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Seismic response analysis of mega-scale buckling-restrained bracing systems in tall buildings

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Abstract. Tall buildings are categorized as important structures because of the large number of occupants and high construction costs. The choice of competent lateral load resisting systems in tall buildings is of crucial importance. Bracing systems have long been an economic and effective method for resisting lateral loads in steel structures. However, there are some potential adverse aspects to bracing systems such as the limitations they inflict on architectural plans, uplift forces and poor performances in compression. in order to eliminate the mentioned problems and for cost optimization, in this paper, six 20-story steel buildings and frames with different types of bracing, i.e., conventional, mega-scale and buckling-restrained bracing (BRB) were analyzed. Linear and modal push-over analyses were carried out. The results pointed out that Mega-Scale Bracing (MSB) system has significant superiority over the conventional bracing type. The MSB system is 25% more economic. Some other advantages of MSB include: up to 63% less drift ratio, up to 38% better performance in lateral displacement, up to 100% stiffer stories, and about 50% smaller uplift forces. Moreover, MSB equipped with BRB attests even a better seismic behavior in the aforementioned parameters.

Keywords: mega-scale bracing; buckling-restrained brace; tall building; seismic analysis; modal push-over analysis

1. Introduction

Design and construction of tall buildings require special expertise. Large number of occupants and high and unforeseeable construction costs make tall buildings very important structures. Studied methods should be employed to optimize costs as long as the safety of the building is assured. A main choice for building construction is definitely the steel structural system, and in these buildings, braces are the favorite to be employed as the lateral load resisting system due to simplicity in erecting, affordability and inexpensiveness, and also high strength and stiffness. But major disadvantages are also associated with bracing systems, namely the uplift forces in columns, low ductility and being impedimental to the architectural plan (Smith and Coull 1991). Concentric bracing, eccentric bracing and special bracing systems constitute the three different bracing types, each one offering specific characteristics and also requiring different design approaches (Mazzolani *et al*. 2009). Opting for the most appropriate type of bracing has a substantial effect on

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the performance of the structure and also on the cost of the construction. The use of bracings was conventionally bounded to story-height and bay-width dimensions, bracings that would not be visible in the completed building and would not allow for openings. The emergence of newer bracing systems not only improved the structural performance, but solved the conventional bracings problems. Mega-braces and mega-scale bracings could be external, extend over multiple stories and bays, which gives the building a new, modern and attractive face and better seismic performance. More recently buckling-restrained braces were suggested as new efficient lateral load resisting system, offering an increase in the resistance of structures by providing huge energy dissipation and stable hysteretic behavior, which is a privilege for the structure undergoing cyclic forces during a seismic event.

2. Mega-scale bracing system (MSB), and buckling-restrained braces (BRB)

2.1 MSB

Mega-scale bracing (MSB) is the title given to a specific arrangement of braces which forms a particular type of space truss. It consists of diagonal elements, coming one after another continuously in specified directions. MSB spans over multiple stories and bays forming a mega diagonal grid on outer frames of the structure or on the face of the building. Numerous studies on the efficiency of mega frames and mega-scale bracing in tall buildings have been carried out. Seismic performance of Taipei 101 under different seismic conditions was evaluated. The results showed that super-tall buildings with mega-frames totally meet the design requirements and could satisfy safety expectations (Fan *et al.* 2009). The obtained results from the analyses in this paper also verify and suggest that mega frame and mega-scale bracings are in perfect compliance with design requirements and safety needs. In another study, which serves to verify the results of this paper, analyses on high-rise mega-braced frame core buildings were carried out to illustrate that optimal stiffness and strength combined are produced by such systems (Brunesi *et al.* 2016). Analyses in the present paper also show that mega-braces provide the buildings with high strength and stiffness, such that the designed frame sections become very smaller. A fair amount of work in earthquake engineering deals with new methods for designing tall buildings namely resilience-based earthquake design. Refined finite element models and simplified models for the design of super tall mega-braced frame-core buildings were proposed recently (Lu *et al*. 2016).

The diagonal elements, with certain degrees of obliqueness, could carry gravity loads in addition to the lateral loads. Therefore there would be no need for any vertical column in this system which is called the diagrid system. In an evaluation of the seismic performance of diagrid system, it was shown that the diagrid structures have higher overstrength with smaller ductility in comparison with the tubular structure. The results also showed that increase in the slope of braces would be followed by the shear lag effect increase and decrease in the lateral strength. The diagonal members then were replaced by buckling-restrained braces, and it turned out that the ductility and strength of the diagrid structure increase significantly by this replacement (Kim and Lee 2010).

In this paper also, the diagonal members in the mega-scale bracing system were replaced by buckling-restrained braces and the result showed significantly increased strength and stiffness.

A good approach to the design of diagrid structures is also of significant importance. For preliminary design and member size determination of diagrid structures, a simple methodology has been proposed which could be applied to 20-60 story buildings (Moon *et al*. 2007). Further studies have been conducted on sustainable design of diagrids which could prove useful for saving structural material and cost (Moon 2012). Needless to say that choosing optimal angle of diagonal members plays an important role in meeting both static and dynamic needs, which has been the subject of many studies (Lee *et al*. 2010).

In this paper the braces carry lateral loads only and span over 4 bays and 4 stories each.

2.2 BRB

2.2.1 Shape and concept

A buckling-restrained brace (BRB) consists of a steel plate as its core which is responsible for resisting axial forces, a restraining member that covers the core plate to prevent flexural buckling, encasing mortar and the two non-yielding ends. To avoid undue friction forces from the core to the restraining member, some unbounded material (mortar or concrete) or a clearance is left between the two. (The unbonded material, commonly referred to as the filler is usually concrete or mortar or grout, however other fillers could be used.) As a result, the BRB can provide an almost equal yield axial force in tension and compression, and balanced hysteretic behavior (Midorikawa *et al*. 2012).

Fig. 1 Mega-scale bracing at leadenhall building in london, opened in 2014 (Levene 2014)

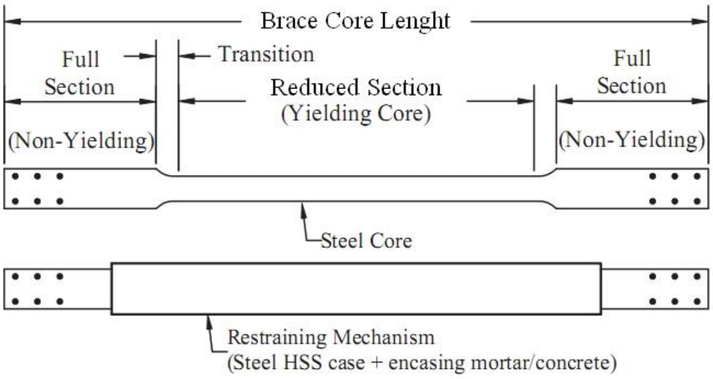

Fig. 2 Schema of a typical buckling-restrained brace (Bazaez and Dusicka 2016)

2.2.2 BRB usage in structures

Owing to some structural performance superiority over conventional braced frames, the BRB frame (BRBF) system seems to be acquiring recognition. In comparison with other available seismic load resisting systems, BRBs have numerous advantages such as easy post-earthquake replacement (if needed), forestalling damages in other structural members, easy assembly and comparatively low cost construction, and simple end connection details.

To evaluate the efficacy and functionality of different types of BRBs and to contribute to the progress of them, many numerical and experimental studies have been conducted so far.

In a very recent study, sequence of hinge formations, inter story drift, residual drift, and also the effect of different bracing configurations were some of the main parameters investigated to help decide upon the performance of buckling-restrained braced frames under near-field earthquakes; the results suggested that new provisions should be provided for the design of BRB frames under near-field motions. It was also found that chevron bracing exhibits brittle behavior and causes extreme collapse of the building when undergoing near-field motion and that chevron bracing experiences many more hinges compared to other types of bracings (Ghowsi and Sahoo 2015). Mega-scale bracing was not investigated in that study.

The effect of beam-column connections was also investigated analytically in another study, And the results suggested that for both pinned and connections, higher values of response reduction factor should be used (Ghowsi and Sahoo 2013). Stability of buckling-restrained braces and their joints was evaluated and it was concluded that joints should have sufficient restrained stiffness, otherwise the unrestrained part of the BRB will buckle unwantedly and prior to the other segments, resulting into a major decrease in the ultimate load bearing of the brace and the maximum compression load would be cut down to almost 65% of maximum tension load (Jia *et al*. 2010).

Three full scale steel braced frames, two of them equipped with two different BRBs and the last one with special concentric brace were tested in Taiwan. And their results showed that both of the systems perform satisfactorily enough in 3 story, single bay frame, however the BRB system excelled marginally in terms of inter-story drift (Tsai *et al*. 2014). The mentioned study is an experimental proof of the authenticity and reliability of this paper. The results also show that both concentrically braced building and buckling-restrained braced building perform satisfactorily, however the BRB building offers better performance. In an analytical study, ductility demands of

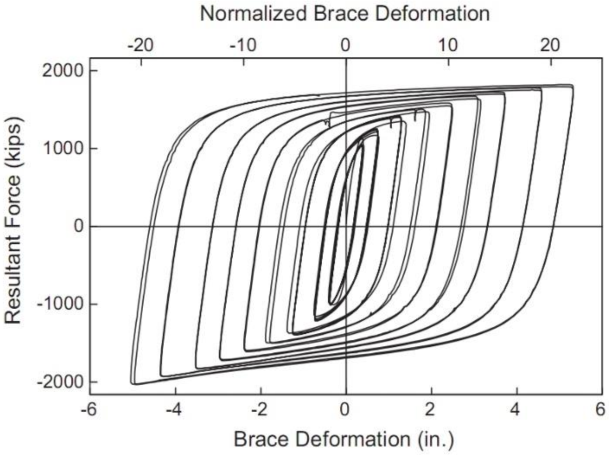

Fig. 3 Balanced cyclic behavior of a typical BRB (Newell *et al.* 2006)

BRBFs were estimated, which is key parameter in performance-based design of BRBFs, and then the results were compared to BRBF recommended provisions that required the ductility demand at 7.5, but the test resulted in ductility demands as high as 20 to 25 (Fahnestock *et al*. 2003). A very recent study compared BRBF to a newer proposed system called yielding brace system by the means of probabilistic assessment only to show that BRBF can meet the expectations (Veismoradi *et al.* 2016). Out-of-plane stability of BRBs and A simple prediction method for the BRB’s capacity of energy dissipation under random loadings was proposed earlier (Takeuchi *et al.* 2008, 2013). Experimental studies were conducted on the buckling prevention condition of BRBs (Usami *et al.* 2008, 2009). Experimental investigations were carried out on finding a way to lighten BRBs which lead to reducing the length of the middle segment of BRB (Tabatabaei *et al*. 2014). Several new shapes for BRBs were developed recently with different configurations and different functionality. Such as perforated core BRB with a partially emptied steel plate as its core (Piedrafita *et al*. 2015). And all new steel BRBs and also constitutive models for their response predictions (Piedrafita *et al*. 2015).

BRBF systems are now employed as chief lateral force resisting elements in new construction and also in seismic retrofit projects. New studies are being carried on to promote the design of BRBs.

A method for preliminary performance-based seismic design of low rise structures equipped with BRB frames was proposed very recently (Guerrero *et al.* 2016). By obtaining design base shear from energy-work balance a new performance-based plastic design was proposed for BRBFs (Sahoo and Chao 2010). In another study which is in agreement with the present paper, an energy-based method was proposed for the design of BRBs to strengthen RC frames. The test and analysis results of the designed frame proved that BRBs caused a major increase in stiffness, lateral force capacity and energy dissipation (Khampanit *et al*. 2014). Some other means and methods for modeling and design of BRBFs were presented recently, such as artificial intelligence methods which can improve modeling accuracy, numerical and finite element models, and also hysteretic energy spectrum design, and methods obtained from modifying existing provisions which can become handy since some codes and provisions lack BRB design regulations (Bosco *et al.* 2015, Assaleh *et al*. 2015, Choi and Kim 2006, López-Almansa *et al.* 2012). There are also recent researches concerning seismic response of buckling-restrained braced structures including soil-structure interactions (Flogeras and Papagiannopoulos 2017). In order to retrofit existing reinforced concrete buildings, an equivalent linearization based method was proposed which could serve to design the required amount of BRB and elastic steel frames capacity (Sutcu *et al.* 2014). An experimental investigation was conducted very recently on seismic performance of reinforced concrete frames retrofitted with eccentric buckling-restrained braces (Yang *et al.* 2017). Seismic demands of different configuration of BRBs was evaluated recently in a probabilistic approach, and results showed that inverted chevron BRB possesses the largest capacity among the other types (Asgarian *et al.* 2016). Precise analysis and brace sizing can result to substantial increase in damping without an unendurable decrease in building period. The stable behavior of these systems, thanks to the elimination of the buckling of the BRB makes these frames favored option for a variety of applications in high seismic regions.

These systems are totally practical and need no extra expertise.

3. Modeling and analysis

In this study a commercial steel building with 20 stories was considered. The building was assumed to have 4 bays in each horizontal direction with constant spacing of 5 meters, see Fig. 4.

The first 4 stories were designed to be parking lot with a height of 3 meters. The next 4 stories were considered to be main commercial floors with a height of 4 meters and the rest of the stories had a constant height of 3.5 meters.

The building was assumed to be located on soil type II (of Iranian standard 2800 for seismic resistant design of buildings, equal to site class C) and in a very high seismically active zone with a PGA equal to 0.35 g. Moment resisting frames and bracings formed the building’s lateral load resisting dual system. Ceiling system was a one-way slab and intermediate ductility was the assumed behavior. Lateral loads were determined according to 2800 standard and the structural members were designed according to the AISC 360-10 requirements. At first the building with mega-scale bracing was designed according to the mentioned provisions, then the braces were replaced with BRB and the building was designed again, and finally the braces were arranged in one bay in the conventional manner. But this lateral load resisting system could not meet the Iranian standard 2800 requirements, so the braces were doubled and rearranged in two bays. All designed sections meet a demand to capacity ratio of 0.9., so the member sizes wouldn’t be included here because of the large number of the members. Then external frames A of all buildings were extracted for push-over analysis and were redesigned to have exactly the same weight. The three buildings and the three frames were analyzed and results are as follows in the next chapter. The frame A of each building is shown in Fig. 5.

The computer program SAP2000 version 14 was used for the analyses. The correct and accurate functionality of the program was verified through comparing the results obtained by the program and the result available from modal pushover curves for SAC-Los Angeles three-story building. The software’s modeling, analysis and design procedures in general are as follows:

First, the projects geometry was drawn through the new model initialization window and draw tools.

Then using Define menu, the materials property and potential frame sections were defined. Mass source and seismic weight parameters were set. Diaphragm constraints and load patterns such as dead, live and seismic load patterns were also defined using the same menu.

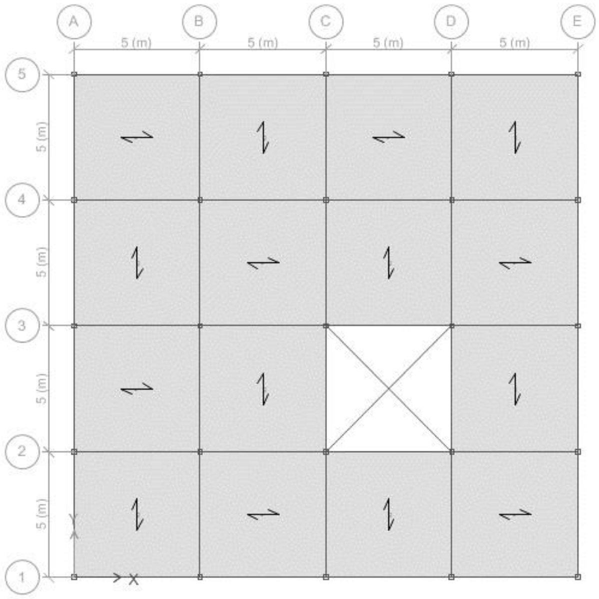

Fig. 4 Plan of the buildings

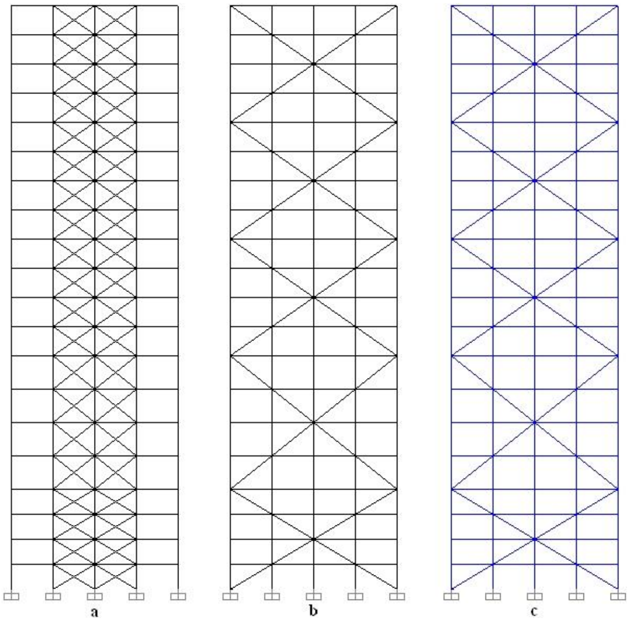

Fig. 5 Analyzed models: (a) Conventional X-type braced frame (CBF), (b) Mega-scale braced frame (MSB) and (c) Mega-scale BRB frame (MSBRB)

Table 1 Material properties

Mass per unit volume	0.785	Coefficient of Thermal Expansion	1.17*10^-5
Weight per unit volume	7.85	Minimum Yield Stress	24000
Modulus of Elasticity	21000000	Minimum Tensile Strenght	37000
Poisson's Ratio	0.3		

Appropriate functions were then introduced to the program. Load cases were built later, which included static and dynamic linear and nonlinear cases. Load combinations were also defined for later use in the buildings' design.

Finally parameter setting for modal push-over analysis were also carried out and the model was ready for the analyses.

There are some previous researches by the authors about different types of analyses (Mazloom 2007, 2008).

The design code provisions were then introduced and set using design menu. Then the design phase started including trial and error and iterative steps and repeated analyses. Then the results came out through the display menu.

For BRB modeling it is needed to provide the diagonal members with the power to withstand buckling. To do so the unbraced length ratio of the braces was assumed to be near zero so the braces wouldn't buckle. To consider the additional axial stiffness of the buckling-restrained braces, the cross-section (axial) area of the braces were multiplied by 1.2 – 1.5, and to consider the additional concrete weight, the weight of the braces were multiplied by 5 – 7. The multiplication numbers were derived from calculations based on the mechanical properties of the braces.

Material properties data are as shown in Table 1. (All the units are tonf-m)

4. Results and discussion

In this section the parameters considered for comparison between the buildings and the frames are presented and are followed by discussions about the results.

The results are obtained from nonlinear analyses which are totally consistent with the linear dynamic analysis results and are as follows:

4.1 Lateral displacement

The lateral displacements of the three buildings are shown in Fig. 6. As shown in the figure, the BRB and MSB buildings behave very close to each other with a maximum difference of 15% at the third story in favor of the BRBF.

But the CBF system experiences more lateral displacement than the MSB system and the gap is a whopping percentage of 38 which occurs at the roof of the buildings and a minimum difference of 6% occurs at the second floor. The MSB system is to praise for the relatively small lateral displacement, in spite of smaller number of braces. The lateral displacement of the CBF model increases considerably in the higher stories in a nonlinear way. However, the change in the curves of the BRB and MSB models is almost linear which bestows upon the building a more secure behavior in a seismic event.

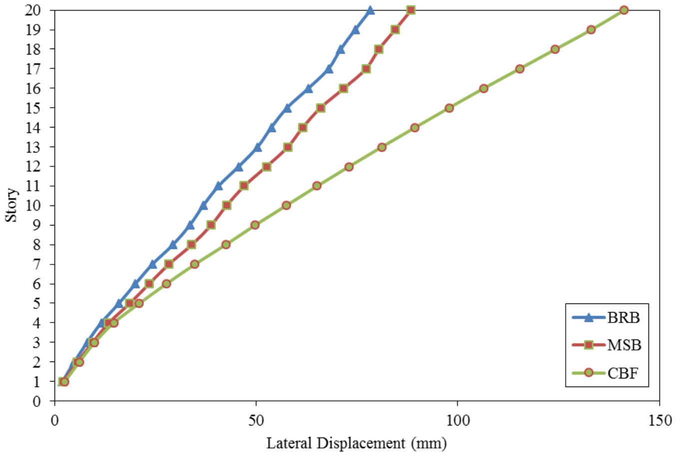

Fig. 6 Lateral displacement of the models

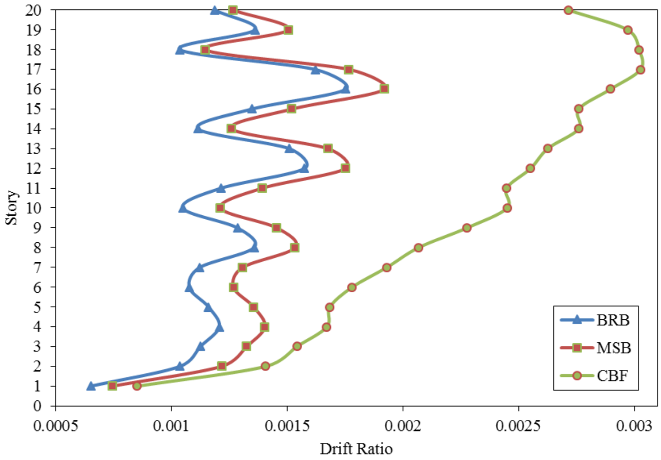

Fig. 7 Drift ratios of the models

4.2 Drift ratio

Drift ratio curves of the different models are presented in Fig. 7.

As shown in this figure the CBF system shows much more story drift and the maximum difference from the MSB systems is seen at the 18th floor which is about 63%, and the minimum is 13% at the first story. Maximum and minimum differences between the BRB and MSB models happen at the third and the last stories respectively for 16% and 7% which credits the BRBF. Again the mega-scale bracing system is to be accredited for the low drift ratio. There is a significant difference between the drift ratios of the first and stories of the CBF building. However in the other two models, the difference in the drift ratios of the stories is almost negligible. As a result, the lateral displacements of higher stories in the two mentioned buildings will always stay in the approved ranges.

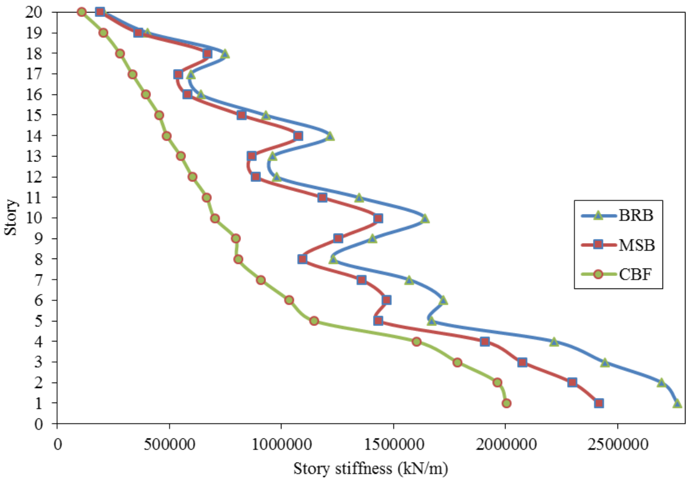

Fig. 8 Stiffness of the stories of the models

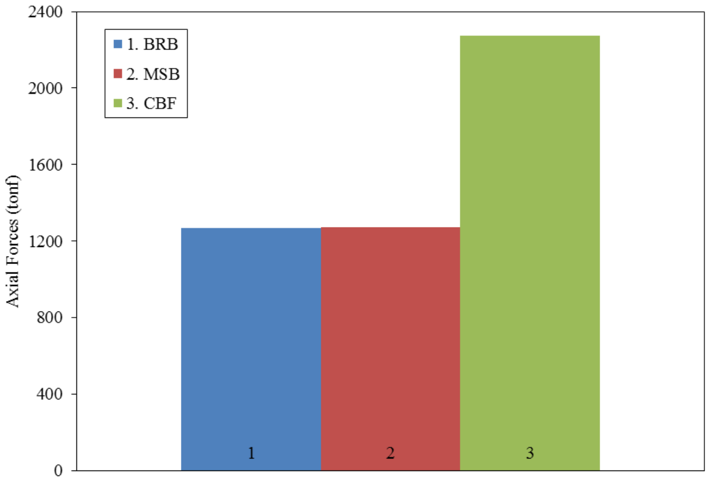

Fig. 9 Summation of the uplift forces in the models

4.3 Story stiffness

As shown in Fig. 8, the MSB system increases the stiffness of the stories significantly. This increased stiffness causes the lateral displacements of the BRB and MSB models to be very low in comparison with the CBF model. The maximum difference between the CBF and MSB systems is seen at the 18th story where the CBF presents half of the stiffness of the MSB model, and the minimum difference occurs at the third floor for 16%. Again the BRBF performs in a range of 6-17% better than the MSB system.

4.4 Uplift forces

Uplift forces, which are the tensile forces produced in a buildings foundations during an earthquake event, is one of the disadvantages of the bracing systems. The braces that are working in tension, transfer the tensile forces to the columns. As a result, the columns tend to move upwards and away from the foundation. Uplift forces, if in great amount, can be very detrimental to the stability of the structure. As shown in Fig. 9. The difference in terms of uplift forces between the models are considerable. The MSB model experiences 45% smaller uplift forces than the CBF model, and the difference between the BRB model and the MSB model is about 1%. This means the mega-scale bracing, if equipped with buckling-restrained or not, changes the amount and patterns of tensile force transfer from braces to columns substantially.

4.5 Story shear absorption

Lateral earthquake forces acting horizontally on the base of the buildings are called base shear. The base shear is distributed between the stories which is called story shear. Story shear is applied at the center of mass of each story. Lateral load resisting systems of each story are responsible to absorb the shear forces. Story shear forces are divided between the lateral load resisting systems on the basis of each system’s stiffness. As a result, the stiffer a lateral load resisting system is, the more shear force it absorbs.

The buildings analyzed in this paper, use dual systems for standing against lateral loads. The systems are moment frame system and bracing system. The percentage of the story shear absorbed by each system is calculated for all buildings and presented in Figs. 10-12. The sum of the shear absorption percentage of the systems in each story is equal to 100% which means the whole story shear.

As shown in Fig. 10, in some stories in the CBF building moment frames carry considerable lateral loads. The maximum shear absorption percentage by moment frames is seen in the 3rd story which is 43%. The correspondent number for the braces in that story is 57%. The fairly large amount of load carried by moment frames might lead to plastic hinge development in the columns which is an adverse happening.

In the last two stories of the CBF building, the braces almost carry all the lateral loads. Mega-scale bracing increases the stiffness of the bracing system significantly. As shown in Fig. 11 moment frames carry less lateral loads compared to the CBF model. The maximum shear load the moments frames absorb in the MSB building is 27% of the story shear which is noticeably smaller a number than 43% of the CBF model. Plastic hinges are expected to develop in the braces of a building.

As a result, the collapse of the building would be avoided. Unlike the plastic hinge development in the columns which could result in collapse of the building.

High energy dissipation and high stiffness are some of the main advantages of buckling-restrained braces. It was shown in Fig. 8 that the BRB model has better stiffness than the other two. The results here also approve the claim that buckling-restrained braces are stiffer and more stable than other braces. As shown in Fig. 12 buckling-restrained braces absorb more shear force than the other braces and subsequently the moment frames carry less loads. The maximum shear force absorbed by moment frames is almost 25 percentage of the story shear and most of the energy is dissipated by the buckling-restrained braces as expected and as verified by the numerous studies cited earlier.

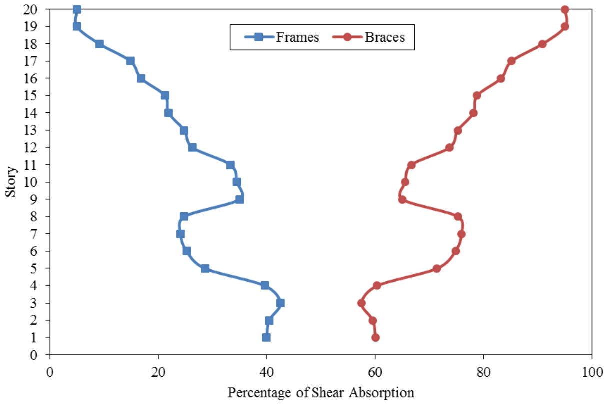

Fig. 10 Shear absorption percentage of lateral load resisting systems in the CBF building

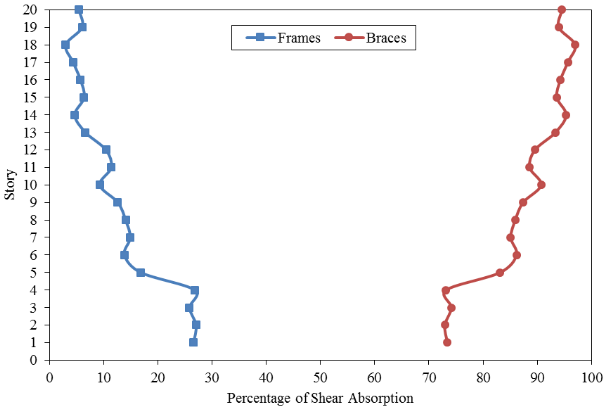

Fig. 11 Shear absorption percentage of lateral load resisting systems in the MSB building

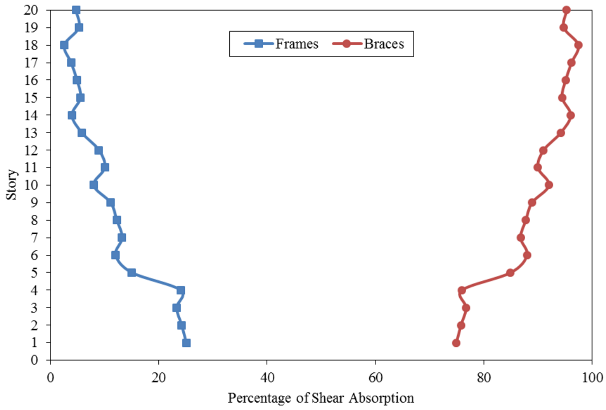

Fig. 12 Shear absorption percentage of lateral load resisting systems in the BRB building

Table 2 Percentage of shear absorption by frames in all models

Model Story	BRB	MSB	CBF
20	4.6	5.4	4.9
19	5.2	6	5
18	2.5	3	9.1
17	3.7	4.3	14.8
16	4.8	5.7	16.8
15	5.5	6.4	21.2
14	3.9	4.6	21.9
13	5.7	6.6	24.7
12	8.9	10.4	26.3
11	9.9	11.4	33.3
10	7.9	9.2	34.4
9	11	12.6	35
8	12.2	14	24.7
7	13.2	14.9	24
6	12	13.8	25.2
5	15	16.8	28.6
4	24	26.8	39.6
3	23.2	25.8	43
2	24.2	27	40.4
1	25	26.6	39.9

For a better comparison between the capacities of shear absorption of the systems in all buildings, the values of their percentages of shear absorption are presented in Tables 2 and 3. The numbers in each column of the tables are percentages and equal 100 percent if added to the corresponding number in the other table.

The average shear force absorbed by the frames in the BRB building is 11.12%, that number in the MSB building is 12.56%, but the frames in the CBF building absorb twice bigger shear forces than the MSB building, as they average 25.64% in different stories.

Table 2 presents the percentages of shear absorption by frames in all models. As shown in this table, the most noticeable difference between the models occurs in stories 13 to 18. In the mentioned stories, the frames in the CBF system carry 3 to 4 times more load than the frames in the other systems.

The average shear force absorbed by the frames in the BRB building is 11.12%, that number in the MSB building is 12.56%, but the frames in the CBF building absorb twice bigger shear forces than the MSB building, as they average 25.64% in different stories.

Table 3 presents percentages of shear absorption by braces in all models. The maximum difference is seen in stories 9 to 11. In these stories mega-scale braces carry 30 to 40 percent more load than the braces in the CBF building.

The average shear force absorbed by buckling-restrained braces in different stories is 88.9%, and it is 87.4% by mega-scale braces and 74.36% by X-type braces.

Table 3 Percentage of shear absorption by braces in all models

Model Story	BRB	MSB	CBF
20	95.4	94.6	95.1
19	94.8	94	95
18	97.5	97	90.9
17	96.3	95.7	85.2
16	95.2	94.3	83.2
15	94.5	93.6	78.8
14	96.1	95.4	78.1
13	94.3	93.4	75.3
12	91.1	89.6	73.7
11	90.1	88.6	66.7
10	92.1	90.8	65.6
9	89	87.4	65
8	87.8	86	75.3
7	86.8	85.1	76
6	88	86.2	74.8
5	85	83.2	71.4
4	76	73.2	60.4
3	76.8	74.2	57
2	75.8	73	59.6
1	75	73.4	60.1

4.6 Push-over analysis

ASCE/SEI 41-13 is the code used in the analysis. Capacity curves of the models are presented in Fig. 13. As shown in this figure the BRBF has the maximum ultimate load bearing capacity which is about 18% more than that of the MSB system and the MSB system stands 44% better than the CBF system when it comes to ultimate load bearing capacity. After the linear phase all models experience a fast drop in the capacity. BRB model’s capacity drops for 29%, MSB model for 27% and the CBF model has the least drop which is about 15%. The reason of the big drops of the first two models is because of the fewer number of braces on them.

4.7 Economical investigation

Economical justification is an indispensable aspect of any new theory or method in construction. And the mega-scale bracing and the mega-scale buckling restrained bracing systems prove to be superior to other systems in terms of economy. Apart from the better seismic performance, the MSB building consumed more than 200 tons less steel compared to the CBF system; which is 25% cut on the weight of the steel used in the CBF building. Moreover, MSB general construction expenses would be cut down even more than 25%. One of the reasons is that the number of braces in the MSB system is half of that in the CBF system. Furthermore, unlike the X-type braces, there are no connections between the braces in the Mega-scale bracing. So there would be no connection cost in mega-scale braces. The X-type braces are usually hidden in the walls of the completed building. However, the mega-scale braces are usually constructed

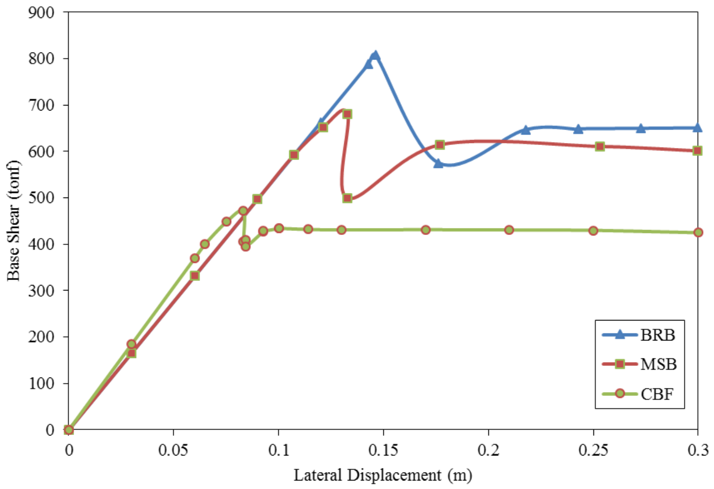

Fig. 13 Modal push-over analysis results

externally on the face of the building. They impart modernization to the appearance of the building and simultaneously trim the cost of the peripheral walls. There should be noted that the mentioned qualities shorten the time of the construction substantially. Therefore, the workplace expenditure would be cut down. The BRB building consumed 30 tons less steel than the MSB building. Therefore buckling restrained braces offer at least another 3% cost savings.

5. Conclusions

The conclusions made out of this study are as follows:

- Mega-scale bracing system decreases the lateral displacement of the building for 6% to 38% in different stories compared to the conventionally X-type braced building. Mega-scale buckling-restrained braces decrease lateral displacement for 10% to 15% compared to mega-scale braced building and 20% to 45% compared to the X-type braced frame.
- Drift ratios in the different stories of mega-scale braced building are 13% to 63% smaller compared to the X-type braced model, and drift ratios in the stories of mega-scale buckling-restrained building are smaller compared to mega-scale braced building and X-type braced building for 7% to 16%, and 24% to 66% respectively.
- Stiffness of the stories is increased up to 140% in the Mega-scale braced building compared to the X-type braces. Mega-scale buckling-restrained braces also increase the stiffness for 6% to 17% compared to mega-scale braces and for 36% to 167% compared to the X-type braced model.
- Mega-scale braces decrease the uplift forces for 45% compared to the conventional X-type braces, and mega-scale buckling-restrained braces act just like mega-scale braces in this case.
- X-type braces absorb 57% to 95% of shear forces in different stories. Mega-scale braces absorb 73% to 97% of shear forces in different stories. Buckling-restrained braces absorb

75% to 97% of shear forces in different stories.

- Mega-scale buckling-restrained frame presents 18% more load-bearing capacity than mega-scale braced frame and 70% more than the conventional X-type braced frame. Mega-scale braced frame has 44% more load-bearing capacity than the X-type braced frame.
- Mega-scale buckling-restrained building and Mega-scale braced building consume 230 and 200 tons of steel less than the X-type braced building. The cost-saving would be at least 25% to 30%.

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