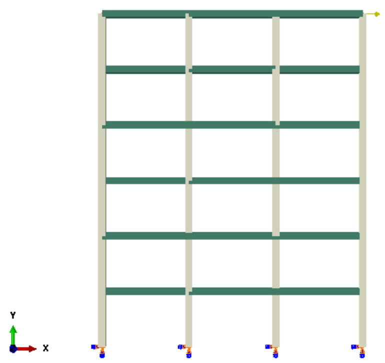


Figure 7. Place of tightening the bases and location of force application

Dislocation starts at 0 and continues to 3000 kilonewtons failure and the results are analyzed.

5. Results

In figure 8, the 6-story building modelled in the software is shown:

Figure 8. Models under study of brigade 1

In the discussed loading on models, displacement starts in a linear curve with the slope of 1 (x=y). In early stages and when the loading is little and slight, the shear wall shows the necessary resistance. In this system, the connection between beams and column can be simple or rigid and due to columns' strength, these components can play a good role in load bearing.

Because of this, the reactive force created in the bases increase with a higher slope until the stage where the created force in the frame gets transferred to concrete plates of the brace. In this stage, the tension created in beam and column gets transferred to the concrete plate. Considering the connection of lower floors to the ground and freedom of higher floors, the shear walls acts as a cantilever.

Also, the strain is increasing in the foot of the wall and the wall starts losing efficiency when the displacement increases beyond the advised standard in the Fema-356 regulation and in the following, Von Mises stress in the shear wall is shown in Figure 9. Due to displacement limitation, the stress is at the maximum in the foot of the wall. What we can understand from reviewing the contours of the 6-story models is the tolerance of compressive forces in braces (Figure 10).

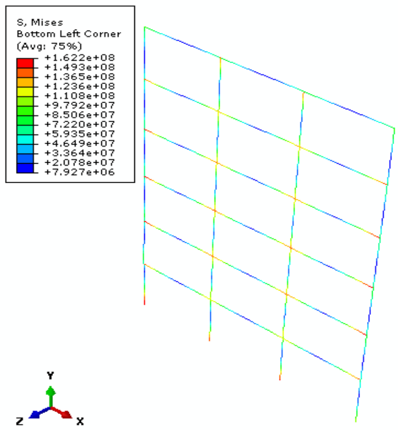


Figure 9. Von Mises Stress in M6 model

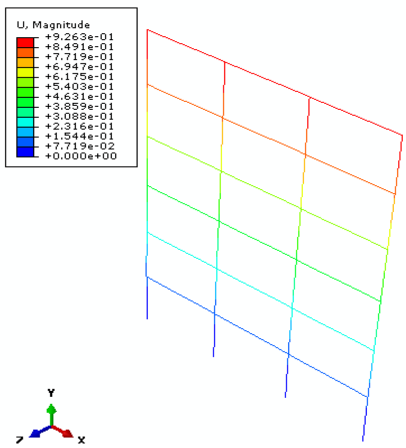


Figure 10. Displacement contour

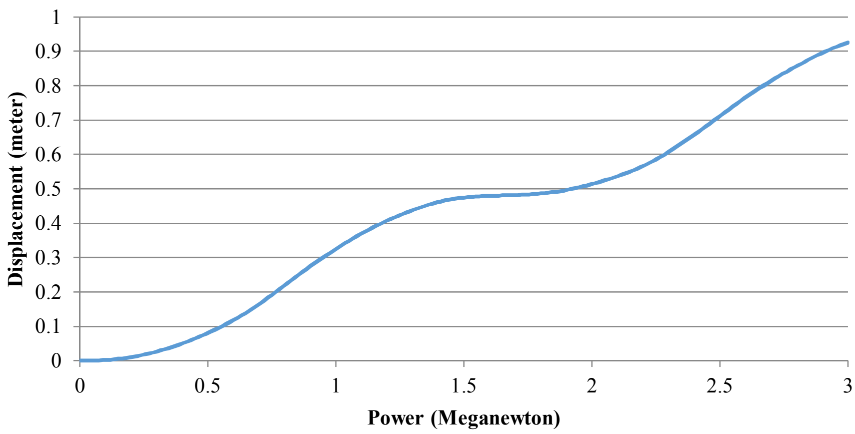
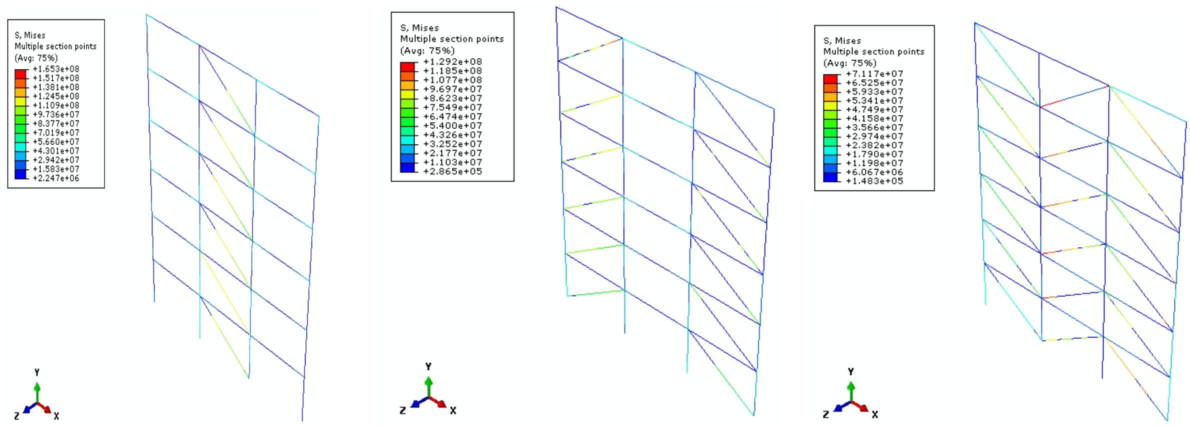


Figure 11. Power-displacement curve of M6 model

As it can be seen in Figure 11, displacement increases linearly with increasing power in a way that 3000 kilonewtons equal 93 cm displacement. In the following and in order to investigate the brace effect with BRBs, other results of the 6-story models are shown.



M6-BRB **M6-BRB2** **M6-BRB3**

Figure 12. Von Mises stress in six stories model

Also, by paying attention to the tables of stress in contours, it can be seen that using two and three braces will lead to significant decrease in stresses created in the model; in a way that in a model with one brace, the maximum stress in 165 mega Pascal, whereas in the model with two or three braces, the stress is 129 and 71 mega Pascal, respectively.

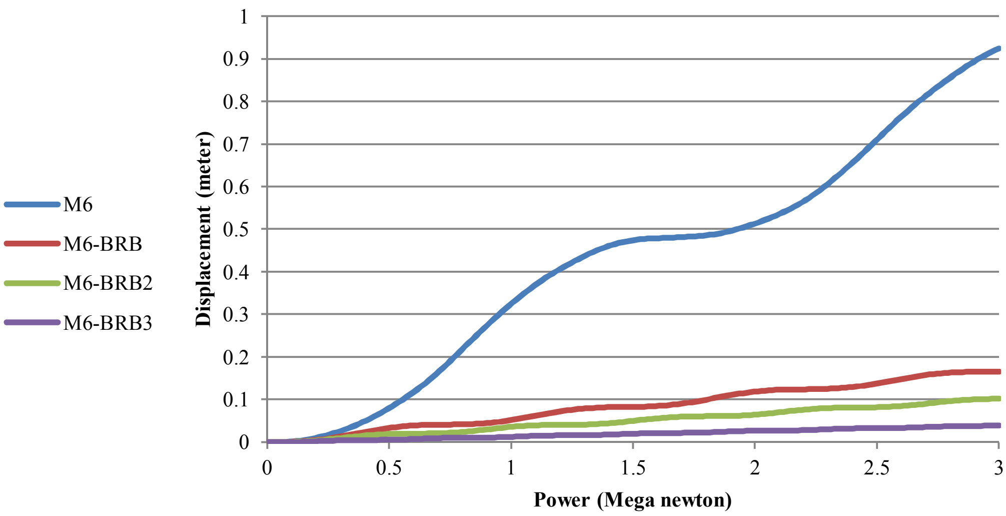


Figure 13. Power-displacement curve of 6-story models with BRB brace

Analyzing the Figure 13 indicates that using BRBs is efficient in increasing the structure's resistance; in a way that using a single brace in one opening causes the displacement to drop from 93 cm to 17 cm which shows an 82% decrease in displacement. This value in models with two and three opening braces is 89% and 96%, respectively.

In order to analyze the usage of shear wall in strengthening concrete structure, we study the M6-SW model with one opening of the shear wall.

What we can understand from analyzing the stress contours of 6-story buildings is the tolerance against compressive forces in the shear wall. Also, by paying attention to tables of stress in contours, it can be seen that using shear wall will lead to significant decrease in stresses created in the model; in a way that in a model with one brace, the maximum stress in 165 mega Pascal, whereas in the model with shear wall, the stress is 45 mega Pascal, which indicates a 73% drop in stresses.

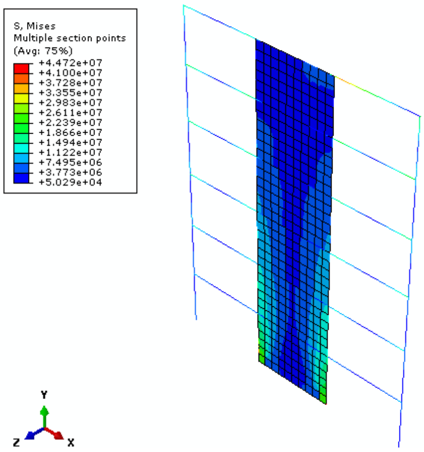


Figure 14. Von Mises stress in M6-SW model

In the following, in order to investigate the effect of using concrete shear wall and BRB in concrete structure walls on the behavior and resistance of the structure, the power-displacement curve of 6-story buildings are shown in Figure 15 and the results are compared to each other.

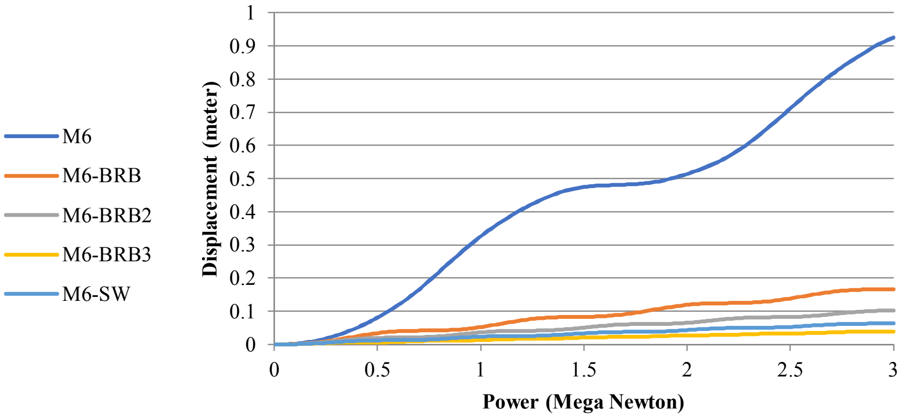


Figure 15. Power-displacement curve of 6-story models

As it can be seen in Figure 16, using shear wall leads to a 94% drop in the model's displacement and this amount shows a better resistance compared to models with BRB with one or two openings braced, whereas it shows a little increase compared to M6-BRB2 with three openings braced. The results imply that in the model under study, using three braced openings show better performance compared to a model with one shear wall opening.

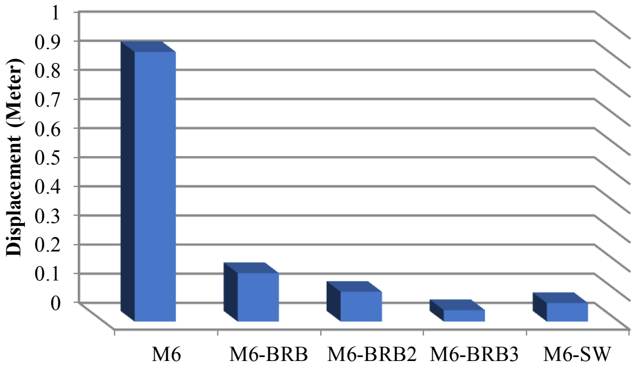


Figure 16. General comparison between 6-story models

6. Conclusions

Using buckling restrained braces (BRB) is very effective in increasing the structure's resistance; in a way that using a single brace in one opening causes a decrease in displacement from 93 cm to 17 cm; which is an 82% drop in model's displacement. This value in models with two and three opening braces is 89% and 96%, respectively.

General analysis of models indicates that the effect of shear wall on strengthening concrete structures is bigger compared to buildings braced with one BRB opening. Also, using a brace significantly reduces the stresses created in the structure and using a shear wall reduces the stresses more than other two models.

7. Recommendations for future research

In this study, we compared the seismic performance and concrete structure strengthening, using BRB and shear wall. General analysis indicates the higher influence of shear wall on concrete structures strengthening compared to a building braced with one BRB opening. Also, using a brace significantly reduces the stresses created in the structure and using a shear wall reduces the stresses more than other two models. For better future researches, we suggest that researchers conduct studies in the following fields:

* Using peripheral BRBs in tall buildings and comparing them to typical co-axial braces (CBF)

* Analyzing the effect of the length of opening and height's effect on the behavior of frames braced with BRB.

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