Journal of Mechanical Engineering *Vol 16(1), 159-173, 2019*

Seismic Behavior of RC Building with and Without Buckling Restrained Braces

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ABSTRACT

Nonlinear analysis for evaluating seismic performance of building under seismic excitation requires nonlinear properties of any component that are quantified by strength and deformation capacities. The nonlinear behavior of beams and column components are modeled in the form of plastic hinges as described in ASCE41-13 [1] guideline. This document provides the hinge rotation capacity for several ranges of detailing assumption. Buckling restrained braces (BRB) can be modeled as a link element with force-deformation behavior through Wen's plasticity model. This paper evaluates possible differences of seismic performance of six-story reinforced concrete moment resisting frame with conforming and non-conforming plastic hinge rotation, with and without BRB in placed. The nonlinear static analysis is performed to obtain capacity curve using inverted triangular load pattern as described in ASCE7-10 [2]. The behaviors of investigating frames are discussed and evaluated by means of capacity curves and plastic hinge formation mechanism. Moreover, nonlinear time history analysis is carried out to investigate the effect of BRB properties on the seismic behavior of building model subjected to selected ground motion records. Furthermore, response parameters of building model are presented and compared in the form of base shear, story displacement, and story drift.

Keywords: *Ground Motion, Nonlinear, Time History, Plastic Hinges, BRB*

Introduction

It is well recognized that the inelastic behavior of structural elements is taken into account through plastic hinge modeling, and commonly, all inelastic

ISSN 1823-5514, eISSN2550-164X

Received for review: 2017-06-10
Accepted for publication:2018-03-28
Published:2019-04-01

deformation is concentrated in zero length plastic hinges. The plastic hinge properties can be computed automatically from element material and section properties according to FEMA-356 [3] or ASCE 41-13 [1] criteria. The seismic behavior or performance of the structure can be investigated using either nonlinear static procedure (NSP) or nonlinear time history analysis (NTHA). However, the accuracy of NSP for assessment of the seismic behavior of the structure is still of pros and cons among structural engineers. Inconsistent results in roof displacement and unreliable estimate of story shear and overturning moment have been reported by Goel and Chadwell [4]. Therefore, nonlinear time history analysis is used herein to evaluate the seismic behavior of building model regardless its complexity and computational time.

Steel damper has been recognized as one of the innovative design concept to improve the seismic performance of the structures have been tested and applied by several authors [5,6,7,8,9]. One of them is well known as Buckling Restrained Braced Frame (BRBF) that combines Moment Resting Frame (MRF) with Buckling Restrained Braces (BRB) as steel damper. BRB systems are unique due to the configuration of the braces components. They are made from three main components where the steel core is to resist entire axial load for providing energy dissipation, the outer steel casing infilled with or without mortar for providing confinement that prevent steel core buckling in compression and allows it to yield in compression or tension, debonding material to minimize or to eliminate transfer force of restrained steel casing, infilled mortar and unrestrained non-yielding segment is a part for connection brace to the structure. In this study, the seismic responses of six stories reinforced concrete (R/C) building having conforming (C) and non-conforming (NC) plastic hinge rotation with and without BRB in placed are evaluated. The plastic hinge is said conforming if transverse reinforcement spacing $\leq$ d/3, then assumed exhibit stable hysteresis loop. While for nonconforming one, the transverse reinforcement deficient in spacing and lead to pinched hysteresis curve. The building model was investigated under three selected ground motion records that scaled down to response spectra design of Indonesian seismic code. The response quantities in the form of base shear, capacity curve, story displacement, and inter-story drift are compared and discussed. Also, plastic hinge formation mechanisms at the end of ground motion records is presented.

Buckling Restrained Braces

The concept BRB was originally developed in Japan by Nippon Steel before they gained attention in United State. In Japan, BRB are used as hysteretic damper that control of the response of moment resisting frames, and the combined system possesses additional stiffness and damping, including when

BRB yield. On the other hand, the design approach in the United States does not require that BRB be used as part of a dual system, and BRB incorporated into moment resisting frame (BRBF) system typically have relatively modest over strength and low post-yield stiffness. Design guidance for BRBF has been developed in USA with various design guidelines and publications as described in AISC 341-10 [10].

Typical BRB Configuration

BRB have two basic components which are the steel core is designed to resist both compression and tension axial load developed in the bracing and restraining parts that prevent the core from buckling in compression and allows it to yield either in tension or compression. The core consists of a middle length that is designed to yield at the design level earthquake and non-yielding lengths on both ends having an increased cross sectional area to ensure it remains elastic. Figure 1 shows the typical BRBF frame in diagonal configuration and Figure 2 provides common assembly of BRB parts [12].

Characteristic of BRB

Although the overall geometric configuration is a similar to conventional Concentrically Braced Frame (CBF) but the members, connections, and behavior of BRBF is completely different. BRB achieves a high level of ductility and stable, repeatable hysteresis loops, BRB can absorb a significant amount of energy during cyclic loadings such as an earthquake event and lead to primary structural components such as beams and columns are remain elastic or minor inelastic deformation. Buckling prevention will lead to almost similar strength and ductile behavior in compression and tension. Compression capacity is slightly higher than the tensile capacity due to the friction force which generated from a number of contact points between core and steel casing as tested by Midorikawa [6]. Several experimental tests were conducted by Iwata and Murai [11] and Midorikawa [6] proved that BRB with mortar infilled were ductile, stable and repeatable hysteretic behavior. It is very important to ensure that the core can slide freely inside the steel casing (buckling restraining unit) and transverse expansion of core can take place when core yields in compression as reported by Xie [9].

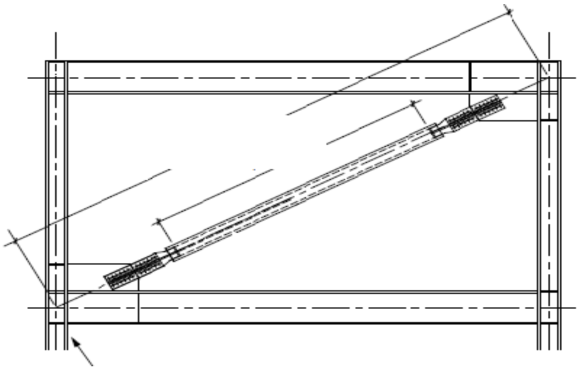


Figure 1: Typical BRB configuration from NIST 2015 [12]

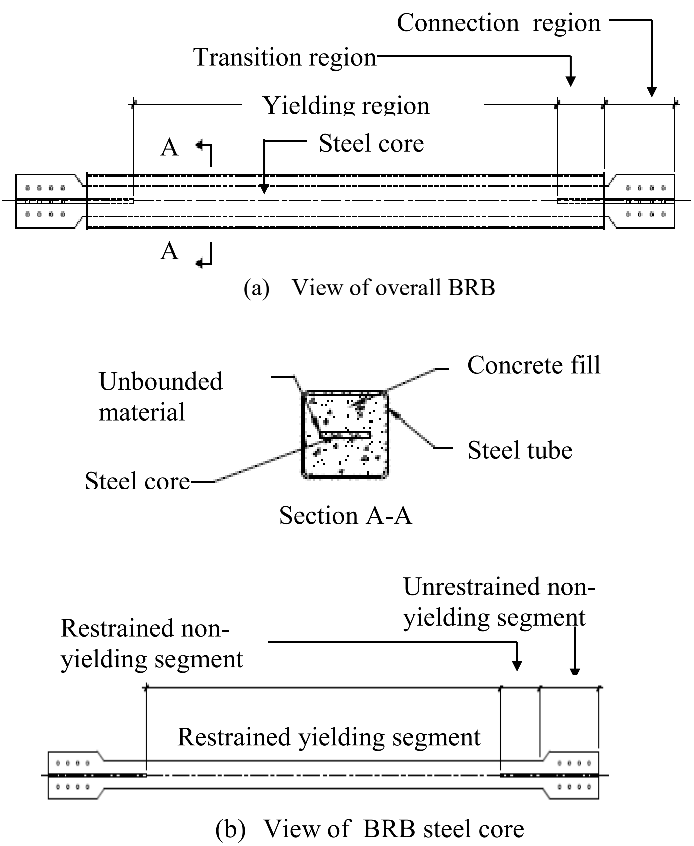


Figure 2: Typical BRB assembly from NIST 2015 [12]

Design of Six Story RC Building

Building Description

A six story moment resisting frame of RC building was designed with the concept of the strong column and weak beam approach. In order to study the effect of stiffness BRB on the seismic response of the building model, the equivalent elastic axial stiffness of BRB (k_{eq}) was selected for 2, 3, 4, and 5 times of MRF elastic lateral stiffness and labelled as BRB-1, BRB-2, BRB-3, BRB-4, respectively. However, the average MRF elastic lateral stiffness for the 2nd and 3rd stories was defined as k_{eq}, and similarly for the 4th and 5th stories. The elevation view of the building is shown in Figure 3. Compressive strength of concrete columns and beams are 40 MPa and 30 MPa, respectively, while the yield stress of reinforcement is 400MPa. The dimensions of column members are 600x700 mm for first-story up to third-story, while for remaining stories are 500x700mm, and all beams are 350x700mm. Furthermore, the detail of reinforcement bars for beams and columns is as listed in Table 1 and the equivalent elastic axial stiffness of BRB (k_{eq}) is given in Table 2. Moreover, the dead load and imposed load on the floors and roof are 22kN/m and 18kN/m, respectively. Live load is assumed to be 12kN/m on all floors and 7kN/m on the roof.

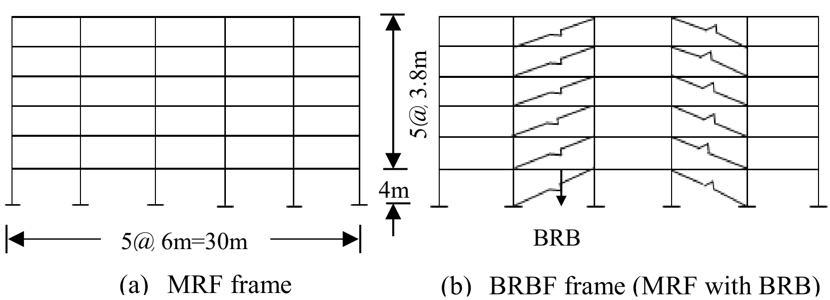


Figure 3: Elevation view of building model

Input Ground Motion

Three selected ground motions record, namely Loma Prieta, Imperial Valley and Kobe Earthquake which was matched to response spectra design of Indonesian seismic code were used in the computer model. These earthquakes are known as destructive earthquakes having the pulse effect. Response spectra design is constructed based on two-third of the maximum considered earthquake (MCE) for site class D. Figure 4 illustrates the response spectra design for 5% of damping. MCE is an earthquake with a 2% probability in 50 years of being exceeded. This is an earthquake with a 2500 year recurring period.

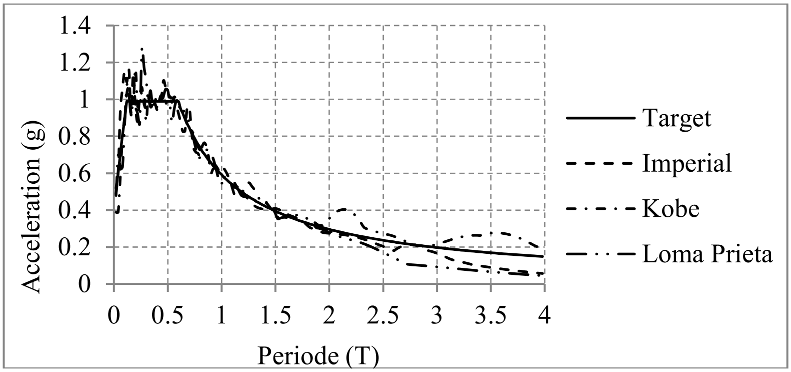


Figure 4: Acceleration scaled to response spectra design

Table 1: Detail of reinforcements for beams and column

Story	Steel reinforcement	
	Column	Beam (top/bottom)
1	20D-22	6D-22/3D-22
2	20D-22	7D-22/3D-22
3	20D-22	6D-22/3D-22
4&5	16D-22	5D-22/2D-22+1D-19
6	16D-22	5D-19/2D-16+1D-19

Table 2: Detail of buckling restrained braces (BRB)

Story	Equivalent axial stiffness of BRB (kN/mm)			
	BRB-1	BRB-2	BRB-3	BRB-4
1	98	147	196	245
2&3	49	73.5	98	122.5
4&5	41	61.5	82	102.5
6	31	46.5	62	77.5

Numerical Analysis

BRB Modelling

The behaviour of BRB in energy dissipation depends on steel core since restraint part of BRB is just to prevent steel core from buckling. Bouc –Wen model was chosen by Bahey and Bruneau [5] to investigate the BRB as structural fuse bars for the seismic retrofit of concrete bridge bents because of its capability and reliability to capture the inelastic behavior of steel material under cyclic loading. In this case, Wen's plasticity model was also selected to describe force versus deformation relation of BRB's (steel core) hysteretic curve which were modeled as Truss elements. The force-deformation relationship can be expressed as follows (given in manual SAP 2000 Ver.10.1 [13]):

$$F(t) = \alpha k d + (1 - \alpha) Q_y z \tag{1}$$

$$\dot{z} = \frac{k}{Q_y} \begin{cases} \dot{d}(1 - |z|^n) & if \quad \dot{d}z > 0 \\ \dot{d} & otherwise \end{cases} \tag{2}$$

where $k$is equivalent elastic stiffness, α is post yield stiffness ratio, $z$is internal hysteresis variable with $|z| \leq 1$, Q_y is yield force,$n$is exponent to control the sharp of yielding. In this study, $n = 2$and $\alpha = 0.1$were selected in the BRB modeling.

Plastic Hinge Modelling

To account inelastic behavior of beam and column elements, plastic hinges with zero length were selected at both ends of elements. Hinges for beam elements are due to bending moment only, while for column elements due to interaction of axial and bending moments. Plastic hinge rotation modeling and acceptance criteria for beam and column elements are given in Table 10.7 and Table 10.8 of ASCE 41-13 [1] standard, respectively.

Nonlinear Structural Analysis

Nonlinear static procedures or pushover analysis (NSP) and nonlinear time history analysis (NTHA) are carried out using SAP 2000. NSP is only intended to obtain capacity curve of the building model of either MRF or BRBF frames by using inverted triangular load pattern as stated in ASCE 7-10 [2] using Equation 12.8.11 and 12.8.12. Both analyses are taken into account the effect of geometric nonlinearity through $P - \Delta$ option. NTHA based on time integration proposed by Hilber-Hughes-Taylor was adopted to solve dynamic equilibrium equations with a 0.01 time step. Rayleigh damping was constructed with the mass and stiffness proportional coefficient are $a_1 = 0.4189,$ and $a_2 = 0.0015$, respectively.

Discussion of The Results

Story Displacement and Inter-story Drift

Figure 5 and 6 show the story displacement and inter-story drift for MRF obtained from NTHA, respectively. It is apparent that story displacement is not influence by conforming and non-conforming plastic hinges as well as inter-story drift. The maximum story displacement is 470mm and inter-story drift is 2.63% which occurred under Loma Prieta earthquake. Based on inter-story drift, the structural performance of MRF is Limited Safety Range (S-4).

Figure 7, 8, 9, and 10 provide information of story displacement for the BRBF1 to BRBF4 which subjected to Imperial Valley, Kobe, and Loma Prieta earthquakes for conforming and non-conforming plastic hinges. Unlike MRF, story displacement for BRBF is affected by conforming and non-conforming plastic hinges. It was also found that all BRBF with conforming plastic hinges exhibit story displacement smaller than BRBF with non-conforming plastic hinges. Additionally, the maximum roof displacement for BRBF1, BRBF2, and BRBF3 were occurred due to Imperial Valley ground motion record, whereas for BRBF4 due to Loma Prieta earthquake. The reason of this phenomenon could be the fundamental period of BRBF4 being closed to predominant period of Loma Prieta Earthquake. Furthermore, Figure 10 demonstrates that when the lateral stiffness of BRBF is increased, sensitivity of story displacement to the characteristics of seismic excitations is reduced. Therefore, the story displacement under three ground motions excitation exhibit almost similar in magnitude and pattern.

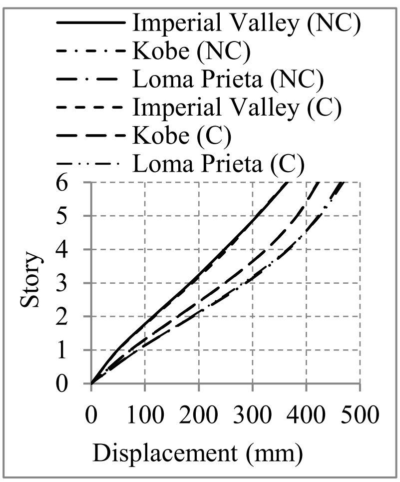


Figure 5: Story displacement (MRF)

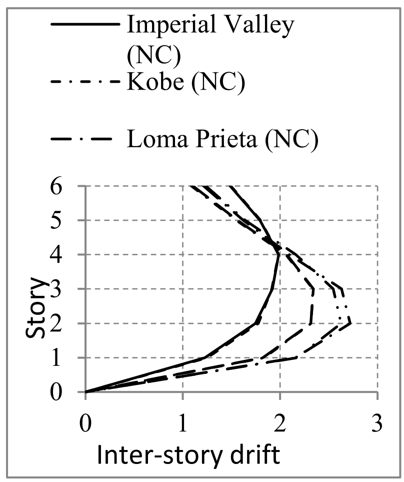
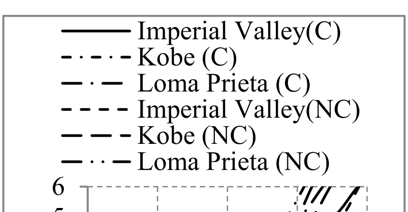


Figure 6: Inter-story drift (MRF)

Figure 11, 12, 13, and Figure 14 illustrate the comparison inter-story drift for all BRBF obtained from NTHA. General results showed that maximum inter-story for conforming plastic hinges occurred on the third floor and for non-conforming on the second floor. There is a tendency for inter-story drift for non-conforming plastic hinges to be higher at lower story than for conforming frame regardless of ground motion used for analysis.



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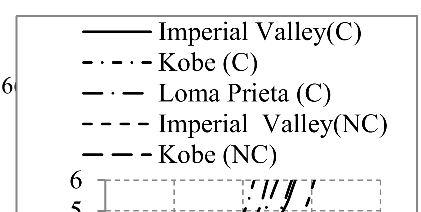


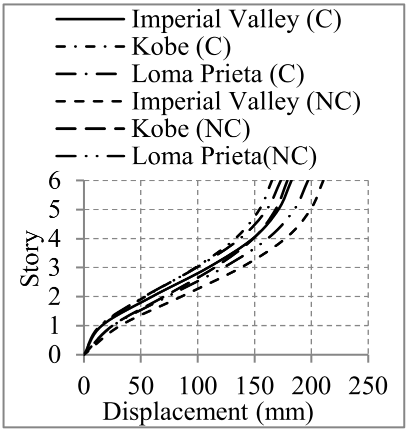


Figure 9: Story drift (BRBF3)

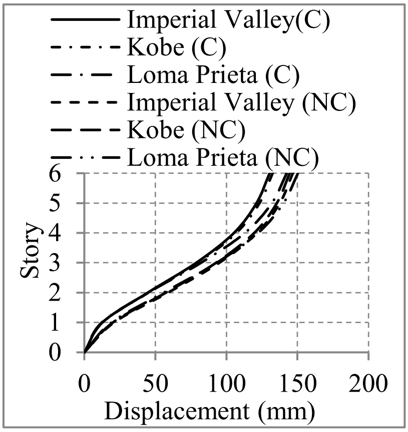


Figure 10: Story drift (BRBF4)

Figure 11 reveals that the largest inter-story drift for conforming plastic hinges are BRBF1(2.58%), BRBF2 (1.99%), and BRBF3 (1.32%) respectively and occurred on the mid story under Imperial Valley excitation, whereas for BRBF4 the maximum inter-story drift (0.99%) due to Loma Prieta earthquake at the similar story. The latest frame confirms that using BRB incorporated in MRF can improve structural performance level into Immediate Occupancy (S-1). In addition, for all non-conforming plastic hinges the maximum inter-story drift caused by Imperial Valley, i.e., 2.5% for BRBF1, 2.1% for BRBF2, 1.7% for BRBF3, and 1.2% for BRBF4, respectively. However, almost all occurred on the second floor. As the BRB lateral stiffness increases, the inter-story drift become less.

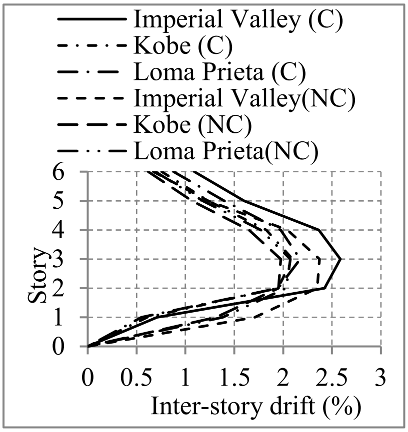


Figure 11: Inter-story drift (BRBF1)

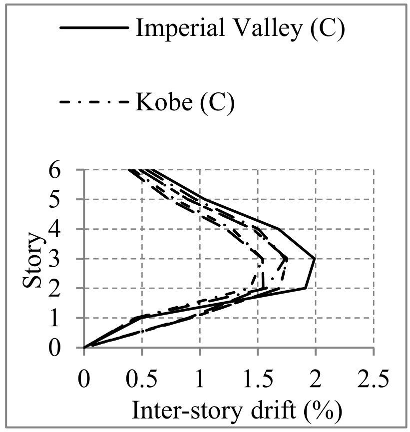


Figure 12: Inter-story drift (BRBF2)

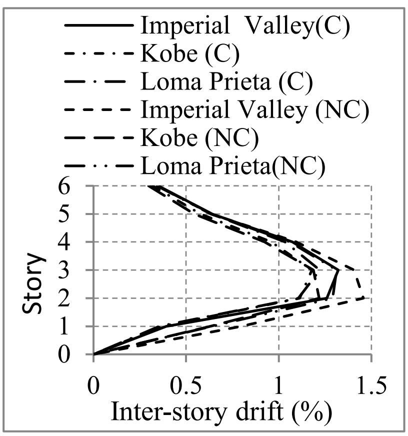


Figure 13: Inter-story drift (BRBF3)

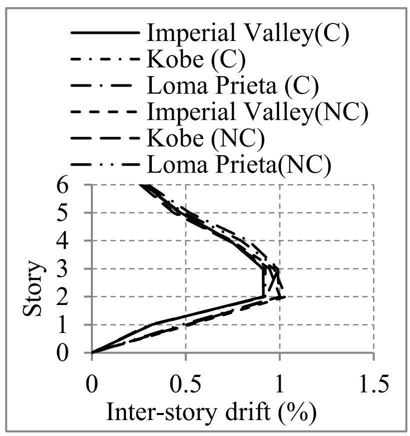


Figure 14: Inter-story drift (BRBF4)

Base Shear Demand

The influence of lateral stiffness on the base shear is shown in Table 3. The results confirm that base shear demand for frames with conforming plastic hinges is almost similar with non-conforming one. Furthermore, it was found that the larger the BRB lateral stiffness, the larger the base shear demand is. The maximum base shear is always occurring due to Imperial Valley earthquake either for conforming or non-conforming plastic hinges.

Table 3: Comparison of base shear demand

Frame	Base Shear Demand (kN)					
	Imperial Valley		Kobe		Loma Prieta	
	C	NC	C	NC	C	NC
MRF	2513	2518	2394	2401	2176	2178
BRB1	5024	4359	4680	4044	4340	4058

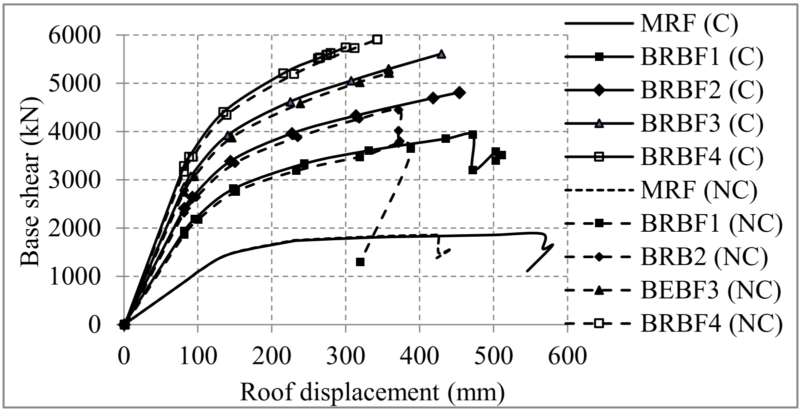


Figure 15: Capacity Curves

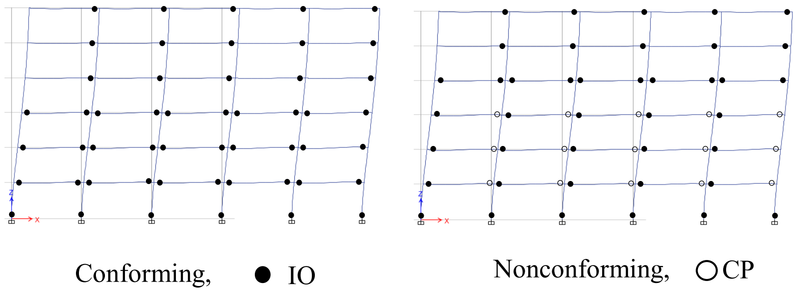


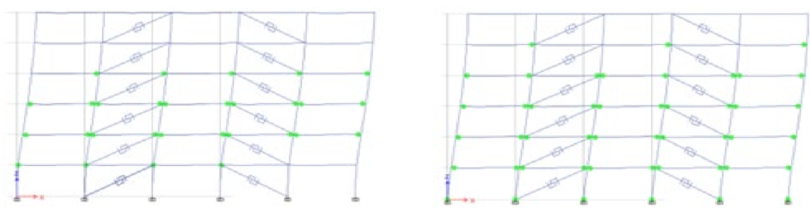
Figure 16: Plastic hinges pattern for MRF

Capacity Curves

Figure 15 shows capacity curve obtained from nonlinear static analysis. It was found that frames with conforming plastic hinges exhibit more ductile than frames with non-conforming plastic hinges. The higher the lateral stiffness of BRBF the smaller the ductility displacement is. Additionally, plastic hinges conforming and non-conforming have considerable effects on the displacement capacity of the frames especially for MRF and for BRBF with the lower of the BRB lateral stiffness.

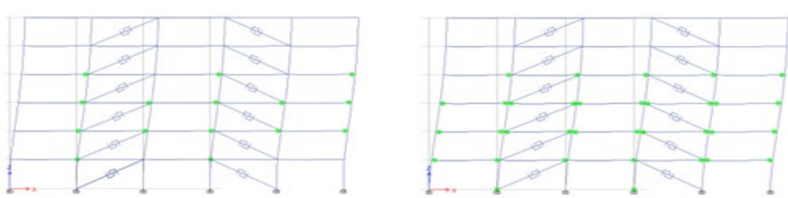
Plastic Hinges Formation Mechanisms

Plastic hinges formation mechanisms for MRF is shown in Figure 16. Limited by availability of space, formation plastic hinges are given under Loma Prieta earthquake only. There was no indication of soft story or weak story mechanism since no plastic hinges was formed at columns members. Another observation can be found that MRF with conforming plastic hinges experience inelastic deformation or minor damage. In this case all plastic hinges formed by round shape showed deformation in Immediate Occupancy level (IO). In contrast, for non-conforming one, MRF exhibits severe damage especially for the beam elements at the second to third floor, although soft or weak story did not occur as well. In this case, several plastic hinges experienced heavy damage in Collapse Prevention level (CP) which indicated by cross shape.



Conforming Nonconforming

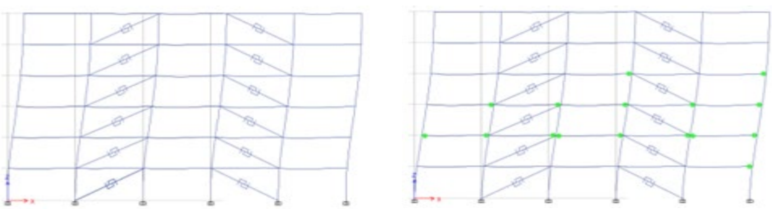
Figure 17: Plastic hinges pattern for BRBF1



Conforming Nonconforming

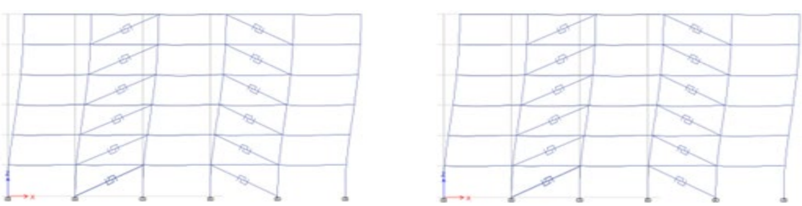
Figure 18: Plastic hinges pattern for BRBF2

Furthermore, plastic hinges pattern for BRBF obtained from NTHA are shown in Figure 17, 18, 19 and 20. It was noted that the highest plastic hinges status is IO level and the number of plastic hinges formed for BRBF with conforming plastic hinges less than for BRBF with non-conforming one. In addition, for conforming of BRBF3, no plastic hinges was formed, while for non-conforming one, plastic hinges were formed at several beams on the second to the fourth floors. However, for BRBF4 – either having conforming plastic hinges or non-conforming plastic hinges – exhibits similar behavior, i.e., no damage or response is still elastic.



Conforming Nonconforming

Figure 19: Plastic hinges pattern for BRBF3



Conforming Nonconforming

Figure 20: Plastic hinges pattern for BRBF4

Summary and Conclusion

This paper evaluates the seismic behavior and performance of six-story RC building through comparison of responses quantities and plastic hinges formation mechanisms. From its application to the building model having conforming and nonconforming plastic hinges, subjected to Imperial Valley, Kobe and Loma Prieta ground motions, and then analyzed using NSP and NTHA, it can be demonstrated that the plastic hinges either conforming or nonconforming *do not have influenced* on the story displacement, inter-story drift and base shear demand. However, for the capacity curve the effect is *considerable,* especially for MRF. It was also confirmed that, the seismic performance of MRF can be *improved significantly* when BRB incorporated to MRF, even *no damage* to beams and columns for the certain degree of BRB elastic axial stiffness. Moreover, ground motion characteristics have considerable effect on the response quantities both MRF and BRBF, and generally results showed that *the sensitivity* of the BRBF on the seismic responses is *reduced* as lateral stiffness of the BRB increases.

References

[1] ASCE/SEI 41-13, Seismic Evaluation and Retrofit of Existing Buildings, ASCE Standard, American Society of Civil Engineers, Reston, Virginia, USA (2013).

[2] ASCE 7-10, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, Virginia, USA (2010).

[3] FEMA-356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, The American Society of Civil Engineers for the Federal Emergency Management Agency, Washington DC, USA (2000)

[4] Goel, R. K. and Chadwell. C, Evaluation of current nonlinear static procedures for concrete buildings using recorded strong-motion data, Data Utilization Report, California Strong Motion Instrumentation Program, CDMG, Sacramento, California (2007).

[5] Bahey, S.E. and Bruneau, M, " Buckling restrained braces as structural fuses for the seismic retrofit of reinforced concrete bridge bents. Engineering structure (33), 1052-1061(2011)

[6] Midorikawa, M., Asari, T., Iwata, M., Murai, M., Tanaka, Y," Cyclic behavior of buckling-restrained braces using steel mortar planks; Buckling mode number and strength ratio," The 15th World Conference on Earthquake Engineering Paper ID: 0572, Lisbon, Portugal (2012)

[7] Tremblay, R., Bolduc, P., Neville, R., and DeVall, R," Seismic testing and performance of buckling restrained bracing systems," Canadian. J. Civil. Engineering, 33(1), 183-198 (2006).

[8] Teruna, D.R., Taksiah, A.M., Bambang, B," Experimental study of hysteretic steel damper for energy dissipation capacity," Advance in civil engineering, http://dx.doi.org/10.1155/2015/631726 (2015)

[9] Xie, Q," State of the art buckling restrained braces in Asia," J. Construction Steel Research (61), 727-748 (2005).

[10] AISC 341-10, Seismic Provision for Structural Buildings. American Institute of Steel Construction, Chicago, Illinois, USA (2010)

[11] Iwata, M., and Murai, M," Buckling restrained Brace Using Steel Mortar Planks; Performance Evaluation as a Hysteretic Damper," Earthquake Engineering and Structural Dynamics (35)-1807-1826 (2006).

[12] NIST, Seismic Design of Steel Buckling Restrained Braced Frames, NERPH Seismic Design Technical Brief No.11 (2013).

[13] SAP 2000 v10.1, Structural Analysis Program, Computers and Structures, Inc (2010).