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Evaluation of Seismic Response of Hybrid Buckling Restrained Braced Frames

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Abstract: *Buckling restrained braced frame (BRBF) is a distinct kind of bracing system in which the braces can reach its yield strength under tension and compression. Despite solving many problems of the conventional bracing, residual displacement is still the most disturbing issue caused by its low post yield stiffness. One way to solve this is the use of different steel materials in the steel core from which its name arises as hybrid buckling restrained braced frame (HBRBF). Most of the studies compare the performance of the two systems under far fault earthquakes. This study looks at the effect of the problematic near fault ground motions with its velocity pulses and high frequency content. Non-linear static and dynamic time history analysis were performed on a building with 3 different heights using BRBF and 2 HBRBF compositions. The HBRBF system is shown to have a better performance based on the seismic factors and residual displacement.*

Keywords: *Hybrid buckling restrained brace, Near fault, Nonlinear analysis, Residual displacement*

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I. Introduction

Buckling of braces in conventional bracing system was found to have many disadvantages as it leads to degradation in both stiffness and strength [1], unbalanced vertical forces, and sometimes the fracture of compression brace under cyclic loading. This led to the development of buckling restrained braces (BRB). A restraining system consists of steel tube filled with mortar surrounds a steel core painted with de-bonding agent to prevent friction and stop the transfer of axial force from the steel core to the restraining system as shown in Figure 1. This leads to a drastic change in the behavior of the brace as illustrated in Figure 2. A nearly symmetrical response in both tension and compression improves the ductility of the system and its energy dissipation with almost no unbalanced vertical forces. A major downside for this system is the residual displacement as a result of its low post yield stiffness [2]–[4]. Sabelli et al. [5] investigated the performance of three and six story BRBF under the effect of 10 ground motions where the permanent deformation reached 60% of the maximum deformation during the earthquake. Fahnestock et al. [6] touched upon the same problem with the testing of large scale BRBF where they noticed large residual deformation under design based earthquake (DBE) and maximum considered earthquake (MCE) levels which imposes serious difficulties to return the building to service. In some cases it was favorable from economic perspective to tear down the building rather than fixing this damage [7], [8].

Different approaches were taken trying to solve this problem. Firstly a dual system combining both BRB and moment resisting frame (MRF) managed to noticeably reduce the residual displacement [4]. The use of shape memory alloys in a self-centering brace is another way to counteract this downside led to enhanced seismic performance limiting permanent deformations [7], [9], [10].

The last innovation was introduced by Atlayan and Charney [11] with a system called hybrid buckling restrained braced frame (HBRBF). The hybrid description came from using steel plates with different yield and different stress strain curves in the steel core, usually Low yield point (LYP) steel and high-performance steel (HPS). This combination in hybrid buckling restrained braces (HBRB) of LYP with its high strain hardening and HPS known for the high strength as in Figure 3, dissipates energy by the early yielding of LYP and prevents the degradation of both stiffness and strength. This difference in behavior reduces the permanent deformation under low to mid earthquakes.

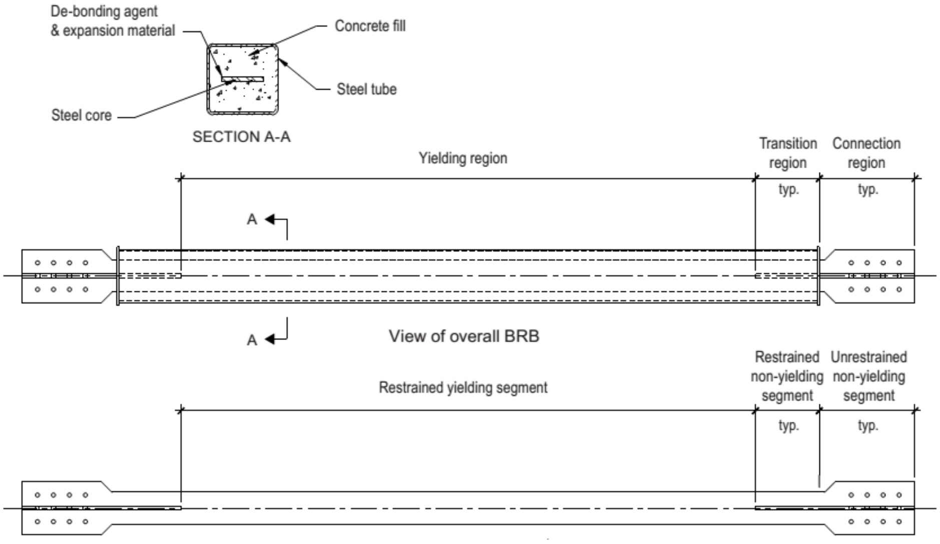


Figure 1 Components of BRB [4]

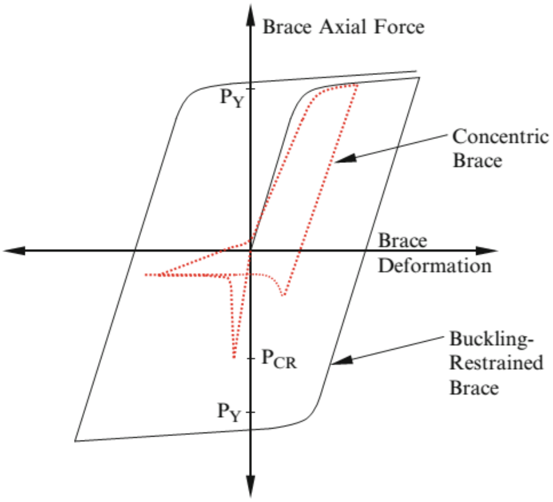


Figure 2 Behavior of BRB vs conventional braces [2]

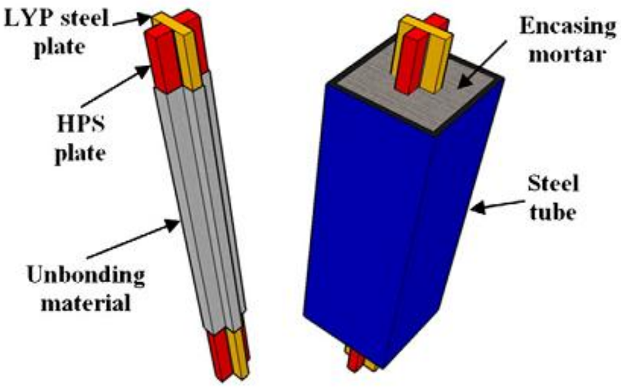


Figure 3 Composition of HBRB [11]

Atlayan and Charney [12] examined the performance of BRB and HBRB under 44 ground motion and concluded a very positive results with 30% and 10% drop in residual displacement and inter story drift respectively. Alborzi et al. [13] compared the behavior of conventional and hybrid BRB 5, 8, and 12 story subjected to earthquakes and found that HBRB has better response modification factor (R) with 20% less permanent deformation. Nearly the same deductions were found by Tahghighi and Alborzi [14] where HBRBF recorded better seismic performance factors. Hoveidae [15] studied the effect of including stainless steel in the steel core composition instead of LYP -as they are similar in having high strain hardening- because of the rarity of LYP steel in some markets and found the same success.

Further, effect of the near fault earthquakes cannot be neglected as it can cause extensive structural damage because of velocity pulses and high frequency contents in the time history and the small distance between the seismic source and the site offer little dissipation of this energy. Energy value and damage potential much exceeds its counterpart in far field earthquakes [16], [17]. Chopra and Chintanapakdee compared the performance of a single degree of freedom system (SDOF) under near fault and far fault earthquakes where the former caused larger strength demands. Structures in near fault domains in which its effect were neglected in seismic design were deemed to be unsafe [13], [18]. Studies of BRBs under near fault earthquakes have concluded that code provisions is not conservative and new recommendations should be provided [19], [20].

II. Building Description

Comparing the performance of BRBs and HBRBs has been done using 5-, 7-, and 9-story braced frames. The Plan and the perimeter frame of the studied building is as the one used by Bruneau et al. [21] and illustrated in Figure 4. A square plan with 45.7 m length, 5.5 m first story height, and 4 m typical height for the other stories. The building is located near an active fault and designed According to the provisions of AISC 341-10 and ASCE 7-10 [22], [23]. The analyses were performed on one of the braced bays.

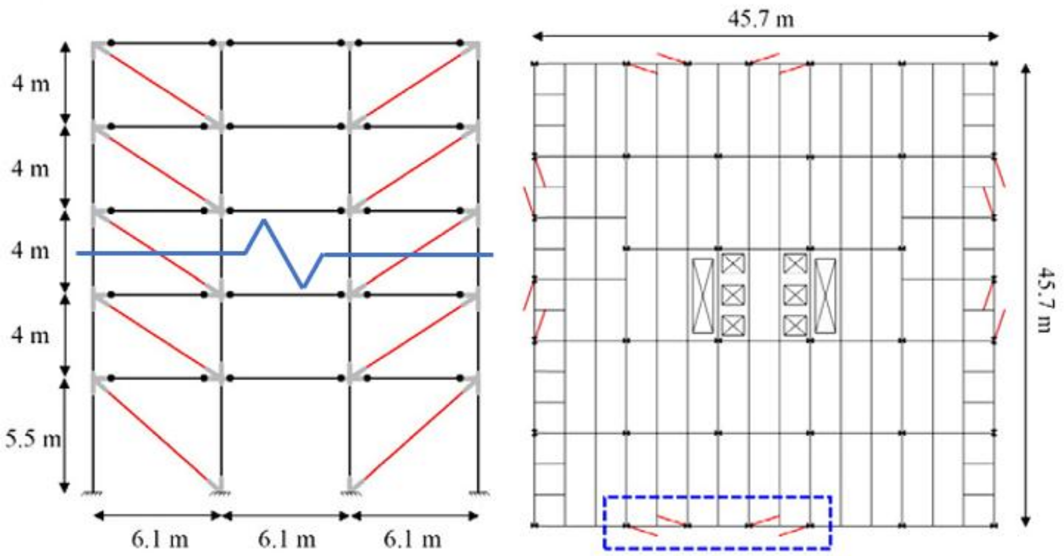


Figure 4 Elevation and typical plan of the investigated building respectively

Material characteristics are shown in Table 1 and St-52 is used for all columns and beams. To compare between BRBs and HBRBs, the composition of bracing members -illustrated in Table 2- in HBRBs were made in a way that the total area and strength of bracing members were kept the same as conventional bracing. Using the same area is beneficial in having the same stiffness and thus the same seismic forces. Using the same strength to have the same members in both systems because the design of columns and beams depends mainly on the adjusted brace strength. Columns are fixed and the bracing system is solely used for resisting lateral loads as a hinged connection is utilized between columns and beams.

Table 1 Material properties

	St-52	LYP 100	HPS70W	HPS100W
Fy (Mpa)	360	107	503	745
E (Gpa)	200	186	200	200

Table 2 HBRB composition

	Material	Conventional BRB	HBRB-1	HBRB-2
Area ratios	St-52	1.00	-	-
	LYP100	-	0.396	0.656
	HPS70W	-	0.631	-
	HPS100W	-	-	0.389
Total stiffness (*A/L)		200,000	199,938	199,952
Total strength (*A)		360.0	360.0	359.9

III. Ground Motion Records

To investigate the structural response 7 ground motion pairs from the peer ground motion database [24] were selected. The chosen records and a summary of their properties are shown in

Table **3**. To study the effect of near field earthquakes all the ground motions have a distance less than 10 Km between the fault rupture and the recording station with strong velocity pulses present in the time history with a range of magnitude between 6 and 7.3. In order to scale the ground motions, spectrum matching was not used in order to preserve the unique characteristic of the time history [25], [26]. A two-step scaling process explained in Charney's Seismic Loads-Guide to the Seismic Provisions of ASCE 7-10 [27] is applied here which scale for each building independently. The response spectrum of the chosen earthquakes before scaling and the 5% damped elastic design-based response spectrum are shown in Figure 5. Each pair of horizontal ground motions are rotated in fault normal and fault parallel directions as recommended by ASCE and FEMA publications [23], [25], [26].

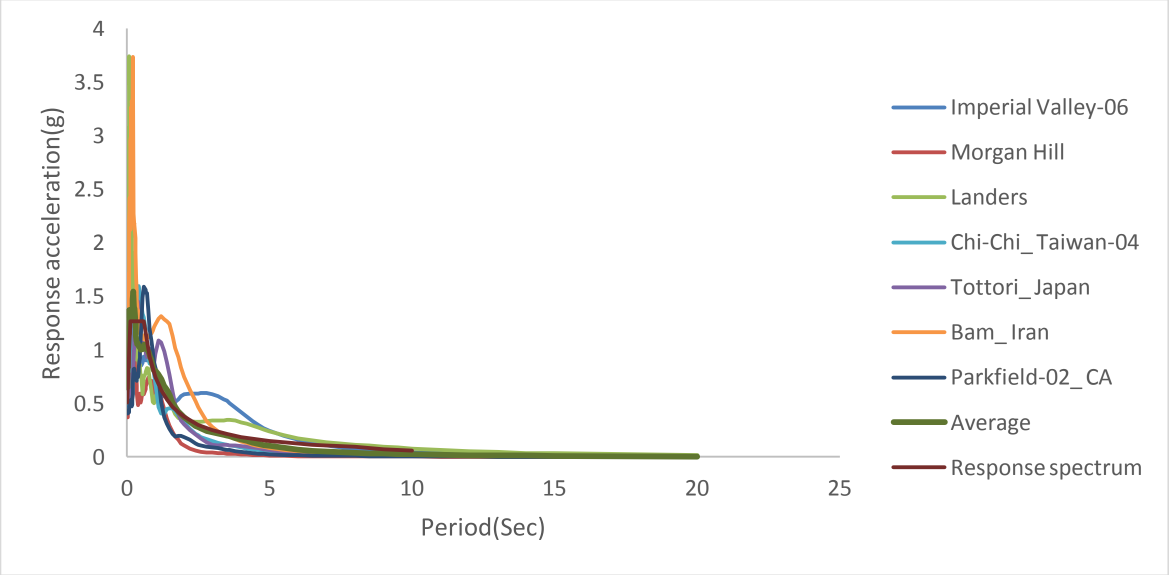


Figure 5 The single record and the 5% damped response spectrum

Table 3 Characteristics of the chosen seismic records

No.	Earthquake (RSN)	Year	Station	Magnitude	R_{rup}(Km)*	PGA (g)*
1	Imperial Valley-06 (181)	1979	El Centro Array #6	6.53	1.35	0.44
2	Morgan Hill (459)	1984	Gilroy Array #6	6.19	9.87	0.27
3	Landers (879)	1992	Lucerne	7.28	2.19	0.75
4	Chi-Chi_ Taiwan-04 (2734)	1999	CHY074	6.2	6.2	0.32
5	Tottori_ Japan (3965)	2000	TTR008	6.61	6.88	0.45
6	Bam_ Iran (4040)	2003	Bam	6.6	1.7	0.9
7	Parkfield-02_ CA (4097)	2004	Slack Canyon	6	2.99	0.35

*R_{rup} is the closest distance to the rupture plane, PGA is the maximum ground acceleration in the ground motion pair and RSN is the number of the earthquake in PEER ground motion database.

IV. Numerical Model

A 2D OpenSees [28] model was made to compare the pushover and time history performance of the BRB and HBRBs. Because the model contains the lateral framing system only, a leaning column was used to model the P-delta effects. Columns are fixed and rotated to resist lateral loads with their major axes and a rigid diaphragm is used at story levels. Gusset plates are presented in the model by rigid offsets at connections' locations.

Modeling of non-linear beams and columns were made using fiber sections. Steel02 material with its hysteretic behavior and isotropic hardening was used. Corotational truss element was used to model the bracing element and in the case of HBRBs two bracing members were placed on top of each other and connected in parallel. The material assigned to bracing members is steelMPF to model any difference in tension and compression behavior. To take account of the non-uniform cross section of the bracing member in the longitudinal direction as in Figure 1, a modified young's modulus is used to model the effective stiffness. All the materials are wrapped by the opensees fatigue material to model the low cycle fatigue. 2% Rayleigh damping [29] at fundamental and third modes was assigned to the models to take account of the inherent damping caused by connections and non-structural components.

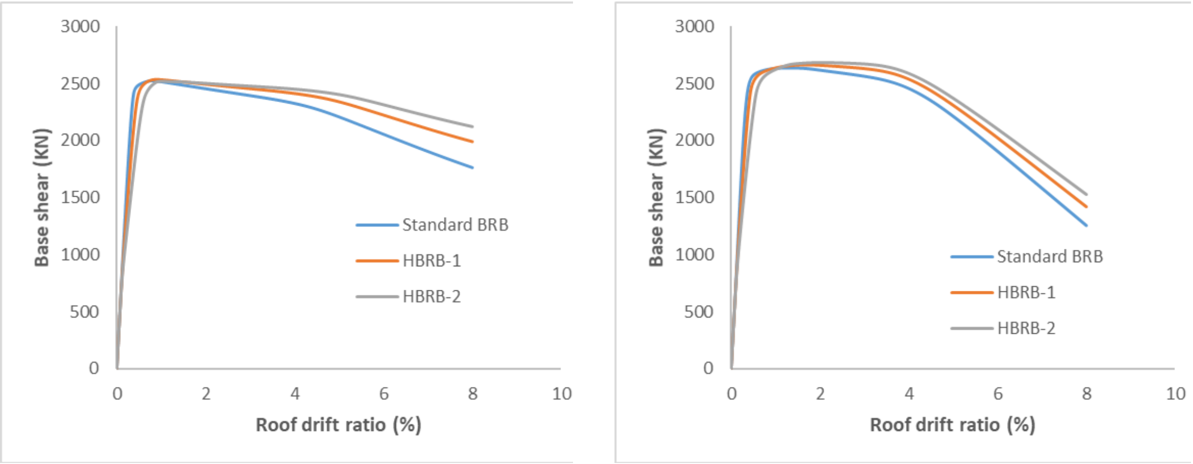
V. Nonlinear Pushover Analysis

As a precursor to the time history analysis, Non-linear static analysis gives a good indication about the behavior of the system. In addition to the lateral load the buildings were analyzed under a gravity load equal to the full dead load and 0.25 of the live load [23]. The distribution of lateral force is proportional to the story mass and fundamental mode shape according to FEMA P695 [30]. Base shear versus roof displacement ratio -up to 8%- for conventional bracing and the 2 hybrid compositions for the 3 buildings with different number of stories is depicted in Figure 6. The graphs clearly show the early yielding of BRBs accompanied by a better post yield stiffness which supports the theory. The destabilizing effect of P delta moment is also shown in the graphs.

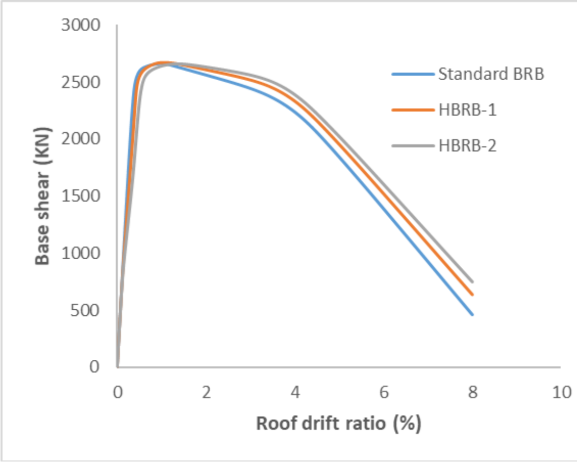
Seismic factors like response modification factor (R) and over strength factor (Ω) are calculated and shown in Table 4.

Table 4 Seismic factors for BRBs and HBRBs

		R	Ω
5-story building	Conventional BRB	20.00	1.15
	HBRB-1	20.91	1.15
	HBRB-2	21.66	1.14
7-story building	Conventional BRB	15.96	1.10
	HBRB-1	16.21	1.11
	HBRB-2	16.47	1.12
9-story building	Conventional BRB	12.35	1.11
	HBRB-1	12.63	1.11
	HBRB-2	12.68	1.11



a- 5-story building b- 7-story building



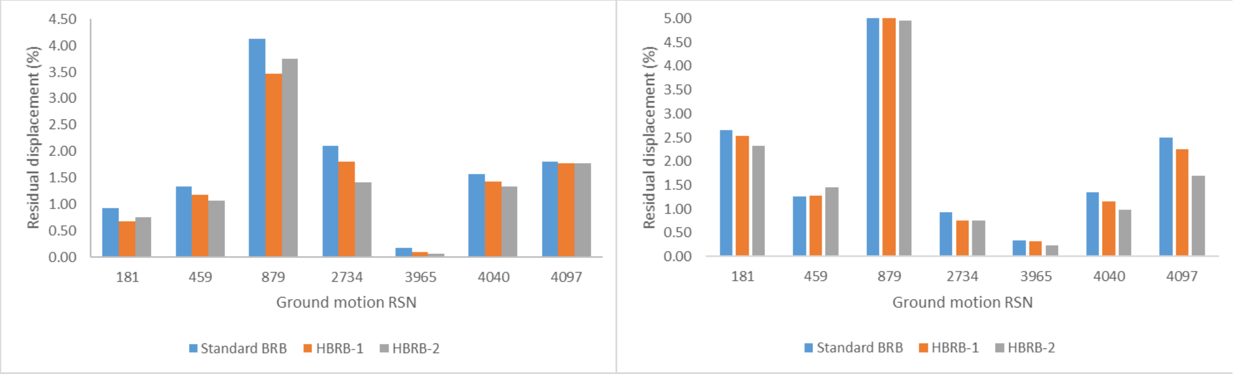
c- 9-story building

Figure 6 BRB and HBRBs Pushover curves for 5, 7, 9 story building respectively

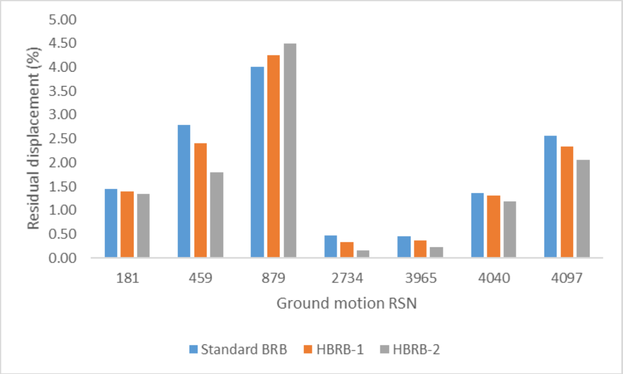
VI. Nonlinear Time History Analysis

The most accurate way to study the building performance was carried out under the effect of the 7 ground motions shown in

Table **3** in fault normal and parallel directions. Residual drift, inter-story drift ratio (IDR), and max roof displacement were the selected parameters to compare between BRBs and different HBRBs and the two orthogonal directions of ground motion. Residual roof displacement as it is the most compelling reason for the invention of HBRBs and the high cost it can cause for repairing the structure or even replacing it. The analysis showed that the use of the HBRB over conventional BRB has almost no effect on the max roof displacement, but it reduced the average residual displacement by 13.5%, 6%, and 5.5% in case of HBRB-1 and 16%, 14%, and 14% in case of HBRB-2 for the 5-, 7-, and 9-story building consecutively. The detailed results for this criterion are shown in Figure 7.



a- 5-story building b- 7-story building

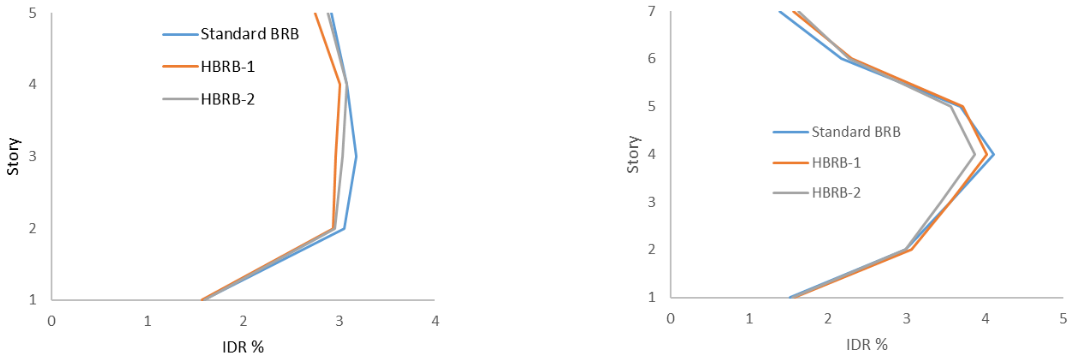


c- 9-story building

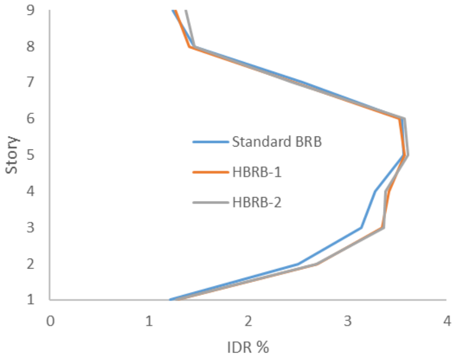
Figure 7 Comparison between residual displacement % for 5, 7, and 9-story building respectively.

IDR to compare between the various BRB systems and between the actual results under near fault earthquakes and the code provisions. The results were similar to the roof displacement ratio as no noticeable change was noticed in the max IDR but with a major improvement in the residual IDR. The max IDR exceeded 3% on average and reached 4% in the most critical case which highly surpass the code provisions that allow 2% max IDR. Figure 8 and Figure 9 depict the results for the max and residual IDR for the 5-, 7-, and 9-story building.

Another comparison was made to study the difference in performance under the two perpendicular directions: fault normal and fault parallel by recording the max roof story drift in all cases as shown in Figure 10. The graphs show that fault normal direction has a more severe effect in most of the cases.

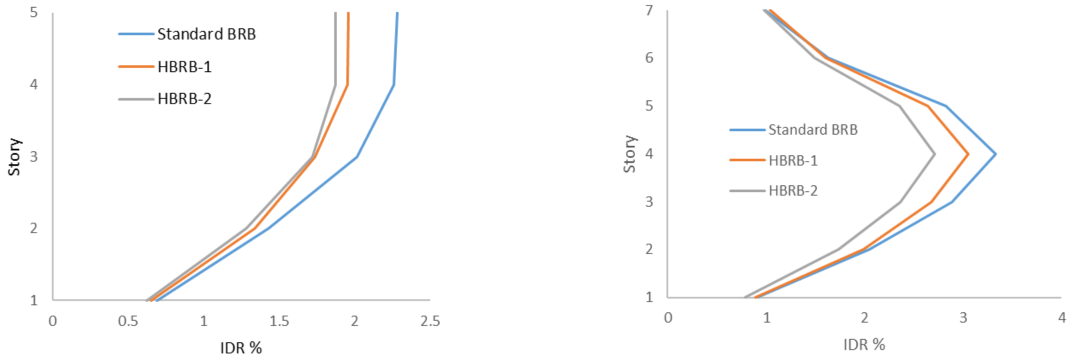


a- 5-story building b- 7-story building

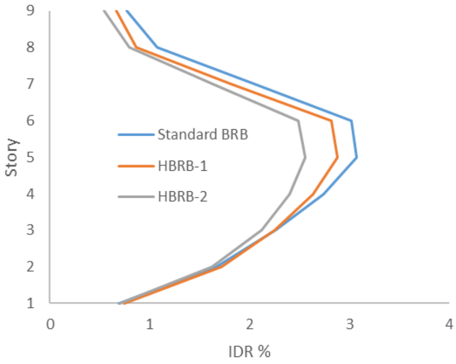


c- 9-story building

Figure 8 Max IDR for 5, 7, and 9-story building respectively

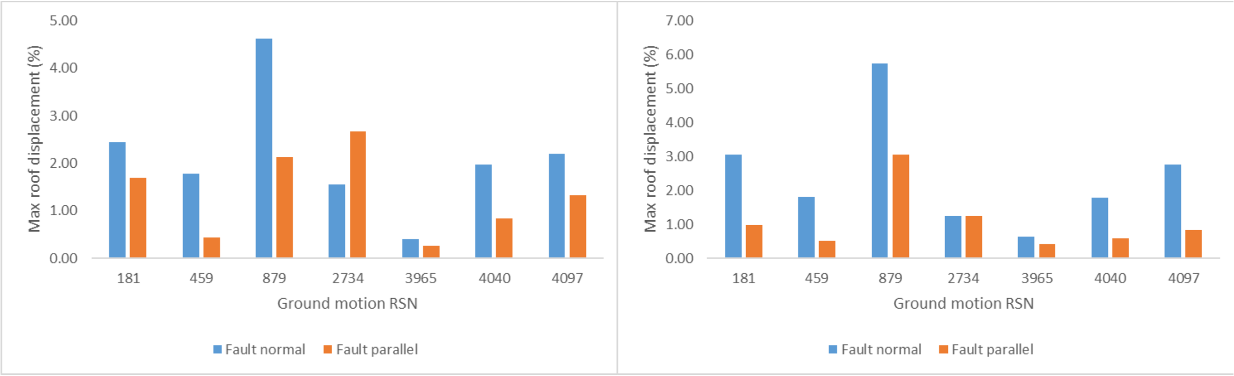


a- 5-story building b- 7-story building

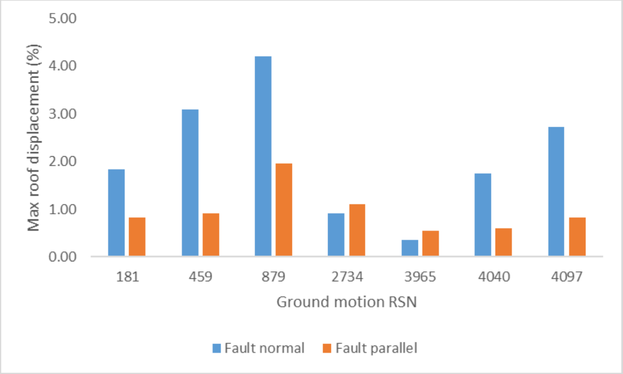


c- 9-story building

Figure 9 Residual IDR for 5, 7, and 9-story building respectively



a- 5-story building b- 7-story building



c- 9-story building

Figure 10 Comparison between max roof displacement% for 5, 7, and 9-story building respectively under fault normal and parallel directions

VII. Conclusions

In this paper the performance of HBRBs in comparison to BRBs under near field ground motions was examined for 3 buildings with varying heights using nonlinear pushover and time history analysis. From the performed numerical analyses these were concluded:

- Although increasing the hybridity of the bracing leads to an early yielding it has the most favorable post yield stiffness.
- An obvious decrease in R factor happens with increasing the building height but using HBRB can lead to a slight improvement with no effect on the over-strength factor.
- High magnitude earthquakes nearly eradicated the effect of HBRBs as it recorded almost the same permanent displacements, however Implementation of HBRBs -especially the most hybrid composition- reduced it by 15% on average which can drastically lessen the repairing cost.
- No correlation was found between the residual displacement and max story drift.
- Regrading IDR using the HBRB system vastly improve the residual IDR with no noticeable effect on the mas IDR % similar to max roof drift.
- Under near fault earthquakes the HBRB hasn’t reached the high limits it achieved under far fault earthquakes as it achieved 20% to 30% reduction in residual displacement in previous research.
- New code provisions should be applied to near fault earthquakes different than that of far fault as the IDR is highly unsafe under the effect of earthquake ground motions.
- Despite fault normal direction being more critical in almost all the studied ground motions, Studying the two orthogonal directions is essential as this can change in some rare cases.

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