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Structures with Added Buckling Restrained Brace Elements

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ABSTRACT: The number of high rise building has increased significantly as supporting infrastructure in many big cities in Indonesia. Most of the high rise buildings in Indonesia are constructed using reinforced concrete (r/c) moment resisting frame systems. However, due to the high seismicity of many of the regions of Indonesia, the use of moment resisting frames as single system, especially for tall buildings, are restricted. This structural system is in general quite flexible, and therefore excessive lateral drifts are experienced under seismic forces. In practice, adding buckling restrained brace (BRB) can be used to limit the lateral drift in high rise buildings. The objective of this paper is to present a study on the use of BRB elements in high rise r/c frame buildings to evaluate their seismic performance. In this paper, a 20 story office building located in a high seismicity region is modeled into two basic distinctions, i.e. building with BRB and without BRB. The adopted system of BRB is UBB (Unbonded Brace) type. The seismic response of the buildings is obtained by conducting non-linear time history analysis with seven scaled ground motions. Then, the performance of these buildings are evaluated and compared. Based on the findings, some recommendations are proposed for the use of BRB in the design of high rise r/c frame buildings located in regions with high seismicity.

KEYWORDS: *ductility, non-linear time history analysis, performance based design*

1 INTRODUCTION

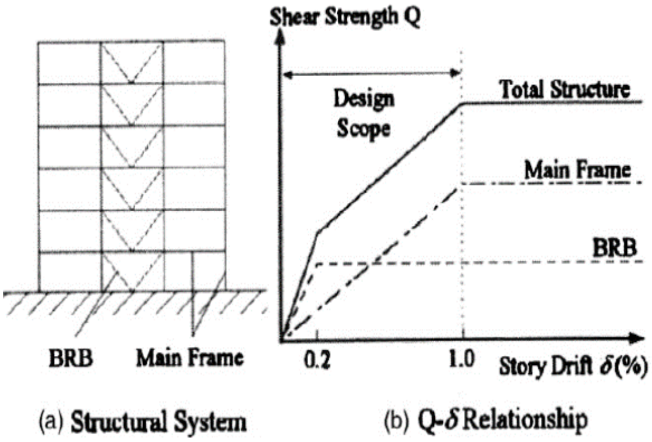
Conventional earthquake resistant structural systems depend on the strength and ductility to control seismic response. In these systems, seismic energy is absorbed by formation of plastic hinges in specific locations that allow the structure to deform into an inelastic range without substantially degrading the strength and stiffness of the structure. This design principle, however, may cause damages to structural and non-structural components which may not be economical to repair. As an alternative, a new strategy named damaged-controlled structure has been proposed (Fig. 1). Damaged-controlled structures in principle consists of an integrated structural system as a combination of two different structures: the primary structure, which is composed of beams and columns, and is designed to resist the service gravity load, and the secondary system, also referred to as the energy dissipating or damage-controlling system, which is designed to control the effects of lateral forces and deformations resulting from an earthquake. The primary structure is designed to behave elastically and to retain its building service functions even during a severe earthquake ground motion, while the secondary system can be repaired or replaced after a severe earthquake takes place.

Damage-controlling systems can be used to limit the lateral drift in high rise buildings. An example of such a system is the incorporation of buckling restrained brace (BRB) elements. This paper presents a study on the use of BRB elements in high rise reinforced concrete (r/c) frame buildings. The performance of the buildings with BRB and without BRB will be evaluated and compared. Based on the findings, some recommendations are proposed for the use of BRB in the design of high rise r/c frame buildings located in regions with high seismicity.

2 BUCKLING RESTRAINED BRACED FRAMES: UNBONDED BRACE

Buckling restrained brace (BRB) is a passive vibration control device that has been used widely in seismic design and retrofitting of buildings and bridges especially in Japan and the United States. In Japan, the BRB is developed based on the concept of damage-controlled structure (Wada & Iwata, 1998).

The seismic performance of conventional braced frames is limited due to the difference in behavior between the tensile and compression capacity, and degradation of tensile capacity under compressive and cyclic loading. The BRB system is developed to avoid the drawbacks of conventional brace system (Fig. 2). Research and development have demonstrated that it is possible to achieve ideal behavior of elastoplastic yielding through metallic yielding while restraining buckling in compression by an external mechanism. This can be achieved by enclosing a ductile metal core in a continuous concrete filled steel tube (Fig. 2). By appropriately selecting the strength of material, the area and length of the portion of the metallic core, the longitudinal deformation of the central yielding core can be controlled and made independent from the mechanisms that restrain lateral and local buckling. As a result, the local buckling behavior is restrained and large inelastic capacities are attainable (Watanabe, 1988; Black, Makris, & Aiken, 2004). This is the main principle of BRB. Figure 3 is an example of test results of Unbounded Braced (UBB), that shows hysteresis loops in tension and compression having equal strength and stiffness in the pre- and post-yield ranges. The results highlight the non-buckling and equal strength performance of BRB.



(a) Structural System (b) Q-δ Relationship

Figure 1 Main concept of damage-controlled design (Wada & Iwata, 1998)

Since introduced in 1980s, BRBs are regarded as dampers and have become viable means of enhancing the seismic performance of buildings and bridges in Japan. The use of BRB has been specified in the Japan Society of Seismic Isolation (JSSI) Manual for Design and Construction of Passively-Controlled Buildings in 2005. In the US, BRBs have been code regulated since the release of NEHRP Recommended Provision for Seismic Regulations for New Buildings and Other Structures (FEMA 450-1) in 2003. Application of BRB for new buildings in Japan has increased significantly since the 1995 Kobe earthquake (Kasai, 2008). Whereas for existing buildings, BRB has been used for seismic retrofit and to increase seismic capacity of existing buildings. not only for steel structures but also for r/c buildings (Sutcu, Takeuchi, & Matsui, 2014; Di Sarno & Manfredi, 2010).

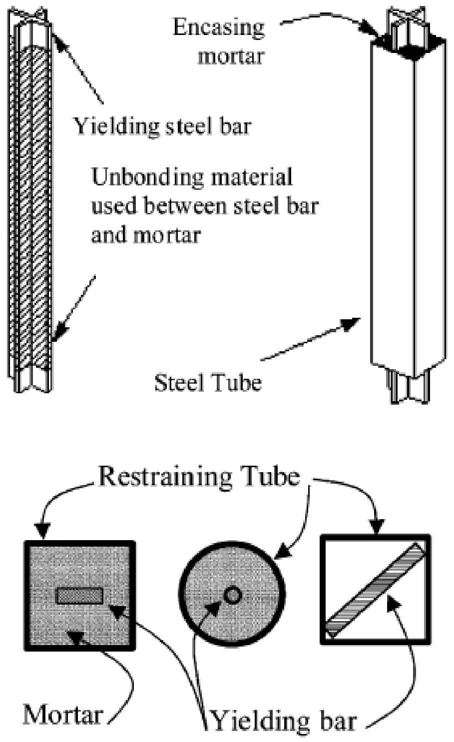


Figure 2 Schematic diagram of BRB and some cross-sections used

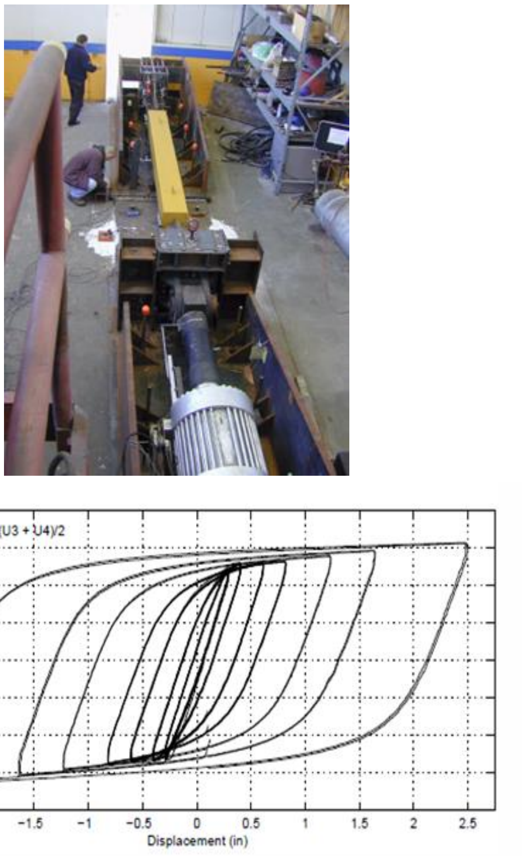


Figure 3 Test results of BRB (Unbounded Braced) showing equal strength in tension and compression (Black, Makris, & Aiken, 2004)

3 CASE STUDY OF SELECTED BUILDINGS

In this paper, a 20 story building located in a region with high seismicity was designed (Fig. 4). All of the stories are 4 m in height. The total length of the building is 30 m long in the north-south (N-S) direction and in the east-west (E-W) direction which divide into 5 typical bays. The typical bays are 6 m long in the north-south (N-S) direction and in the east-west (E-W) direction. The location of this study was Jakarta, Indonesia with soft soil site classification. As Jakarta is classified as a high-seismic region, the primary system shall consider special moment resisting frame design. Hence, the lateral force resistant elements consist of beams, columns, and joints. The slab was designed with gravity loads only using one-way slab system. It was assumed that the diaphragm is rigid. The compressive strengths of concrete, fc', are 30 MPa for the columns and 25 MPa for the beams and the slab. The yield strength of the reinforcement bars, fy, is 400 MPa. The structural basic configuration was defined based on preliminary process using gravity loads only, which are defined based on the building's function. The structural design follows SNI 2847-2013 for r/c special moment resisting frame systems using a response modification factor, R, of 8. The building is classified in II Risk Category, therefore, the lateral drift limit is 2%.

Initially, non-linear dynamic time history analyses (NLTHA) were conducted to obtain the building response as single structural system. Seven scaled ground motions were used for the initial analyses. Based on the initial analyses, it was observed that the single structural system building maintains adequate performance level (i.e. Life Safety), however, it experiences large lateral drifts (Fig. 5). Using a single structural system in high-rise building incites inherent flexibility which is causing the excessive lateral drifts under seismic forces. It is understandable that in practice dual systems are commonly used for high-rise building systems.

To limit the lateral drift in the building assessed in this study, BRBs were added in certain locations in the moment resisting frames. The installment of BRB was varied to analyze the effectivity of vertical addition and the effectivity of expanding the bracing core's area. Therefore, analyses were conducted on several alternative models:

1. Building without BRB
2. Building with BRBs,
   a. BRBs applied in Level 1 to Level 10
   b. BRBs applied in Level 1 to Level 14
   c. BRBs applied in Level 1 to Level 10 with doubled core area

There are several controlled beams and columns for analyzing the results, i.e. for beams: B2, B4, and B5; for columns: K3 and K5. See Figure 4.

4 DESIGN OF BUCKLING RESTRAINED BRACES

The type of BRB for this paper is single diagonal type (Fig. 6). There are four applied braces in each story with two pair braces resisting lateral drift for each direction. BRB's dimension was calculated in accordance to required additional story shear stiffness, K_a, for providing accepted lateral drift in each stories. The value of K_a is defined by subtracting the inelastic shear stiffness of the building without BRB and the targeted story shear stiffness which is equivalent to 2% drift limit. The inelastic story shear stiffness is estimated from multiplication of elastic story shear using targeted overstrength, Ω_o; for Special Moment Frame System the value is 3. In addition to include safety factor (design judgement), the modified required additional story stiffness, K_a', for this paper is 200.000 kN/m in each stories. The required additional story shear stiffness was then distributed to four braces in one story.

The axial stiffness, Kb, for single diagonal BRB is defined by following equation,

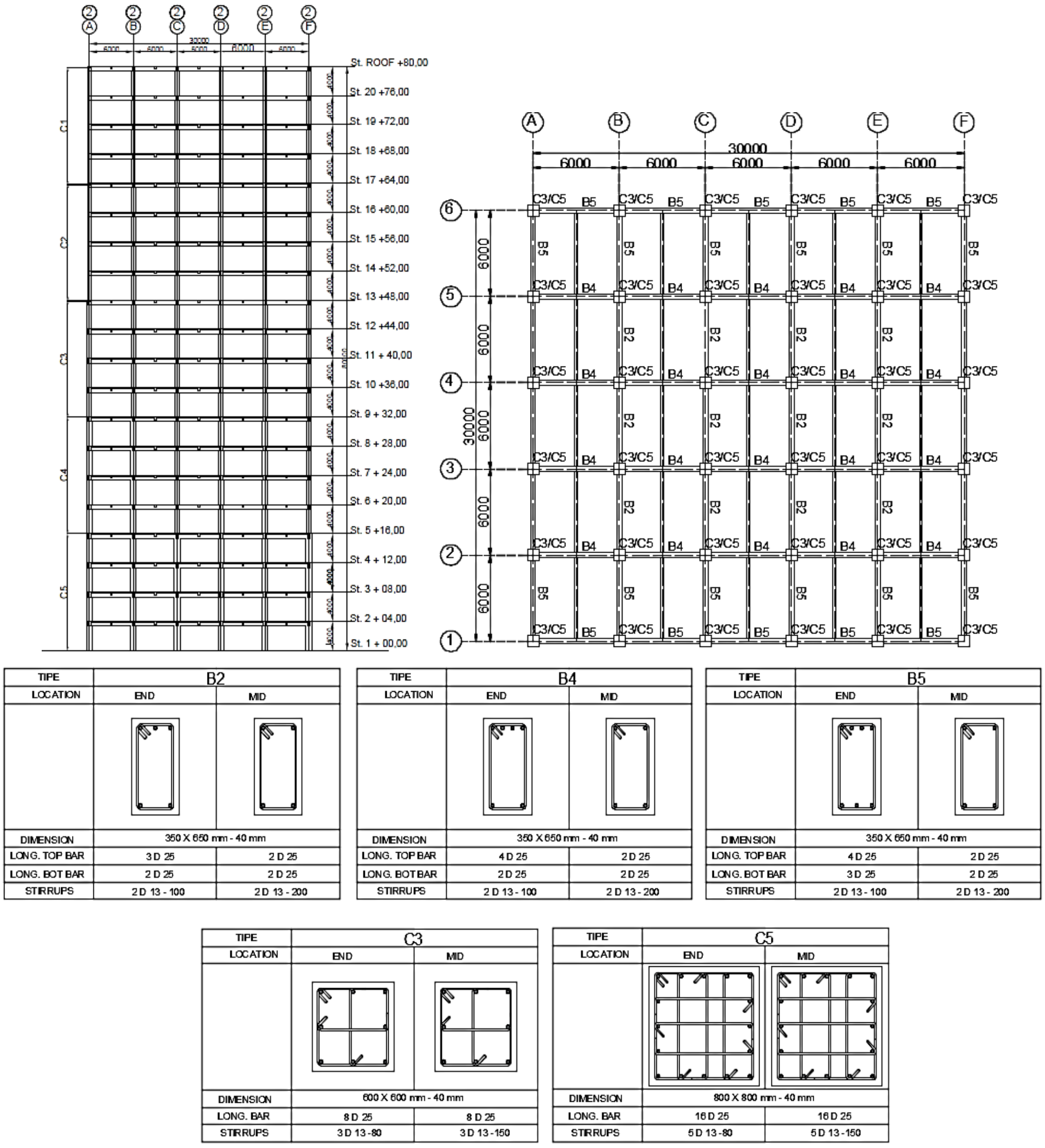
$$K_b = \frac{K_a'}{n\cos^2(\theta)} \tag{1}$$

where n is total number of applied BRB in one direction and θ is an angle between BRB and beam. For this study, the value of K_b is 144.928 kN/m.

Based on the required story shear stiffness and the axial stiffness, the core steel element is selected to be PL 16x200 mm using A36 and steel tube of BRB is 250x250x6 mm. This design property was applied for each case study model. See Figure 6.

5 PROPERTIES OF SELECTED GROUND MOTIONS

For performance-based analysis of specific high-rise structures, a design requires more complex dynamic nonlinear analysis using horizontal components of time-history. This study performed two dimensional NLTHA. According to SNI 1276-2012, ground motions should be selected with similar characteristic through magnitude value, type of fault, and epicentral distance of earthquakes events and be scaled to design seismic target. The design seismic criteria are developed based on level of hazard of 10% PE in 50 years – i.e. rare hazard. Probabilistic Seismic Hazard Analysis (PSHA) with design seismic target for Jakarta has already been conducted (Sengara, 2014). Jakarta is classified as a high seismic area in accordance to values of design spectral acceleration in 0.2 second, S_{ds}, and in 1.0 second, S_{d1}. The PSHA proposed seven selected strong-motion records to represent high seismicity of Jakarta. See Table 1.



TIPE	B2	
LOCATION	END	MID
DIMENSION	350 X 650 mm - 40 mm	
LONG. TOP BAR	3 D 25	2 D 25
LONG. BOT BAR	2 D 25	2 D 25
STIRRUPS	2 D 13 - 100	2 D 13 - 200

TIPE	B4	
LOCATION	END	MID
DIMENSION	350 X 650 mm - 40 mm	
LONG. TOP BAR	4 D 25	2 D 25
LONG. BOT BAR	2 D 25	2 D 25
STIRRUPS	2 D 13 - 100	2 D 13 - 200

TIPE	B5	
LOCATION	END	MID
DIMENSION	350 X 650 mm - 40 mm	
LONG. TOP BAR	4 D 25	2 D 25
LONG. BOT BAR	3 D 25	2 D 25
STIRRUPS	2 D 13 - 100	2 D 13 - 200

TIPE	C3	
LOCATION	END	MID
DIMENSION	600 X 600 mm - 40 mm	
LONG. BAR	8 D 25	8 D 25
STIRRUPS	3 D 13 -80	3 D 13 -150

TIPE	C5	
LOCATION	END	MID
DIMENSION	800 X 800 mm - 40 mm	
LONG. BAR	16 D 25	16 D 25
STIRRUPS	5 D 13 -80	5 D 13 -150

Figure 4 Structural Configuration and Controlled Beam/Column Reinforcement of Selected Building (Purba, 2016; SNI, 2013)

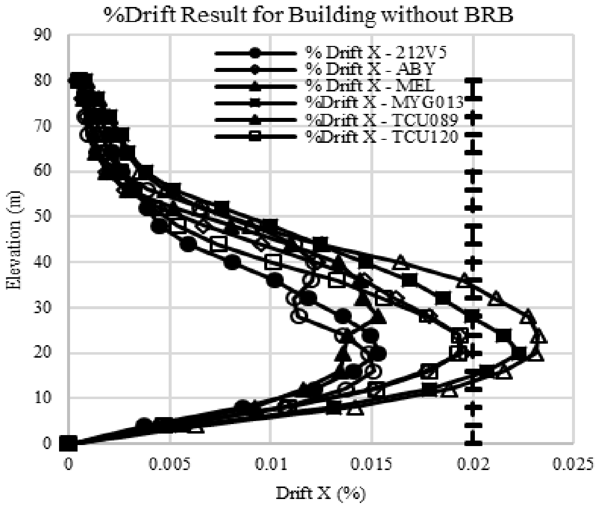


Figure 5 %Drift Result for Building without BRB – NLTHA Result

6 NONLINEAR MODEL USED IN NONLINEAR TIME HISTORY ANALYSIS

Earthquake-resistant building's principle introduces idea to not design structural elements elastically resist earthquake load. The idea allows design structural elements to perform its nonlinear behavior to dissipate the earthquake energy. Non-linear behavior is initiated after the yield condition is achieved, then, the structural elements will redistribute force through physical local hinge. The non-linear mechanism of steel is commonly presented in moment-deformation and the nonlinear mechanism of reinforced concrete is presented in moment-curvature graph.

In this paper, the hysteretic behavior for BRB nonlinear model used Kinematics Model (Fig. 7). This behavior is based upon kinematic hardening behavior that is commonly observed in ductile materials, such as steel, where enables a significance amount of energy dissipation (Prager, 1956; Ziegler, 1959). The hinge properties were assigned using a simplified bi-linear model. The maximum deformation for BRB is taken to be 3% of the effective length (Table 2). The hinge length, applied at both end nodes, is taken as 0.2 of the total length. The parameters of the level performance of BRB in this paper follows ASCE 41-13 where plastic deformation of BRB for Immediate Operation (IO) level is $3\delta_y$, for Life Safety (LS) level is $10\delta_y$, and for Collapse Prevention (CP) Level is $13.3\delta_y$.

The hysteretic behavior for r/c beams and columns non-linear model used Takeda Model (Fig. 8). This model demonstrates a degrading nonlinear strength in concrete due to increment of local deformation before failure (Takeda, Sozen, & Nielsen, 1970). For this paper, the non-linear model is defined based on ASCE 41-13 and is considered as flexure dominated elements. The hinge length, applied in two-end nodes, is taken as 0.05 of the total length (Deierlein, Reinhorn, & Willford, 2010).

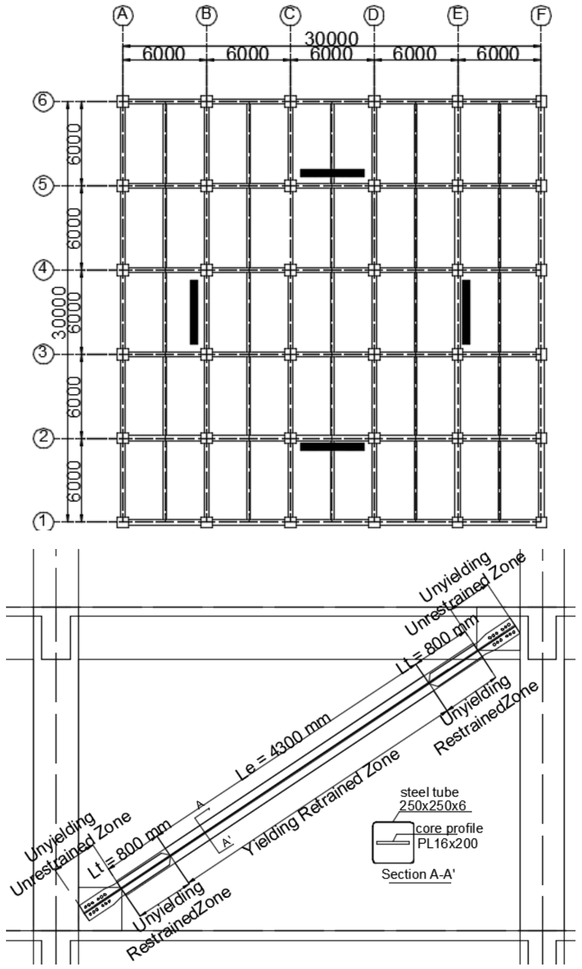


Figure 6 The Configuration of Single Diagonal BRB and Design of Single Diagonal BRB

Table 1 Selected Strong-Motion Records Associated with De-Aggregation Analysis

Earthquake	Station	Magnitude	Epicentral Distance (km)	Acceleration (g)	
				Maximum	Minimum
Tohoku	MYG013	9	170	-0.301	0.352
Sitka	212V5	7.68	42.85	-0.269	0.268
Chi - chi	TCU089	7.62	7.04	-0.300	0.275
Chi - chi	TCU 136	7.62	48.75	-0.291	0.293
Chi - chi	TCU120	7.62	25.57	-0.215	0.236
Landers	MEL	7.28	138.49	-0.306	0.308
Landers	ABY	7.28	75.2	-0.215	0.236

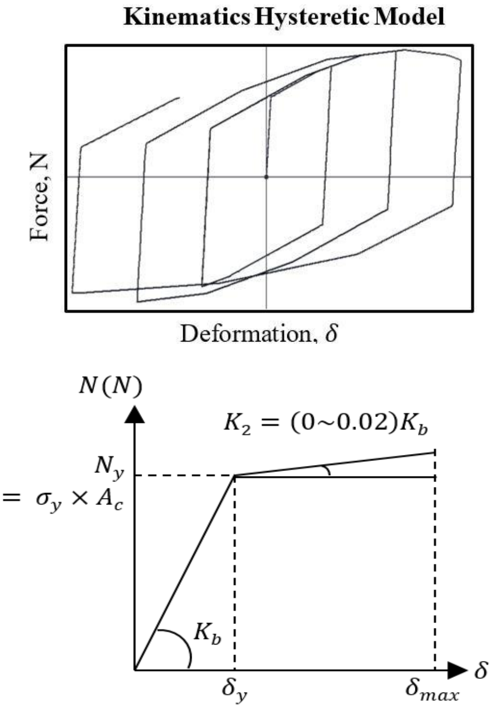


Figure 7 Kinematics Hysteretic Model and Simplified Bilinear for BRB Nonlinear Model

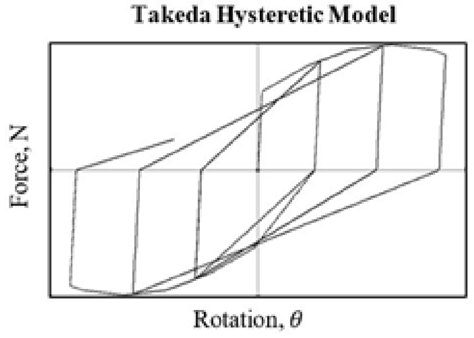


Figure 8 Kinematics Hysteretic Model and Simplified Bilinear for BRB Nonlinear Model

Table 2 Parameter of Nonlinear Properties for BRB PL16x200 and BRB Doubled Core Area

Parameter	BRB PL16x200	BRB Doubled Core Area
BRB Axial Stiffness, K_b (kN/m)	144927.54	289855.07
Core Area, A_c (mm2)	3200	6400
Young Modulus, E (GPa)	205	205
Yield Axial Force, N_y (kN)	768	1536
Yield Deformation, δ_y (m)	0.005	0.005
BRB Second Axial Stiffness, K_2 (kN/m)	2898.55	5797.10
Maximum Deformation, δ_{max} (%)	3.00%	3.00%

7 ANALYSIS RESULTS

7.1 *Total displacement*

Figure 9 shows maximum displacement of the buildings for several installment cases of BRB including building without BRB when subjected to ground motions with different accelerations. The reduction of displacement in buildings with BRB indicates that BRB significantly provides appropriate stiffness to maintain lateral displacement. Further evaluation of the two cases, i.e. lower-half stories (Level 1-10) and upper-half stories (Level 11-20), are discussed in this section.

Table 3 Total Displacement Result at Level 10

Earthquake Station	Without BRB (mm)	BRBs at Level 1-10		BRBs at Level 1-14		Doubled-core BRBs	
		Disp. (mm)	%	Disp. (mm)	%	Disp. (mm)	%
MYG013*	684.727	585.714	14.46	594.791	13.13	480.396	29.84
212V5	450.113	350.204	22.20	365.119	18.88	246.492	45.24
TCU089*	748.470	498.694	33.37	559.610	25.23	388.323	48.12
TCU136	478.327	283.611	40.71	309.278	35.34	234.837	50.90
TCU120	576.020	302.049	47.56	314.354	45.43	234.748	59.25
MEL	498.137	318.919	35.98	551.962	10.81	584.338	17.30
ABY	590.882	485.035	17.91	531.951	9.97	405.884	31.31
Average Reduction			**30.31**		**22.69**		**40.28**

* Earthquake stations that produced excessive lateral displacement for the building without BRB

Table 4 Total Displacement Result at Level 20

Earthquake Station	Without BRB (mm)	BRBs at Level 1-10		BRBs at Level 1-14		Doubled-core BRBs	
		Disp. (mm)	%	Disp. (mm)	%	Disp. (mm)	%
MYG013*	879.353	862.762	1.89	758.849	13.70	802.520	8.74
212V5	559.894	506.027	9.62	493.065	11.94	441.827	21.09
TCU089*	932.366	770.933	17.31	745.844	20.01	728.158	21.90
TCU136	630.276	442.048	29.86	422.532	32.96	447.336	29.03
TCU120	691.346	461.952	33.18	427.965	38.10	530.050	23.33
MEL	722.847	558.210	22.78	551.962	23.64	584.338	19.16
ABY	710.680	636.729	10.41	628.507	11.56	660.510	7.06
Average Reduction			**17.86**		**21.70**		**18.61**

* Earthquake stations that produced excessive lateral displacement for the building without BRB

Based on the results as shown in Figure 9 and Table 3, the addition of BRB reduces the displacement for lower-half stories of the buildings:

a. For the building with BRB in Level 1-10, seven analysis results show significant reduction of story-displacement compared to the initial building.
b. For the building with BRB in Level 1-14, seven analysis results show significant reduction of story displacement compared to the initial building, but less significant reduction compared to building with BRB in Level 1-10. of the inclusion of more BRB may possibly lead to increasing the fundamental periods of building, hence, it causes an increase in total dissipation energy. Installment of BRBs in 14 stories improves total dissipation energy of the building with tolerable increment of displacement.
c. For the building with doubled core area BRB in Level 1-10, seven analysis results show the most significant reduction of story-displacement compared to other models.

For upper-half stories, the results in Figure 9 and Table 4 also show reduction of displacement due to additions of BRB:

a. For the building with BRB in Level 1-10, seven analysis results show significant reduction of story-displacement compared to initial building, however, they have higher story displacements in comparison to the building with BRB in Level 1-14. This condition contradicts the results on lower-half stories. This result is possibly led by the difference of story stiffness in the interchange zone. Compared to higher story, lower half stories are subjected to more seismic load due to accumulation from above. Therefore, the story stiffness designates seismic behavior of the building in terms of both the total seismic load and total displacement.
b. For the building with BRB in Level 1-14, seven analysis results show the most significant reduction of story-displacement compared to other models. It is observed that this configuration maintains story stiffness difference more effectively compared to the others.
c. For the building with doubled core area BRB in Level 1-10, seven analysis results show quite significant reduction of story-displacement compared to initial building, but less significant compared to other BRB configurations. This condition, also, contradicts the results on lower-half stories, which is possibly due to the sudden change of the story stiffness at the interchange zone between Level 10 and Level 11. This leads to much higher story-displacement in Level 11 and above as compared to other buildings.

According to the findings of this study, the incorporation of BRB reduce the displacements experienced by the building and hence lead to an overall improved seismic behavior of the building. Despite the large additional stiffness, the configuration of BRB with doubled core area in Level 1-10 seemingly is only effective for lower-half stories but not effective for upper-half-stories. In contrast, the configuration of BRB in Level 1-14 with considerable BRB stiffness consistently provides more effective results in limiting the total displacement of building. However, total displacement in Level 10 is significantly reduced than in Level 20. Therefore, the difference displacement (drift) due to the variations of BRBs installment in adjacent stories should be examined.

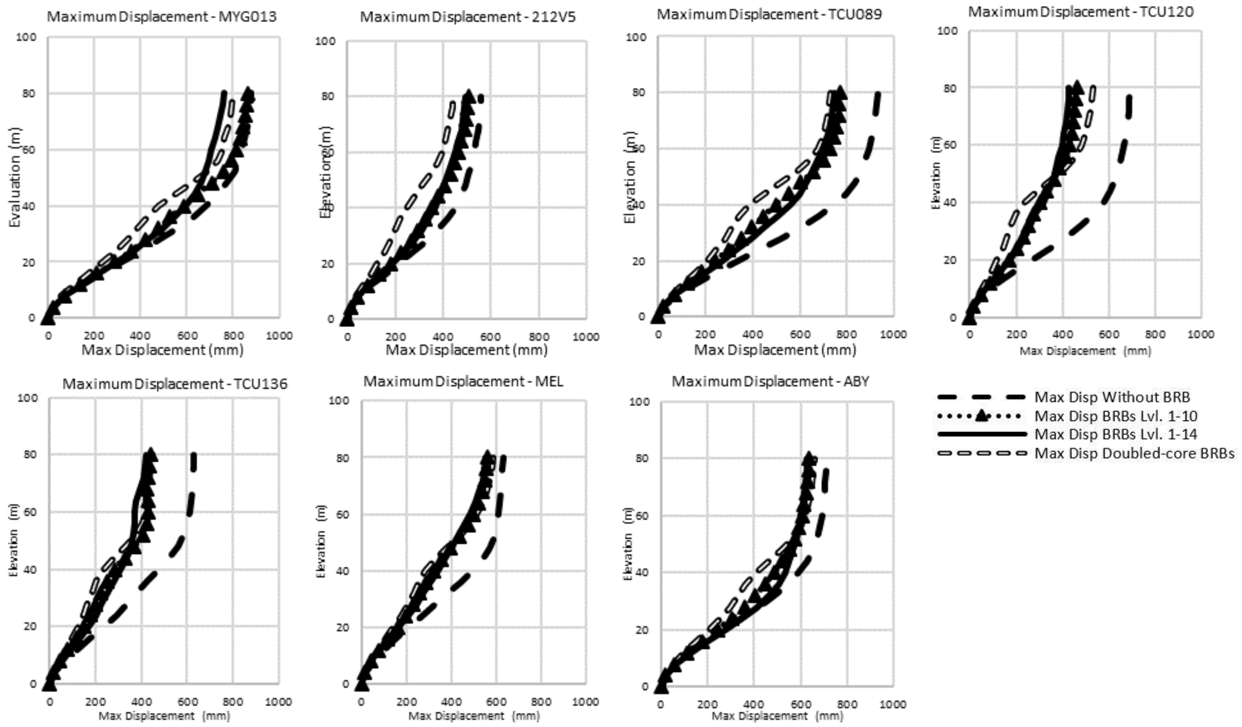


Figure 9 Maximum Displacement Result from seven ground motions

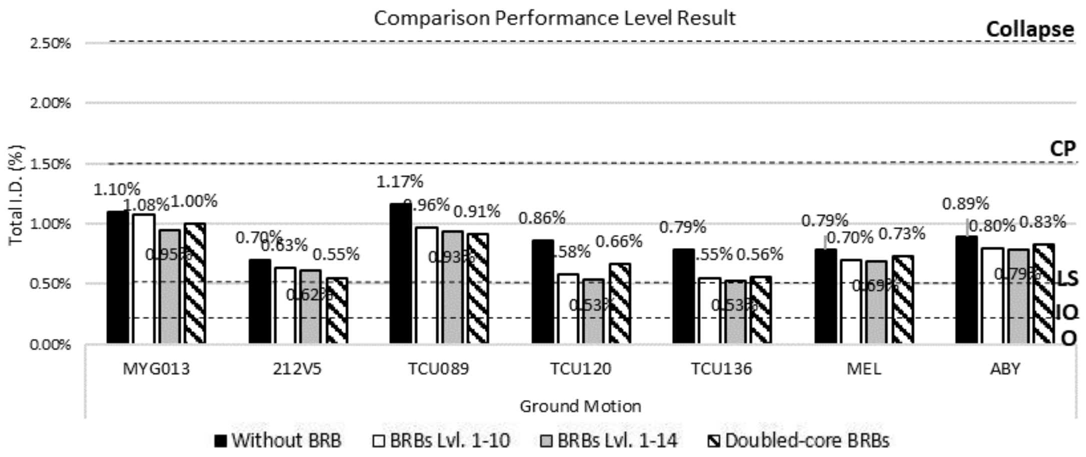


Figure 10 Comparison of Performance Level Result from seven grounds motion

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7.2 *Building Performance*

Performance level is described by designating the maximum allowable damage state for an identified seismic hazard. There are several performance levels, including: Operational (O), Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) where are defined by a certain range of the total interstory drift (I.D.) (FEMA, 1997). See Table 5.

$$Total\ I.D.(\%) = \frac{Max.Displacement}{H_{building}} \quad (2)$$

where $Max.Displacement$ is the total displacement at the top of the building (m) and $H_{building}$ is the height of building (m). According to SNI 1276-2012, the required performance level is LS.

Table 5 Damage Parameters for Building Performance

Building Levels	O	IO	LS	CP	
I.D. (%)	0	0.2	0.5	1.5	2.5

Figure 10 shows the building drift and the building performance levels for several installment cases of BRB including the building without BRB when subjected to ground motions with different accelerations. Overall, the four studied building models showed an acceptable level of performance for Life Safety. The incorporation of BRBs shows a reduction of Total I.D. ratio and implies improved seismic performance of the buildings. The reduction indicates that the required additional stiffness is attained effectively (Table 6). For the building with BRB in Level 1-14, the analysis results show that the incorporation of BRB improves more effectively the reduction of building drift compared to other models.

Table 6 Total I.D. Ratio Result

Earthquake Station	Without BRB (%)	BRBs at Level 1-10		BRBs at Level 1-14		Doubled-core BRBs	
		I.D. (%)	%	I.D. (%)	%	I.D. (%)	%
MYG013*	1.10	1.08	1.82	0.95	13.64	1.00	9.09
212V5	0.70	0.63	10.00	0.62	11.43	0.55	21.43
TCU089*	1.17	0.96	17.95	0.93	20.51	0.91	22.22
TCU136	0.86	0.58	32.56	0.53	38.37	0.66	23.26
TCU120	0.79	0.55	30.38	0.53	32.91	0.56	29.11
MEL	0.79	0.70	11.39	0.69	12.66	0.73	7.59
ABY	0.89	0.80	10.11	0.79	11.24	0.83	6.74
Average Reduction			**16.32**		**20.11**		**17.06**

* Earthquake stations that produced excessive lateral displacement for the building without BRB

This study shows that the incorporation of BRBs reduces the overall building drift and thus leads to improved building performance. However, the difference displacement (drift) due to the variations of BRBs installment in adjacent stories should be examined to evaluate BRBs effects to each stories locally.

7.3 *Inter-story drift*

Figure 11 shows percentage of story drift for several installment cases of BRB and initial building without BRB when subjected to several ground motions with different accelerations. The story drift illustrates the effect of additional stiffness and its sensitivity to seismic behavior. The results show that the story drift located in lower-half stories of the initial building without BRB exceeds the drift limit as 2.00%. However, the three case study models of buildings with the incorporation of BRB show a reduction of story drift. Further evaluation is also discussed for two cases, i.e. lower-half stories (Level.1-10) and upper-half stories (Level 11-20).

Figure 11 shows reduction of story drift for lower-half stories due to the incorporation of BRB in the buildings:

a. For the building with BRB in Level 1-10, the results from the analysis using seven ground motions show a significant reduction of story drift compared to initial building.
b. For the building with BRB in Level 1-14, the analysis indicates quite significant reduction of story-displacement compared to initial building, however the reduction seems not significant to the building with BRB in Level 1-10. Moreover, the plots indicate that the story drift in this configuration has slightly higher story drift than the building with BRB in Level 1-10. The addition of BRBs incites the increment of overall building stiffness and weight. The increment of building stiffness of the building with BRB in Level 1-14 is bigger than the building with BRB in Level 1-10. Considering the stiffness-weight relations to determine seismic load, it is reasonable that the story drift in the building with BRB in Level 1-14 is bigger than the building with BRB in Level 1-10.
c. For the building with doubled core area BRB in Level 1-10, the results from the seven analyses show the highest reduction of story drift compared to other models. However, the ratio of the story drift of this building and the story drift of the building without BRB is less than 2. This indicates that the increment of stiffness from cross section is not linear to the reduction of the story drift.

For upper-half stories, the incorporation of BRB interestingly performs an increment the story drift at certain story, i.e. Level 12, compared to the building without BRB:

a. For the building with BRB in St. 1-10, the results from the seven analyses show an indication of the presence of the secondary maximum story drift of the building. However, this story drift value is not significant as the story drift in lower-half stories.
b. For the building with BRB in St. 1-14, the results from the seven analyses also show an indication of the presence of the secondary maximum story drift of the building. However, this story drift value is not significant as the story drift in lower-half stories.
c. The building with doubled core area BRB in St. 1-10 exhibits higher difference in lateral story stiffness at Level 12 compare to its lower-half story drift. This may possible lead to the development of a soft-story mechanism.

According to upper-half stories result, the secondary story drift is appeared as compatibility mechanism of structural dynamic behavior. The occurrence of this story drift located in the interchange position where BRB is no longer applied. This story may subject a huge stiffness difference where leads the story to have constrained movement in bottom side and flexible movement in top side. This mechanism results a “jump” story drift or the secondary story drift to maintain building compatibility in interchange zone.

Based on the overall results, the installment of BRB in the building as damage-controlling system seems to produce a good performance, however, the building’s response is sensitive to the BRB’s configuration. In order to produce an effective performance, the configuration shall consider to the position of the applied BRB and the cross section of the BRB, to optimize its impact to the increment of building stiffness and the secondary story drift which is possible become the significant story drift.

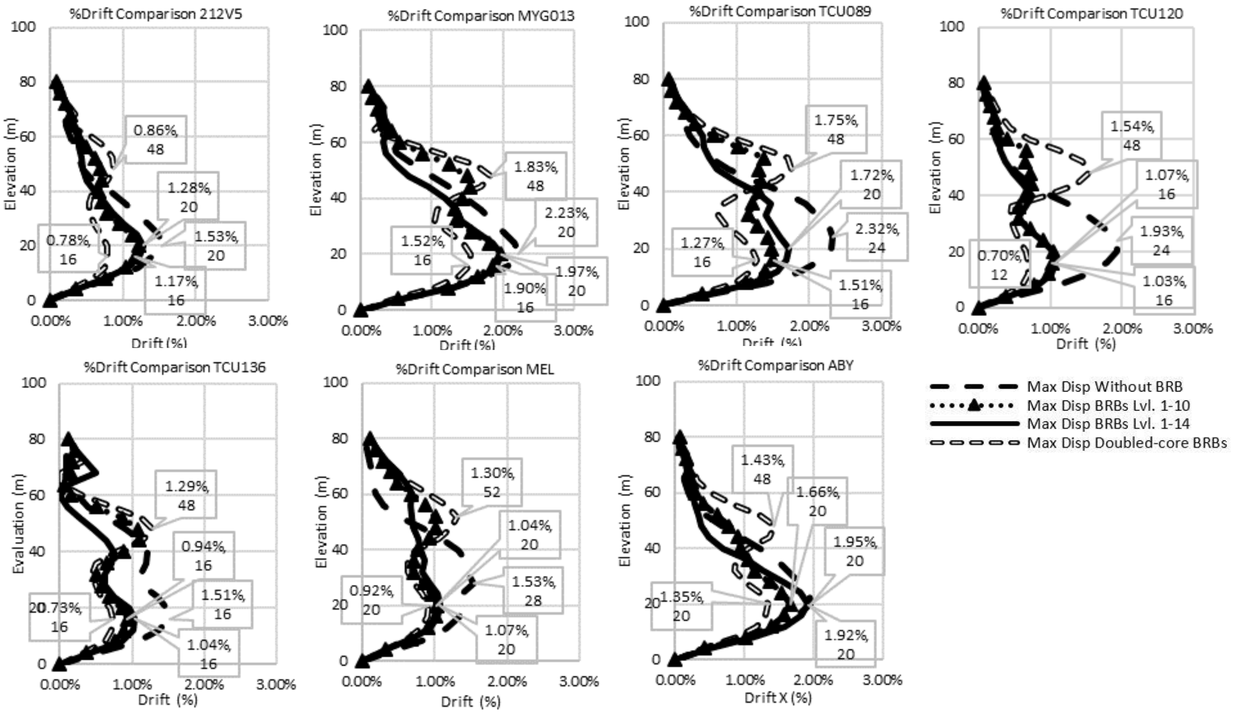

Figure 11 %Drift Result from seven ground motions

7.4 *R/C beams hinge result*

The performance of r/c special moment resisting frames is represented by the number of plastic hinges that was developed in beams to dissipate the energy due to the earthquake loading. The incorporation of BRBs obviously improves the capacity of the building to dissipate energy. Figure 13 shows that the incorporation of BRBs to the r/c frames effectively improved the rotation in r/c beams and reduced the number of LS and CP plastic hinges in several beams of the building frames.

However, it is also noticed that there are decreasing number of elastic beam members due the addition of BRB. The increment of IO hinge is the results of the impacts of BRBs' configuration to the increment of building stiffness and the secondary story drift. Additionally, the increment of IO hinge also represents the impact of the improvement of LS hinge into IO hinge. Therefore, the results show that the BRB improve the overall building performance.

Figure 14 shows the increment of beam member as IO due to the incorporation of BRBs based upon the performance of the three controlled beams, i.e. B2, B4, and B5. The B2 beam is typical beam for Level 10-12, hence, the increment of IO hinge corresponds to the sudden change of story stiffness at the interchange zone. The improved performance of beam B4 as IO by the additional BRB is more significant under the ground-motion 212V5, TCU120, and MEL. For beams B5, simulations using ground-motions 212V5, TCU089, TCU120, and MEL, also show large increment number of member B5 in IO condition. The increment of IO hinge is caused by the change of performance of several B4 and B5 members from LS hinge into IO hinge, and the increment of building stiffness which allows building to subject bigger earthquake load.

Table 7 The Significant %Drift Result for Lower-Half Stories

Earthquake Station	Without BRB (%)	BRBs at Level 1-10		BRBs at Level 1-14		Doubled-core BRBs	
		%Drift	%	%Drift	%	%Drift	%
MYG013*	2.23	1.90	14.80	1.97	11.66	1.54	30.94
212V5	1.53	1.17	23.53	1.28	16.34	0.78	49.02
TCU089*	2.32	1.51	34.91	1.72	25.86	1.27	45.26
TCU136	1.93	1.03	46.63	1.07	44.56	0.70	63.73
TCU120	1.51	0.94	37.75	1.04	31.13	0.73	51.66
MEL	1.53	1.04	32.03	1.07	30.07	0.92	39.87
ABY	1.95	1.66	14.87	1.92	1.54	1.35	30.77
Average Reduction			**29.22**		**23.02**		**44.46**

* Earthquake stations that produced excessive lateral displacement for the building without BRB

Table 8 The Comparison of %Drift Result in Lower-half stories and in Upper-Half Stories

Earthquake Station	Without BRB		BRBs at Lvl. 1-10		BRBs at Lvl. 1-14		Doubled-core BRBs	
	L	U	L	U	L	U	L	U
MYG013*	2.23	-	1.90	1.54	1.97	-	1.54	1.83**
212V5	1.53	-	1.17	0.71	1.28	-	0.78	0.86**
TCU089*	2.32	-	1.51	1.38	1.72	-	1.27	1.75**
TCU136	1.93	-	1.03	0.75	1.07	0.74	0.70	1.54**
TCU120	1.51	-	0.94	1.08**	1.04	0.74	0.73	1.29**
MEL	1.53	-	1.04	1.10**	1.07	-	0.92	1.30**
ABY	1.95	-	1.66	-	1.92	-	1.35	1.66**

* Earthquake stations that produced excessive lateral displacement for the building without BRB

** The secondary story drift in upper-half zone exceeds the primary story drift in lower-half zone

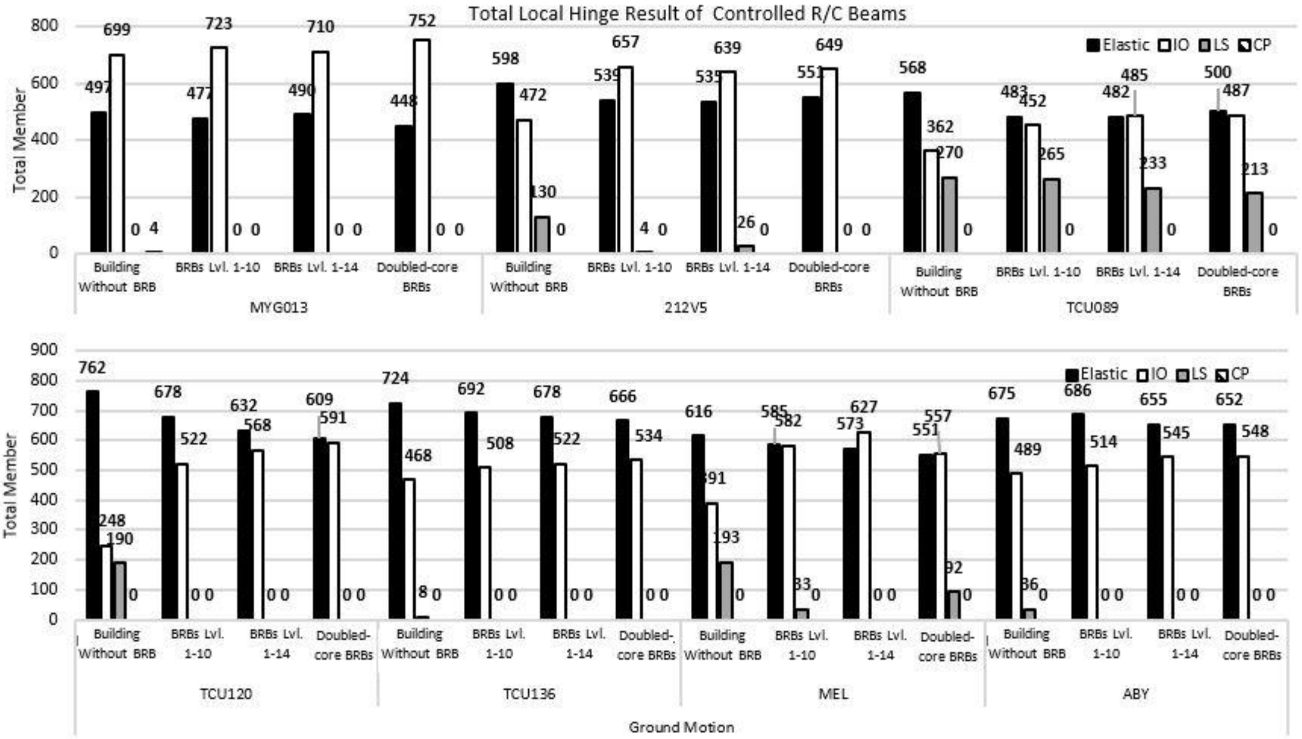

Figure 12 Total Local Hinge Result of Controlled R/C Beams

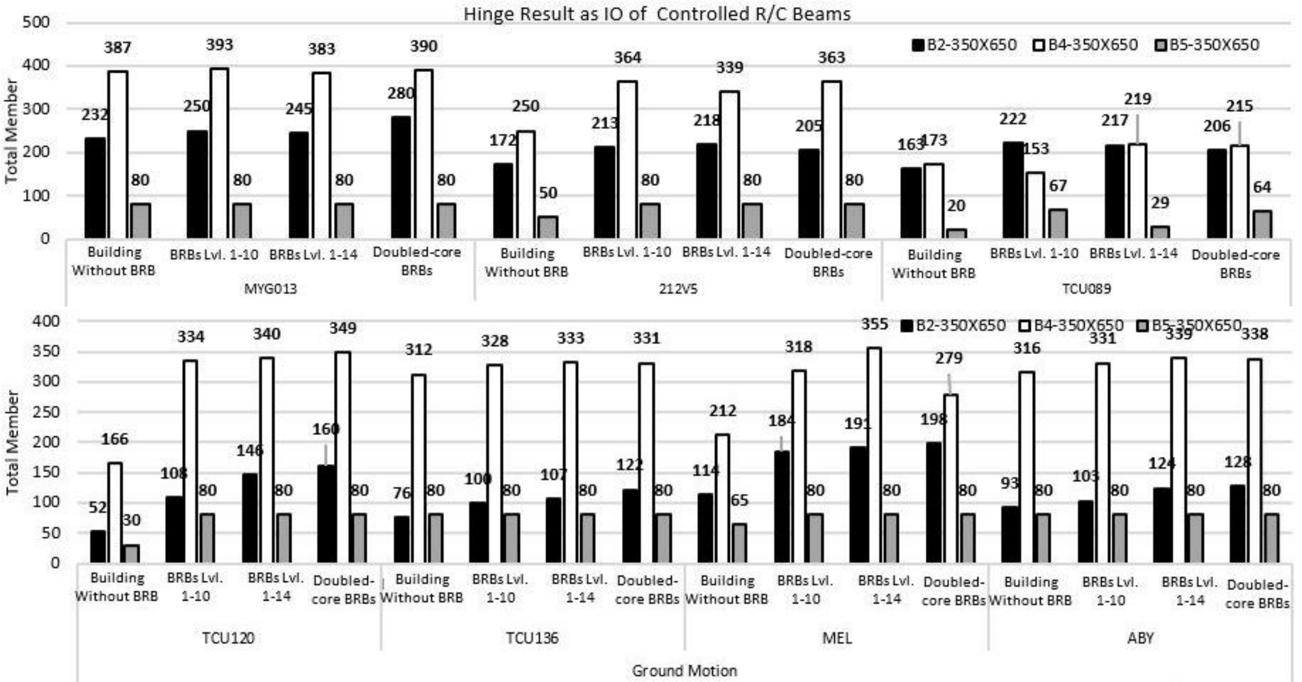

Figure 13 Hinge Result as IO Level of Controlled R/C Beams

7.5 *R/C columns hinge result*

The performance of r/c columns for different BRB configurations is evaluated based on the performance of two controlled columns, i.e. column K3 (in the middle height of building) and K5 (in the bottom of building).

Figure 14 shows that the incorporation of BRB increases the number of inelastic r/c column members with IO hinge in the K5 column. The column rotation and bending moment increase corresponding to higher lateral loads due to the increase in the building stiffness caused by the incorporation of BRB. Furthermore, the incorporation of BRB initiates substantial axial forces to the adjacent columns.

Figure 14 also shows that the highest number of columns with IO hinge in the K3 column for all ground motions occurs in buildings with doubled-core area in St.1-10. This is likely caused by the sudden change in story stiffness between St.10 and St.11. It is important that the inelastic rotations in the K3 column should be anticipated, which could possibly develop a soft-story mechanism and progressive failure in the building.

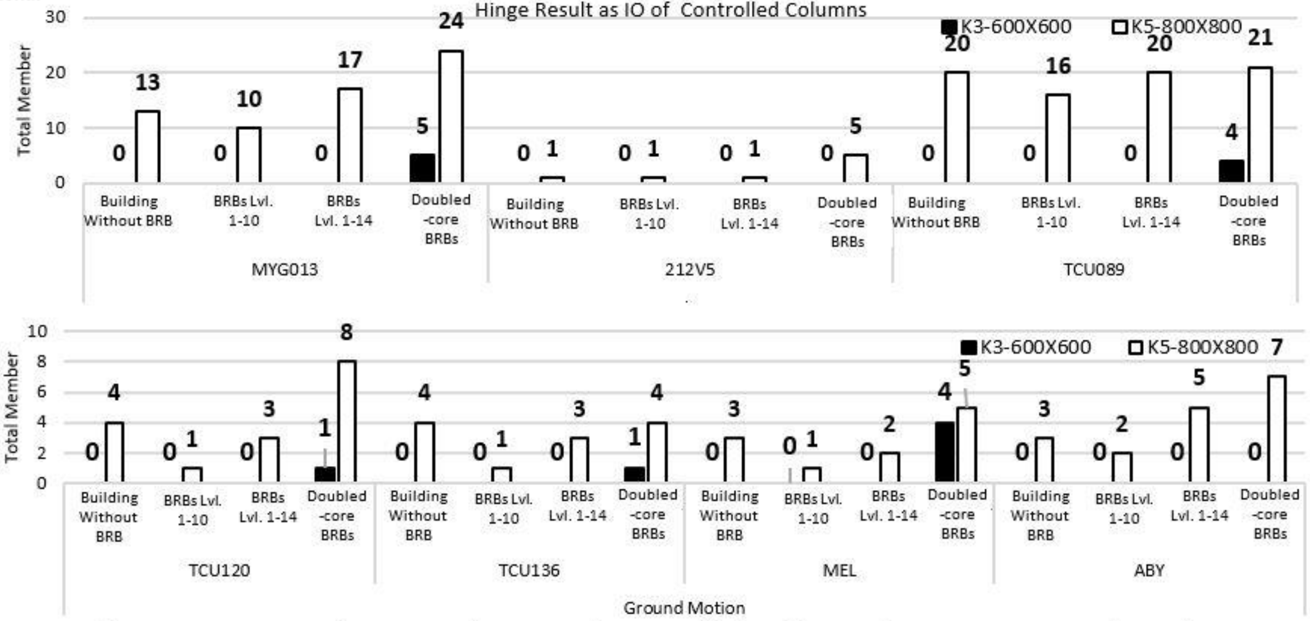

Figure 14 Hinge Result as IO Level of Controlled R/C Columns

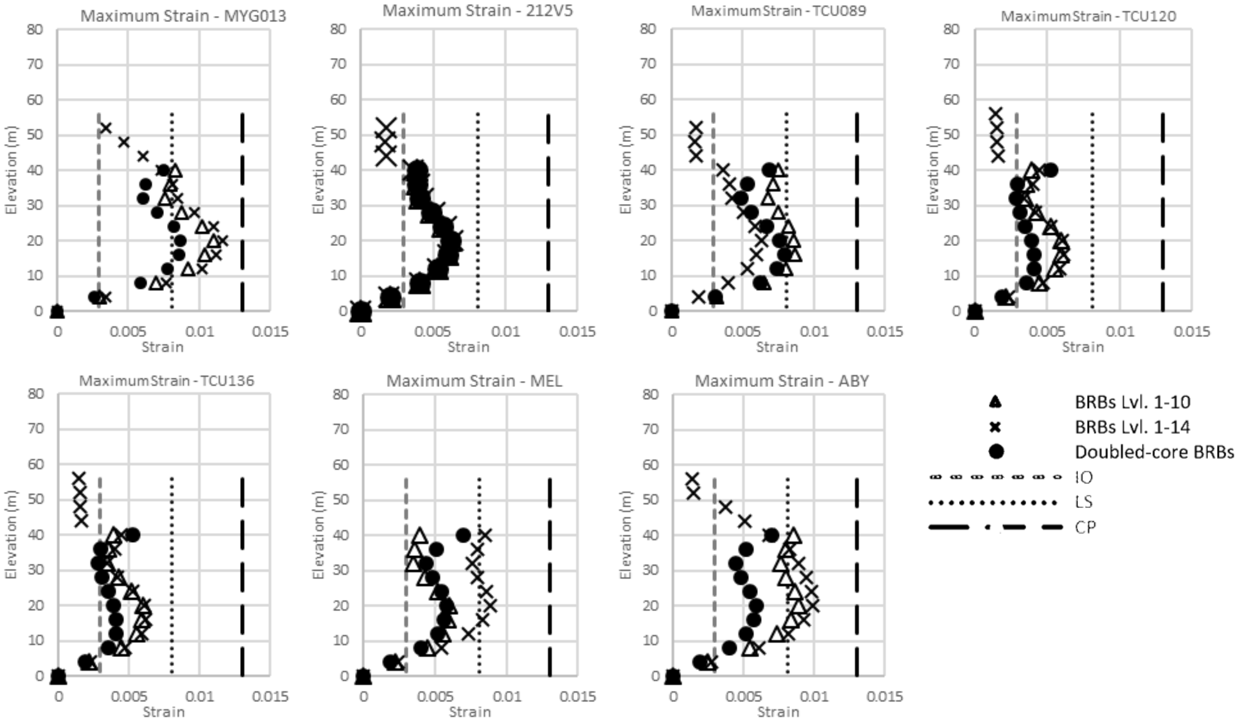

Figure 15 Maximum response of BRB's strain Due to Seven Ground-Motions

7.6 *BRB Strain*

Figure 15 shows maximum strain of BRB element for three installment cases of BRB when subjected to ground motions with different accelerations. This parameter indicates the effect of BRB in dissipating seismic energy in each story.

The maximum BRB strain developed in three installment cases of BRB due to seven ground motions indicates that the performance of all of the BRBs are within the Life Safety (LS) damage limit state as expected and the strain values are far from the maximum capacity of the BRBs (i.e. 3.00% axial strain). This shows that the design of BRB is effective to perform as damage-controlling system.

8 CONCLUSIONS

Based on the analyses conducted in this study on the performance of a 20-story r/c frame building with the incorporation of BRBs under seven different scaled earthquake ground motions, the following conclusions are presented:

1. The incorporation of BRBs effectively reduces excessive lateral drift of the r/c special moment resisting frame to satisfy the drift limit. The reduction indicates that the additional stiffness at each story improves the lateral drift of the building.

2. Based on plastic hinge conditions in r/c frame members, the addition of BRB adequately shows a reduction of damage level in several r/c frame members. It is understandable that the additional bracing provided by the BRBs increases the entire building stiffness and reduces rotation of r/c frame members, especially in beams elements; and at the same time increases the base shear due to a reduction in the building period. However, the study shows that the incorporation of BRBs ensures improved damage level for the r/c frame.
3. The configuration of BRB installment affects the seismic performance of the buildings. The incorporation of BRB could induce a large difference of story stiffness to adjacent stories with no BRB. Thus, damage of some r/c frame members may occur in the area where the stiffness is significantly changed. To obtain optimum performance of the building, more comprehensive study is needed to determine the ideal configuration of BRBs, by considering the location and the capacity (i.e. geometry, core area, and material) of the BRBs.

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