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Multi-material core as self-centering mechanism for buildings incorporating BRBs

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Abstract. Conventional buckling restrained braces used in concentrically braced frames are expected to yield in both tension and compression without major degradation of capacity under severe seismic ground motions. One of the weakness points of a standard buckling restrained braced frame is the low post-yield stiffness and thus large residual deformation under moderate to severe ground motions. This phenomenon can be attributed to low post-yield stiffness of core member in a BRB. This paper introduces a multi-core buckling restrained brace. The multi-core term arises from the use of more than one core component with different steel materials, including high-performance steel (HPS-70W) and stainless steel (304L) with high strain hardening properties. Nonlinear dynamic time history analyses were conducted on variety of diagonally braced frames with different heights, in order to compare the seismic performance of regular and multi-core buckling restrained braced frames. The results exhibited that the proposed multi-core buckling restrained braces reduce inter-story and especially residual drift demands in BRBFs. In addition, the results of seismic fragility analysis designated that the probability of exceedance of residual drifts in multi-core buckling restrained braced frames is significantly lower in comparison to standard BRBFs.

Keywords: buckling restrained brace; multi-core BRB; nonlinear time history analysis; fragility analysis

1. Introduction

Buckling restrained braced frames (BRBFs) for seismic load carrying, have been broadly used in recent years. The behavior of a BRB varies from a conventional brace element because it yields in both tension and compression without degradation of compressive capacity.

A conventional buckling restrained brace member is typically comprised of a steel core and a buckling restraining mechanism. The restrainer inhibits the brace overall buckling and minimizes the core local buckling. Therefore, the core can yield in compression as well as tension. Several findings exist on BRBs' seismic performance in the literature. Black *et al*. (2000) performed component testing of BRBs and modeled a hysteretic curve to compare the test results. It was found that the hysteretic curve of a BRB is stable, symmetrical, and ample. Inoue *et al*. (2001) introduced buckling restrained braces as hysteretic dampers to increase the ductility of building structures. Qiang (2005) examined the use of BRBs for practical applications in buildings located in Asia. Clark *et al*. (1999) proposed a design method for buildings including BRBs. Sabelli *et al*. (2003) investigated seismic demands on BRBs through nonlinear time history analysis of braced frames.

Hoveidae and Rafezy (2012) investigated the global buckling behavior of all-steel BRBs through finite element analysis method. Guo *et al*. (2017) proposed a new type of BRBs namely core-separated buckling-restrained brace (CSBRB), and theoretically and experimentally investigated the behavior of the brace. The results showed that the material utilization efficiency of the CSBRB is significantly improved compared with common BRB, since its cross-section spreads outwards by spacing two cores, thus improving the flexural rigidity of the restraining system.

The significant shortcoming of an ordinary buckling restrained braced frame is the low post-yield stiffness and consequently large residual deformation under moderate to severe ground motions. Current research by McCormick *et al*. (2008) has revealed that residual drifts after tremors that are greater than 0.5% in structures, may characterize a complete loss of the structure from an economic view. Studies have shown that it is compulsory to consider these residual drifts to fully characterize the performance of a structural system after a seismic excitation and the prospective destruction that the system has suffered (Christopoulos *et al*. 2003, Pampanin *et al*. 2003, Wu *et al*. 2004).

McCormick *et al*. (2008) conducted a study of one-occupied building at Kyoto University in Japan and conducted a review of previous research in Japan, including consideration of both physiological and psychological effects of residual drifts on inhabitants. They concluded that residual drifts of 0.5% are generally perceivable by occupants, and occupants of a building experience dizziness and nausea as residual drifts approach 1.0%. More decisively, they concluded that in Japan, it was generally less costly to rebuild a structure than to repair it when an earthquake resulted in residual drifts greater than 0.5%.

The quantification of residual deformations of buckling restrained braced frames and special moment-resisting

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frames has been explored by Sabelli *et al*. (2003), in which the seismic response of 3 and 6-story buckling restrained braced frames subjected to a set of design-based earthquake (DBE) ground motions was evaluated. Based on the findings, average of maximum residual story drifts of 0.5 and 0.7% were reported, respectively. Under a set of maximum considered earthquake (MCE) ground motions, the mean residual drift value amplified to 2.2%.

Pettinga *et al*. (2007) performed nonlinear analyses of 4-story BRBFs and found the average maximum residual story drifts between 0.85 and 0.89% when subjected to New Zealand design-level earthquakes. Fahnestock *et al.* (2007) performed nonlinear analyses on a 4-story BRB frame and determined the mean maximum residual story drifts as 0.5 and 1.2% under DBE and MCE ground motion ensembles, respectively. In a hybrid test of the same scaled-down frame, the observed experimental maximum residual story drifts were determined as 0.2, 1.3, and 2.7% under individual ground motions representing the frequently occurring earthquake (FOE, 50% in 50 years), DBE, and MCE levels, respectively. Similarly, nonlinear analyses directed by Tremblay *et al*. (2008) predicted median residual drifts varying between 0.84 and 1.38% under DBE ground motion for 2 to 16-story BRB frames.

Residual drifts may be reduced or completely eliminated by using systems that have self-centering capability. This approach has been successfully implemented in steel moment-resisting frames (Christopoulos *et al*. 2002, Garlock *et al*. 2005, Ricles *et al*. 2001, Rojas *et al*. 2005, Kim and Christopoulos 2009). Tremblay *et al*. (2008) showed that residual drifts could be entirely eliminated under DBE ground motions by using self-centering braces, the development of which is described in Christopoulos *et al*. (2008). However, the drawback of self-centering braces is the increase in the cost of the systems. They found that one of the main downsides of yielding hysteretic energy dissipative systems like BRBs is that they become active only after they sustain inelastic deformations. Thus, they are not effective in providing damping under low intensity vibrations.

Hoveidae *et al*. (2015) proposed a new type of buckling restrained brace, called short-core all-steel buckling restrained brace, in which a shorter core component was serially connected to a semi rigid non-yielding member. The results of extensive nonlinear time history analyses showed that the short-core BRBs can considerably reduce the residual drifts of BRBFs.

Furthermore, Pandikkadavath and Sahoo (2016) proposed a type of bracing system called hybrid brace, in which a buckling restrained brace was serially connected to a buckling type brace. The results of dynamic analyses showed that the hybrid brace could significantly reduce the residual drifts of the braced frames.

Chou *et al*. (2016) experimentally and theoretically investigated the seismic response of dual-core self-centering sandwiched BRBs. The results indicated that the proposed BRBs provide stable hysteretic response and high energy dissipation capacity before low cycle fatigue fracture.

Craft and Jennifer (2015) investigated the seismic response of BRBFs with elastic stories in height. The analyses results showed that providing elastic stories can significantly reduce the residual drifts in BRBFs. Additionally, Amador *et al*. (2015) studied the seismic response of dual buckling restrained braced frames. They determined that if the flexible moment resisting frames provide at least one-sixth of the lateral stiffness of the dual structural system while remaining practically undamaged after the ground motion, the system will show adequate self-centering behavior in spite of the fact that the bracing system may develop significant plastic behavior.

In another work, the seismic demands of low and mid-rise BRBFs and dual-BRBFs were studied using the probabilistic seismic demand analysis. The results exhibited that using of buckling restrained braced frames as dual system could significantly decrease residual drift demands. In addition, deterioration in moment resistant frames makes a slight effect on dual-BRBFs demands. Besides, it was found that deterioration in dual-BRBFs is not serious because of large stiffness of BRBs (Deylami and Mahdavipour 2016). Dong *et al*. (2017) proposed an innovative self-centering buckling restrained brace for mitigating seismic response of bridge structures with double column piers. The research outcomes indicated that the proposed system can reduce residual drifts and exhibited moderate energy dissipation capacity.

Recently, Atlayan and Charney (2014) studied the behavior of hybrid BRBFs in which a hybrid core component including low-yield point steel (LYP), high performance steel, and A36 steel was implemented. The results showed that the hybrid BRBF experiences smaller residual drifts in comparison to standard BRBFs.

The main objective of this paper is to introduce a Multi-Core Buckling Restrained Brace (MCBRB) in order to have a better control on inter-story and especially residual story drift demands. LYP grade steel proposed by Atlayan and Charney (2014) for BRB core material, is available in plates in Japan market, but currently not available in other markets such as Iran. Due to the low yield point and high ductility, the LYP grades have been specifically developed and studied extensively for the development of the axial-yield type hysteretic dampers. Another alternative for highly ductile, low strength steel, is stainless steel (SS). This paper aims to investigate the possibility of using stainless steel together with a high performance steel material as BRB core materials. In the proposed MCBRB, the stainless steel component of the BRB core yields earlier than the carbon steel and the energy dissipation due to early yielding helps the multi-core BRBF to minimize the response under low to mid-level tremors. The high performance steel (HPS) as another material in the core, provides the strength of the brace, and the high strain hardening of stainless steel material is likely to counteract the low post-yield stiffness of the standard BRBFs and to reduce the possibility of dynamic instability under high intensity ground motions. The main purposes are to acquire better performance, to minimize the residual displacements at design basis and maximum considered earthquake levels, and to increase the reliability of the existing systems. While enhancing the performance, it is also necessary to preserve the economic impact at a minimum.

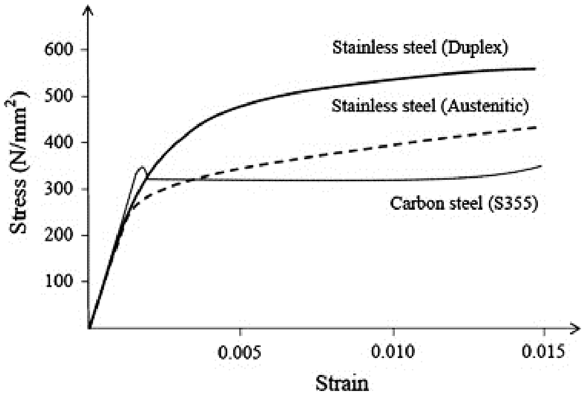

Fig. 1 Comparison of stress-strain curves in stainless steel and carbon steel (Gardner *et al*. 2006)

2. MCBRB material combination

Multi-core BRB proposed in this paper is developed by combining two steel materials with different yield strengths in a single brace. It is supposed that different steel cores are connected in parallel. The paper aims to compare the seismic performance of Multi-Core Buckling Restrained Braced Frames (MCBRBFs) and standard BRBFs. The total brace stiffness and strength in a multi-core BRB is kept the same as the standard BRB during the brace design process. The stiffness is not changed in order to make a distinct and real comparison between standard and MCBRBFs. In this case, the standard BRBF and MCBRB will absorb the same level of seismic force. Also, since the beam and column design in BRBFs depends on the adjusted brace strengths, the total strength of the brace was kept unchanged, so that the same beam and column sections could be used in standard and multi-core BRBs. Tables 1 and 2 provide material properties and combination of steel material used in the core of standard and multi-core BRB. In Table 2, the core area, total stiffness and total strength are shown as ratios. The steel core areas are specified in a way that total stiffness and strength of standard BRBs and MCBRBs will be the same. In the standard BRB, only structural steel A572-Gr50 with yielding strength of 353 MPa was implemented. However, in multi-core BRB, stainless steel 304L type, and high performance steel HPS-70W were used as core materials.

Stainless steel is approximately four times the cost of carbon steel and is not a common choice of material in building construction (Sarno *et al*. (2006)). Most common type of stainless steel (SS) grades used in structural purpose is austenitic and ferric type. Nevertheless, the ferric stainless steel alloys do not possess required ductility. Duplex material as another type of stainless steel has a two-phase microstructure of austenite and ferrite grains. Duplex stainless steels are generally stronger in comparison to regular austenitic or ferritic stainless steels. The austenitic stainless steel alloys have low yield stress and relatively high ultimate tensile stress compared to standard carbon steel. Moreover, stainless steel is durable and has excellent corrosion resistance features. Since, the core of a BRB is a small part in comparison to other structural elements, the application of stainless steel as a part of brace core does not significantly affect the total cost of construction (Atlayan and Charney (2014)). The higher strain hardening properties of stainless steel compared to regular steels used in BRB core may compensate the lower post-yield stiffness of a BRB, and decrease the residual drifts of BRBFs, subsequently. The comparison of strain-stress curves of carbon steel and stainless steel is provided in Fig. 1.

Table 1 Steel material properties used in the core of standard and multi-core BRB

	A572-G50	HPS-70W	SS (304L)
F_y (Mpa)	353	503	252
E (GPa)	186.2	201.3	194.5

Table 2 Material combination in standard and MCBRB

	Material	Standard BRB	MCBRB
Area ratio	A572-G50	1.00	-
	HPS-70W	-	0.46
	SS (304L)	-	0.48
Total stiffness (*A/L)	-	186.20	186.20
Total strength (*A)	-	353.00	353.00

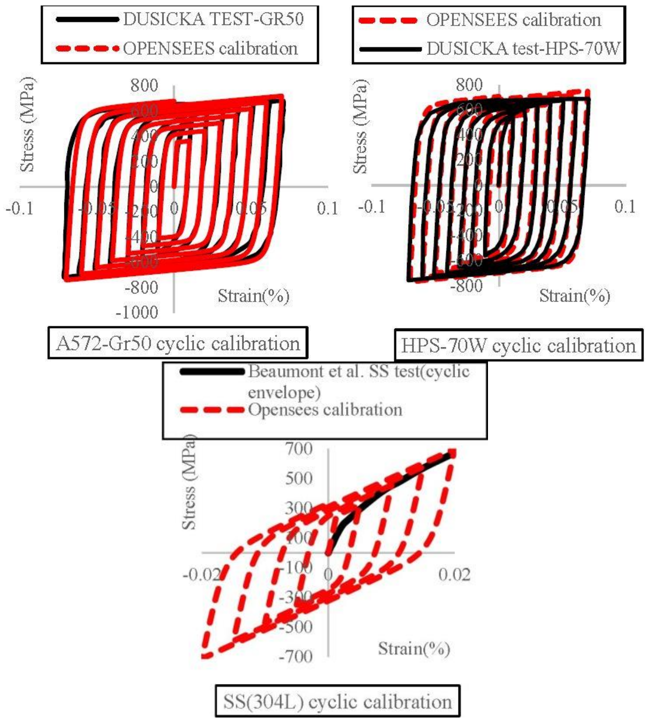

Fig. 2 Calibrated cyclic response of different steel materials

3. Material calibration

In order to accurately capture the response of structural models during nonlinear dynamic time history analysis, material calibration is conducted for cyclic response of steel materials used in BRB core. For this purpose, cyclic test results reported by Dusicka *et al.* (2007) were used to calibrate the cyclic responses of HPS-70W and A572-Gr50 steels. In addition, the test results by Beaumont and Annan (2016) were used for calibration of cyclic response of

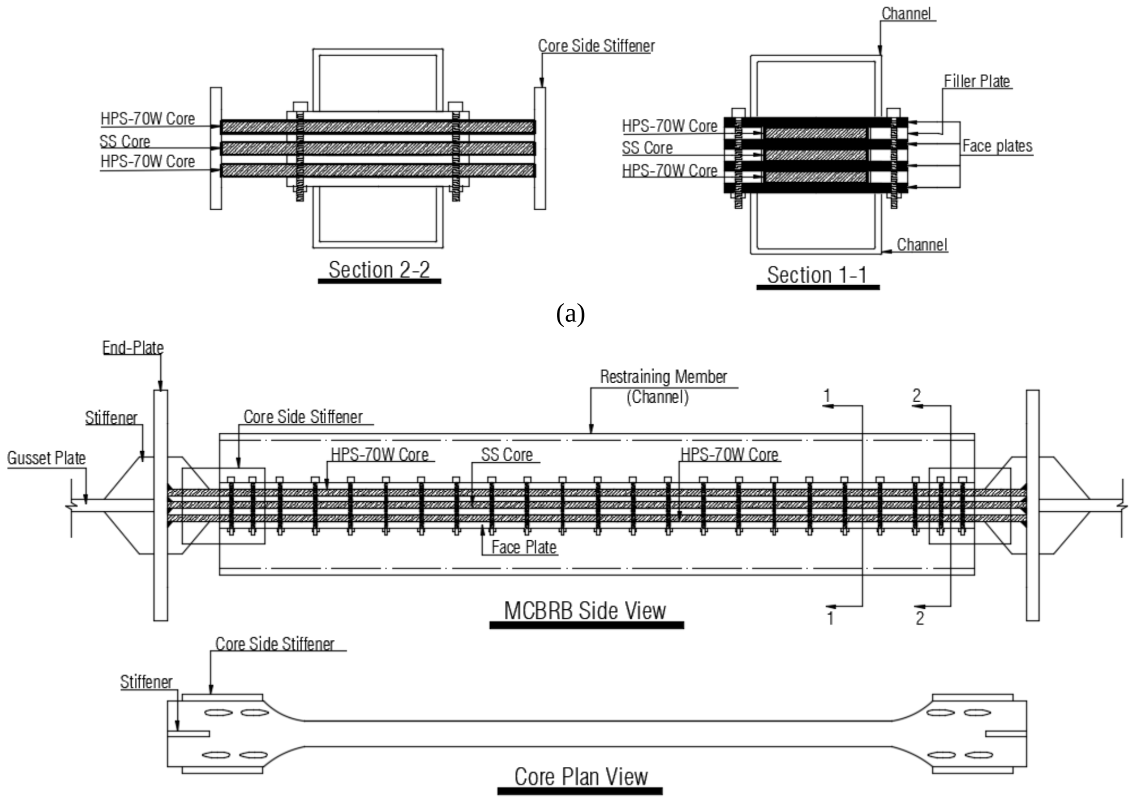

Fig. 3 (a) Cross section of proposed all-steel MCBRB, (b) Brace longitudinal and core plan views

stainless steel 304L. The calibration of material was made in OpenSees (2007). A single truss element was specified for the BRB core. The BRB core areas and lengths were set to the values in test specimens The Giuffre-Menegotto-Pinto (Steel02) material was implemented for HPS-70W and A572-Gr50 steels. Furthermore, Ramberg-Osgood material model was introduced for the stainless steel core. Fig. 2 represents the calibrated cyclic response of different steel materials. The steel02 material properties for HPS-70W including strain hardening ratio, b, transition parameters, CR_1, CR_2, R_0, and isotropic hardening parameters a_1 and a_2 were specified as 0.005, 0.925, 0.15, 40, 0.5, and 35, respectively. The corresponding values for Gr50 steel were defined as 0.006, 0.925, 0.15, 40, 1, and 40, respectively. Moreover, for stainless steel material, Ramberg-Osgood parameters, n and a, were introduced as 2.75 and 0.002, respectively. The cyclic calibrated material data was applied in nonlinear time history analysis in the next section.

4. Implementation of MCBRB in practice

Multi-core BRB may be developed in different detailing. The core components may be encased by a concrete filled steel tube. An all-steel encasing system may also be implemented in a MCBRB. Fig. 3 illustrates a proposed detail of a MCBRB. In such a detail, a stiffened end-plate is used to connect all core segments for equal elongation at the brace ends. This corresponds with the analytical model where the multi-core BRB is created by connecting the cores in parallel. The stiffened end-plates also increase the overall stability of the brace by preventing the core out of plane buckling. Face plates are provided between core components and a small gap maybe provided between the cores and face plates in order to accommodate core free axial deformations. A bolted connection is used to connect all face plates, as illustrated in Fig. 3(a). A connection part should be used beyond the end-plates for connecting the brace to the gusset plates. This paper aims to examine the seismic response of braced frames incorporating multi-core BRBs and does not emphasis on detailing and also design of a MCBRB. The exact performance of a multi-core BRB considering the effect of core arrangements and possible bending moments developed in the brace due to asymmetric core materials should be investigated through extensive finite element analyses and also laboratory physical tests, and may be considered as the topic of future studies.

5. Design of Archetype BRBFs

In order to compare the seismic behavior of standard and multi-core BRBFs, nonlinear dynamic time history analyses on three low to mid-rise archetypes including 4-story, 10-tory, and 14-story diagonally braced frames were conducted. In the Iranian building documents, the structure height for bracing the singular lateral resisting system is limited to 50 meters. This allows having buildings with the

Table 3 Seismic data in archetype building models

Site Class	*D*
PGA	0.35 g
Importance factor	1
Response modification factor	7
Base shear ratio, 4-story	0.1375
Base shear ratio, 10-story	0.117
Base shear ratio, 14-story	0.0925

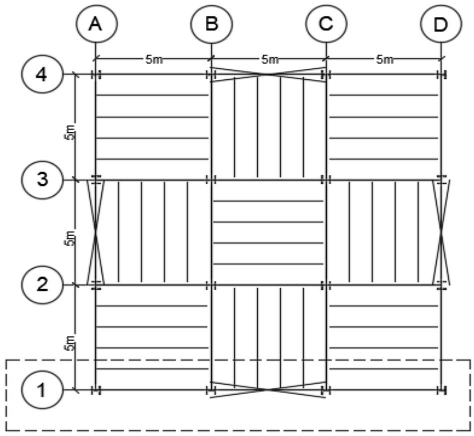

Fig. 4 Plan view of archetype models

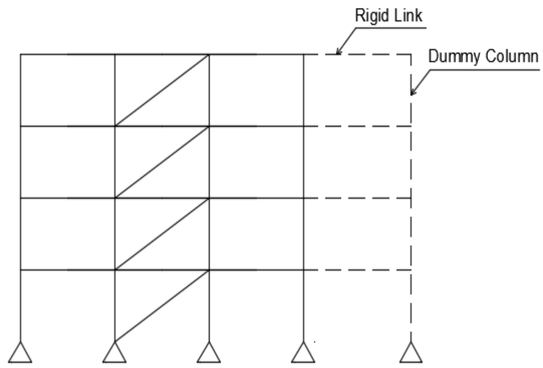

Fig. 5 The sketch of 4-story BRBF in OpenSees

selected story ranges and at most, 14 stories. The story height was set to 3.2 m which is a typical value in building construction. The braced frames were selected from code-based designed buildings. For this purpose, the seismic loading on archetype buildings was specified according to Iranian Earthquake code (2014) using ETABS-2015 software. Table 3 summarizes the seismic data for building models used for design purpose. A dead load of 5.2 and 5.6 KN/m^2 were assigned for stories and roof, respectively. In addition, the live loads assigned to the stories and roof were 2.0 and 1.5 KN/m^2, respectively. BRBs were modeled using single truss elements with axial stiffness property modifiers equal to 1.4, which account for the additional stiffness of brace connections, transition zones, and end parts. The design procedure included the p-delta effects as well. The Young modulus, yielding stress, and Poisson ratio of steel material were set to 186.2 GPa, 353 MPa, and 0.3, respectively. AISC (2010) regulations were used for design of steel frames. Fig. 4 illustrates the plan view of archetype models. In addition, Table 4 summarizes the designed section of beams, columns, and BRB core areas.

As represented in Fig. 5, frame-1 is selected for conducting two dimensional dynamic time history analyses in OpenSees software.

6. Description of models in OpenSees

Two dimensional dynamic time history analyses were conducted in OpenSees to evaluate the seismic response of diagonally braced standard and multi-core BRBFs. As discussed former, in order to compare the seismic behavior of standard and multi-core BRBFs, the lateral stiffness in two systems were kept constant. The capability of multi-core BRBs to reduce lateral inter-story and residual drifts was evaluated through nonlinear dynamic time history analysis and totally 264 analyses were conducted in OpenSees.

The two dimensional braced frames were assumed to have pinned connections at beam ends and also at the bases.

Table 4 Design data of beams, columns, and BRBs

Story	Column section			Beam section			BRB core area (cm^2)		
	4-Story	10-Story	14-Story	4-Story	10-Story	14-Story	4-Story	10-Story	14-Story
1	w14×109	w14×500	w14×730	w14×22	w14×22	w14×22	39	90	87.5
2	w14×109	w14×500	w14×730	w14×22	w14×22	w14×22	37.5	90	75
3	w14×48	w14×342	w14×550	w14×22	w14×22	w14×22	26	75	75
4	w14×48	w14×342	w14×550	w14×22	w14×22	w14×22	16	75	72.5
5	-	w14×233	w14×398	-	w14×22	w14×22	-	70	72.5
6	-	w14×233	w14×398	-	w14×22	w14×22	-	70	66
7	-	w14×120	w14×342	-	w14×22	w14×22	-	52	66
8	-	w14×120	w14×342	-	w14×22	w14×22	-	45	54
9	-	w14×53	w14×233	-	w14×22	w14×22	-	42	54
10	-	w14×53	w14×233	-	w14×22	w14×22	-	28	54
11	-	-	w14×120	-	-	w14×22	-	-	54
12	-	-	w14×120	-	-	w14×22	-	-	52
13	-	-	w14×61	-	-	w14×22	-	-	52
14	-	-	w14×61	-	-	w14×22	-	-	36

Table 5 Specification of selected ground motion records (ATC-63, far-field record set)

Record No.	Magnitude	Year	Event Name	PGA_{max} (cm/s^2)	PGV_{max} (cm/s)
1	6.7	1994	Northridge	0.52	63
2	6.7	1994	Northridge	0.48	45
3	7.1	1999	Duzce, Turkey	0.82	62
4	7.1	1999	Hector Mine	0.34	42
5	6.5	1979	Imperial Valley	0.35	33
6	6.5	1979	Imperial Valley	0.38	42
7	6.9	1995	Kobe, Japan	0.51	37
8	6.9	1995	Kobe, Japan	0.24	38
9	7.5	1999	Kocaeli, Turkey	0.36	59
10	7.5	1999	Kocaeli, Turkey	0.22	40
11	7.3	1992	Landers	0.24	52
12	7.3	1992	Landers	0.42	42
13	6.9	1989	Loma Prieta	0.53	35
14	6.9	1989	Loma Prieta	0.56	45
15	7.4	1990	Manjil, Iran	0.51	54
16	6.5	1987	Superstition Hills	0.36	46
17	6.5	1987	Superstition Hills	0.45	36
18	7	1992	Cape Mendocino	0.55	44
19	7.6	1999	Chi-Chi, Taiwan	0.44	115
20	7.6	1999	Chi-Chi, Taiwan	0.51	39
21	6.6	1971	San Fernando	0.21	19
22	6.5	1976	Friuli, Italy	0.35	31

Columns in the braced spans were oriented to resist lateral forces through strong axis bending. Nonlinear beam-column elements with fiber section were used to model beams and columns. The BRB elements included two parts serially connected together, one part, which represents the yielding portion of the brace core, was modeled by a force-beam-column element. The end part of the BRB was modeled with elastic-beam-column element which represented the elastic response of brace end-connection and also the non-yielding portion of the core plates. Based on previous studies (Sabelli *et al.* 2003), in a common BRB, the length of yielding part of the core segment is approximately equal to 50 to 60% of the work- point to work-point length of the brace. The work-point to work-point length is the length of the line connecting the centerlines of beam and column at the brace ends. The zero-length elements were used to model the pinned connection of beam and brace ends. To consider the P-delta effects, a dummy column was used in the model. In Fig. 6, an OpenSees model of 4-story BRBF is shown. Dummy columns were included to account for the additional stiffness required at each level in order to calibrate the model, which additional stiffness represents the combined stiffening effect of those elements of the building not explicitly included in the two dimensional model (e.g. non-structural components, partition walls, etc.). The dummy columns were modeled as elastic beam-column elements. These columns had moments of inertia and areas about two orders of magnitude larger than the frame columns in order to represent aggregate effect of all the gravity columns. The columns were connected to the beam-column joint by zeroLength rotational spring elements with very small stiffness values so that the columns did not attract significant moments. Truss elements as rigid links were used to connect the frame and leaning columns and transfer the P-Delta effect. The trusses had areas about two orders of magnitude larger than the frame beams in order to represent aggregate effect of all the gravity beams. Gravity loads tributary to the frame members were assigned to the frame elements while the remaining gravity loads were applied to the leaning columns. The amount of gravity load applied on each dummy column was around 1000 KN. Inherent damping was modeled as Rayleigh damping by setting the critical damping ratio to 2% at the fundamental and third modes of the structure. Steel02 material with isotropic hardening rule was assigned to all beams, columns, and BRBs. The hardening parameters of the steel were introduced to the model based on the calibration data represented in Fig. 2.

In the multi-core BRBF, it was assumed that different steel cores are connected in parallel, thus, in the numerical model, two brace elements were assigned on top of each other. The rigid diaphragm at the story levels was modeled using the constraint of equal degree of freedom of story nodes. A lumped mass system was considered in dynamic time history analysis. The procedure for the modeling of braces and other structural elements was similar to that used in another paper by the author, in which the OpenSees models were verified by test results.

7. Nonlinear dynamic time history analysis

7.1 Selection of ground motion records

Earthquake engineering practice is gradually using nonlinear response history analysis to investigate the performance of structures. This thorough technique of time

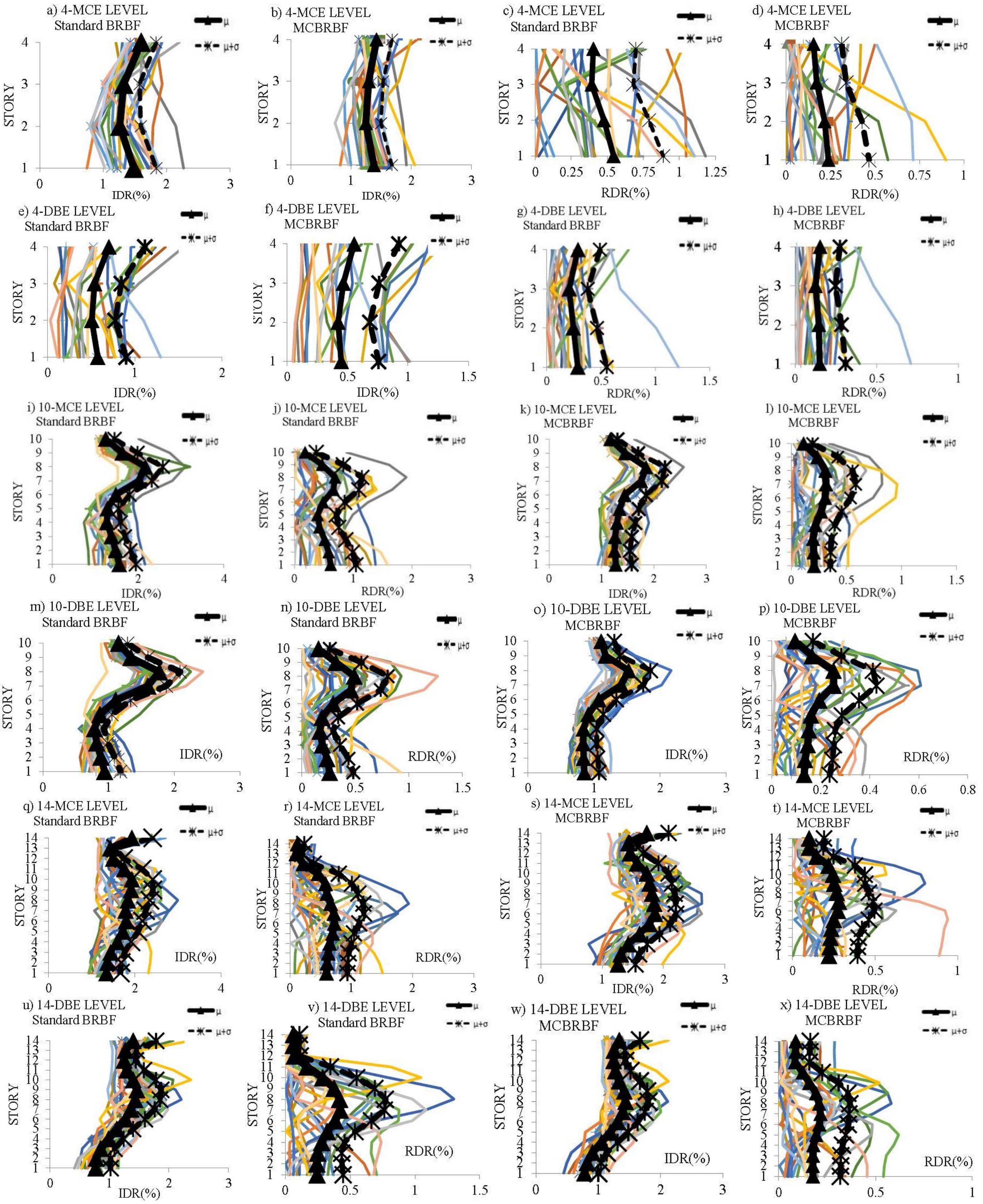

Fig. 6 IDR and RDR demands in BRBFs under selected ground motions

history analysis requires selection and scaling of ground motion records appropriate to selected hazard levels. Thus, ground motions are scaled to characterize a range of earthquake intensities up to collapse level ground motions.

In this paper, twenty-two far-field ground motion records suggested by ATC-63 (2008) were selected to perform nonlinear time history analyses. Table 5 summarizes the selected records and their specifications. Two hazard levels were selected for the analysis, first DBE level which corresponds to the design basis earthquake with an occurrence probability of 10% in 50 years, and the latter, MCE level, which corresponds to the maximum considerable earthquake with occurrence probability of 2% in 50 years. SeismoMatch (2016) software was used to closely scale and match the selected records to DBE and MCE earthquakes for periods ranging from 0.2T to 1.5T, where *T* is the natural period of the structure in the fundamental mode for the direction of response being analyzed. The spectral matching method was used to match the ground motion records.

Spectral matching of ground motions is defined as the modification of a real recorded earthquake ground motion in some manner such that its response spectrum matches a desired target spectrum across a period range.

The target DBE and MCE earthquakes were assumed as the design earthquake for soil type III, and 1.5 times the design earthquake, respectively, which could be found in the Iranian seismic code for buildings (2014). SeismoMatch is an application capable of adjusting earthquake accelerograms to match a specific target response spectrum, using the wavelet algorithm. It is also possible to concurrently match a number of accelerograms, and then obtain a mean matched spectrum whose maximum misfit respects a pre-defined tolerance. Since the matching procedure depends on the fundamental period of structure, the matching procedure was conducted separately for 4, 10, and 14-story BRBFs and the corresponding matched records were used in OpenSees. It should be noted that the frequency content of the records during matching in SeismoMatch software is closely kept unchanged.

7.2 Response history analysis results

Nonlinear time history analysis was performed to assess the seismic response of standard and multi-core BRBF under DBE and MCE earthquakes and the maximum of mean absolute values of inter-story and residual story drifts were computed as a result.

Fig. 6 depicts the Inter-story Drift Demand (IDR) and Residual Drift Demand (RDR) in 4-story, 10-story, and 14-story standard BRBFs and MCBRBFs at two hazard levels. Several statistical quantities of RDR and IDR demands, such as mean (μ), standard deviation (σ), and (μ+σ) are evaluated for all analytical models. The μ and (μ+σ) values of drift response are demonstrated in Fig. 6. Furthermore, Tables 6 and 7 summarize the maximum of mean values of IDR and RDR demands in standard and multi-core BRBFs subjected to selected ground motion records.

As can be deducted from Fig. 6, the multi-core BRBs reduce the lateral inter-story and especially the residual drift demands in the braced frames. This fact can be associated to the higher strain hardening of stainless steel material and the higher post-elastic stiffness of MCBRBF, consequently. These findings are in a good agreement with relevant previous research results (Atlayan and Charney 2014, Hoveidae *et al.* 2014, Pandikkadavath and Sahoo 2016).

As represented in Tables 6 and 7, and also Fig. 6, the inter-story drift demands at DBE hazard level in all braced frames are less than 2% which is consistent with design

Table 6 IDR and RDR demands in Standard BRBFs (%)

No. of Stories	MCE Hazard		DBE Hazard	
	$RDR_{\text{max-average}}$	$IDR_{\text{max-average}}$	$RDR_{\text{max-average}}$	$IDR_{\text{max-average}}$
4	0.54	1.60	0.29	0.70
10	0.70	2.17	0.50	1.77
14	0.72	1.93	0.43	1.46

Table 7 IDR and RDR demands in MCBRBFs (%)

No. of Stories	MCE Hazard		DBE Hazard	
	$RDR_{\text{max-average}}$	$\text{IDR}_{\text{max-average}}$	$RDR_{\text{max-average}}$	$IDR_{\text{max-average}}$
4	0.24	1.42	0.15	0.55
10	0.32	1.85	0.25	1.52
14	0.28	1.85	0.21	1.43

rules. Based on the analysis results and data represented in Tables 6 and 7, at DBE hazard level, the multi-core BRBs reduce the inter-story drifts up to 21%, 14%, and 2%, in 4,10, and 14-story BRBFs, respectively. The corresponding value of RDR reduction is approximately 50% in all braced frames. Furthermore, at MCE hazard level, the multi-core BRBs decrease the inter-story drifts up to 11%, 14%, and 4%, in 4,10, and 14-story BRBFs, respectively. The corresponding value of RDR reduction at MCE hazard level is almost 50% in all BRBFs. Based on time history analysis results, the residual drifts in MCBRBFs are significantly lower in comparison to standard BRBFs. Therefore, the multi-core BRBs are found to counteract the low post-yield stiffness of BRBFs. However, multi-core BRBs inconsiderably affect the maximum inter-story drift demand of BRBFs. Thus, the MCBRBs are able to significantly enhance the re-centering capability and reduce the residual drifts of BRBFs.

8. Seismic fragility analysis

A seismic fragility curve characterizes the likelihood of reaching or exceeding a damage state at an identified seismic hazard level. Hence, log-normal probability density function has been considered for the fragility analysis in this paper, in which μ and σ values of the Engineering Demand Parameter (EDP) have been calculated for all the ground motions. The probability of exceedance of each demand parameter, calculated using a cumulative normal distribution function (ϕ), can be expressed as follows

$$P(EDP > x) = 1 - F(\lambda) = 1 - \phi\left(\frac{\ln(x) - \mu}{\sigma}\right), \quad x > 0 \qquad (1)$$

Where, $F(\lambda)$ is the cumulative distribution function (Ghowsi and Sahoo 2015).

The story drift and residual drift responses are usually used as indicators of damage in a structure. The fragility curves were developed for all study frames considering the maximum inter-story and residual drifts as damage parameters. The probabilities of collapse were calculated by fitting the fragility curves to the IDR and RDR data acquired from nonlinear time history analyses of standard and multi-core BRBFs subjected to predefined ground

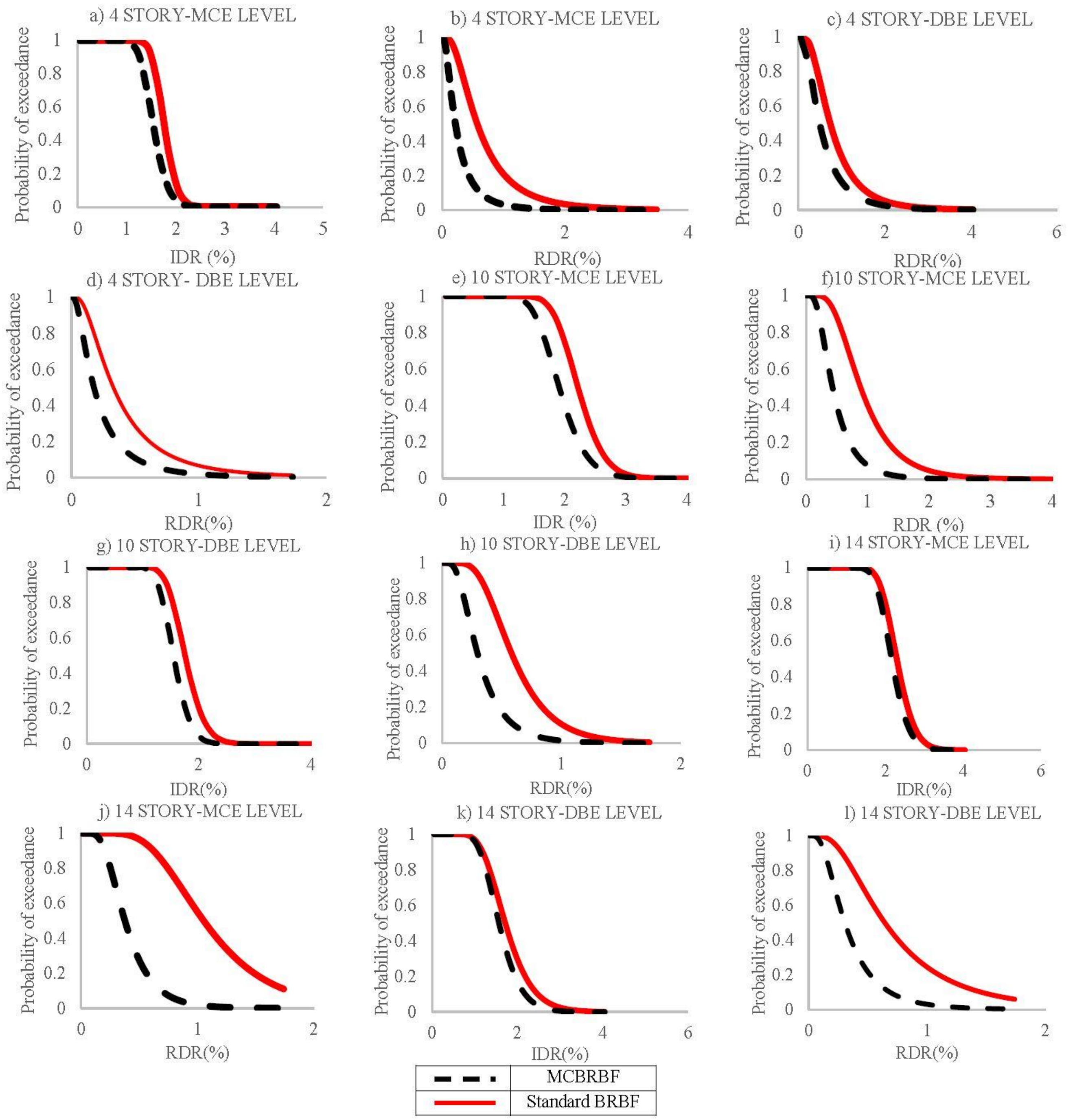

Fig. 7 Peak IDR and RDR fragility curves in multi-core and standard BRBFs

motions record set. Fig. 7 depicts the probability of exceedance of the absolute peak IDR and RDR responses in MCBRBFs and standard BRBFs. As shown in Fig. 7, the probability of exceeding the peak IDR and RDR values in standard BRBs is higher in comparison to multi-core BRBFs.

In all 4,10, and 14-story braced frames, the fragility curves of RDR and IDR demands in multi-core BRBFs stay below the fragility curves of standard BRBFs. In the other words, multi-core BRBFs exhibit significantly lower probability of exceedance of IDR and especially RDR response in comparison to standard BRBFs, at both MCE and DBE hazard levels. The maximum difference between the exceedance probability of RDR response of standard and multi-core BRBFs belongs to 14-story building under MCE earthquakes. This phenomenon can be associated to the higher strain hardening of stainless steel provided in multi-core buckling restrained brace. Hence, multi-core BRBs are found to be capable of solving the main drawback of BRBFs, which is large residual deformations, and can be distinguished as replacements for ordinary buckling restrained braces. Since, the core of a BRB is a small part in comparison to other structural elements, the application of stainless steel as a part of brace core does not significantly affect the total cost of construction. However, the results of accurate finite element analysis and also experimental observations would be more affirmative to better recognize the seismic response of proposed multi-core BRBs.

9. Conclusions

One of the weakness points of a common buckling restrained braced frame is the low post-yield stiffness and thus large residual deformation under moderate to severe ground motions. This paper numerically investigates the seismic response of multi-core buckling restrained braces. The proposed multi-core BRB includes high-performance steel (HPS-70W) and Stainless steel (304L) as core materials and its response is compared to standard BRB, in which only the A572 (Grade 50) steel is used. Nonlinear dynamic time history analyses are conducted in order to compare the seismic performance of 4,10, and 14-story diagonally braced frames. Future works may include the experimental and theoretical investigation of seismic response of multi-core BRBs with different detailing and also sub-assemblage tests on multi-core buckling restrained braced frames. The main outcomes of this paper can be summarized as follow:

1. Regarding time history analysis results, the peak RDR demands in multi-core BRBFs are significantly lower in comparison to standard BRBFs subjected to the ground motions scaled to DBE and MCE target spectrums. The multi-core BRBs were found to decrease residual drifts of BRBFs up to 50% at both DBE and MCE hazard levels.
2. From the seismic fragility analysis, higher probability of exceedance of peak IDR and especially RDR responses of standard BRBFs in comparison to multi-core BRBFs are observed. The multi-core mid-rise BRBFs (i.e., 14-story) experience considerably lower probability of exceedance of peak residual drift demands, which indicates that multi-core BRBs are capable of providing more reliable performance in buckling restrained braced frames. The application of stainless steel in multi-core BRB considerably compensates the low post-elastic stiffness and provides self-centering mechanism in BRBFs.
3. Further laboratory tests along with finite element analyses are needed to examine the overall performance and also to demonstrate the advantages of multi-core BRBs over standard BRBs.
4. Future studies may include the investigation of different core materials than stainless steel, in order to provide self-centering mechanism in BRBFs.

References

AISC (2010), Seismic Provisions for Structural Steel Buildings, American Institute of Steel Construction, Chicago, IL, USA.

Amador, T., Jorge, R. and Edén, B. (2015), “Flexible frames as self-centering mechanism for buildings having buckling-restrained braces”, *J. Earthq. Eng.*, **19**, 978-990. https://doi.org/10.1080/13632469.2015.1011813.

ATC 63 (2008), Quantification of Building Seismic Performance, FEMA project, U.S.

Atlayan, O. and Charney, F. (2014), “Hybrid buckling-restrained braced frames”, *J. Constr. Steel Res.*, **96**, 95-105. https://doi.org/10.1016/j.jcsr.2014.01.001.

Beaumont, E. and Annan, C. (2016), “Cyclic response of structural stainless steel plate under large inelastic strains”, *Proceeding of Resilient Infra-Structure*, London, CA.

Black, C.J., Makris, N. and Aiken, ID. (2000), “Component testing, stability analysis, and characterization of buckling restrained braced frames”, PEER Report No 8, Berkeley, CA.

Chou, C., Tsai, W. and Ping-Ting, C. (2016), “Development and validation tests of a dual-core self-centering sandwiched buckling-restrained brace for seismic resistance”, *J. Eng. Struct.*, **121**, 30-41. https://doi.org/10.1016/j.engstruct.2016.04.015.

Christopoulos, C., Filiatrault, A., Folz, B. and Uang, C. (2002), “Posttensioned energy dissipating connections for moment-resisting steel frames”, *J. Struct. Eng.*, **128**, 1111-1120. https://doi.org/10.1061/(ASCE)0733-9445(2002)128:9(1111).

Christopoulos, C., Pampanin, S. and Priestley, M. (2003), “Performance-based seismic response of frame structures including residual deformations, Part I: Single degree of freedom systems”, *J. Earthq. Eng.*, **7**, 97-118.

Christopoulos, C., Tremblay, R., Kim, H. and Lacerte, M. (2008), “Self-centering energy dissipative bracing system for the seismic resistance of structure, Development and validation”, *J. Struct. Eng.*, **134**, 96-107. https://doi.org/10.1061/(ASCE)0733-9445(2008)134:1(96).

Clark, P., Aiken, I., Kasai, K., Ko, E. and Kimura, I. (1999), “Design procedures for buildings incorporating hysteretic damping devices”. *Proceedings of the 69th annual convention, SEAOC,* Sacramento, CA..

Craft, J. and Jennifer, L. (2015), “Reducing drifts in buckling rstrained braced frames through elastic stories”, BYU university Scholar Archive, PhD Thesis, No. 4430.

Deylami, A. and Mahdavipour, M. (2016), “Probabilistic seismic demand assessment of residual drift for Buckling-Restrained Braced Frames as a dual system”, *Struct. Saf.*, **58**, 31-39. https://doi.org/10.1016/j.strusafe.2015.08.004.

Dong, H., Du, X., Han, Q., Hao, H., Bi, K. and Wang, X. (2017), “Performance of an innovative self-centering buckling restrained brace for mitigating seismic responses of bridge structures with double-column piers”, *Eng. Struct.*, **148**, 47-62. https://doi.org/10.1016/j.engstruct.2017.06.011.

Dusicka, P., Itani, A. and Ian, G. (2007), “Cyclic response of plate steels under large inelastic strains”, *J. Constr. Steel Res.*, **63**, 156-164. https://doi.org/10.1016/j.jcsr.2006.03.006

Fahnestock, L., Ricles, J. and Sause, R. (2007), “Experimental evaluation of a large-scale buckling-restrained braced frame”, *J. Struct. Eng.*, **133**, 1205-1214. https://doi.org/10.1061/(ASCE)0733-9445(2007)133:9(1205).

Fahnestock, L., Sause, R. and Ricles, J. (2007), “Seismic response and performance of buckling-restrained braced frames”, *J. Struct. Eng.*, **133**, 1195-1204. https://doi.org/10.1061/(ASCE)0733-9445(2007)133:9(1195).

Gardner, L., Bu, Y., Francis, P., Baddoo, N., Cashell, K. and McCann, F. (2016), “Elevated temperature material properties of stainless steel reinforcing bar”, *Constr. Build. Mater.*, **114**, 977-997. https://doi.org/10.1016/j.conbuildmat.2016.04.009.

Garlock, M., Ricles, J. and Sause, R. (2005), “Experimental Studies of full scale posttensioned steel connections”, *J. Struct. Eng.*, **131**, 438-448. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:3(438).

Ghowsi, A. and Sahoo, D. (2015), “Fragility assessment of buckling-restrained braced frames under near-field earthquakes”, *Steel Compos. Struct.*, **19**, 173-190. http://dx.doi.org/10.12989/scs.2015.19.1.173.

Guo, Y., Tong, J., Zhang, B., Zhu, B. and Pi, Y. (2017), "Theoretical and experimental investigation of core-separated buckling-restrained braces", *J. Constr. Steel Res.*, **135**, 137-149. https://doi.org/10.1016/j.jcsr.2017.04.019.

Hoveidae, N. and Rafezy, B. (2012), "Overall buckling behavior of all-steel buckling restrained braces", *J. Constr. Steel Res.*, **79**, 151-158. https://doi.org/10.1016/j.jcsr.2012.07.022.

Hoveidae, N., Tremblay, R., Rafezy, B. and Davaran, A. (2015), "Numerical investigation of seismic behavior of short-core all-steel buckling restrained braces", *J. Constr. Steel Res.*, **114**, 89-99. https://doi.org/10.1016/j.jcsr.2015.06.005.

Inoue, K., Sawaizumi, S. and Higashibata, Y. (2001), "Stiffening requirements for unbonded braces encased in concrete panels", *ASCE J. Struct. Eng*., **127**, 712-719. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:6(712).

Iranian Code of Practice for Seismic Resistant Design of Buildings (2014), Standard No. 2800, 4th Edition, Building and Housing Research Center, Tehran, Iran.

Kim, H. and Christopoulos, C. (2009), "Numerical models and ductile ultimate deformation response of post-tensioned self-centering moment connections", *Earthq. Eng. Struct. Dyn*., **38**, 1-21. https://doi.org/10.1002/eqe.836.

McCormick, J., Aburano, H., Ikenaga, M. and Nakashima, M. (2008), "Permissible residual deformation levels for building structures considering both safety and human elements", *Proceedings of the 14th World Conference Earthquake Engineering*, Seismological Press of China, Beijing.

OpenSees, (2007), Open System for Earthquake Engineering Simulation, University of California, Berkeley, California: Pacific Earthquake Engineering Research Center.

Pampanin, S., Christopoulos, C. and Priestley, M. (2003), "Performance- based seismic response of frame structures including residual deformations, Part II: Multi-degree of freedom systems", *J. Earthq. Eng*., **7**, 119-147.

Pandikkadavath, M. and Sahoo, D. (2016), "Analytical investigation on cyclic response of buckling-restrained braces with short yielding core segments", *Int. J. Steel. Struct*., **16**, 1273-1285. https://doi.org/10.1007/s13296-016-0083-y.

Pettinga, D., Christopoulos, C., Pampanin, S. and Priestley, N. (2007), "Effectiveness of simple approaches in mitigating residual deformations in buildings", *Earthq. Eng. Struct. Dyn*., **36**, 1763-1783. https://doi.org/10.1002/eqe.717.

Qiang, X. (2005), "State of the art of buckling-restrained braces in Asia", *J. Constr. Steel Res.*, **61**, 727-748. https://doi.org/10.1016/j.jcsr.2004.11.005.

Ricles, J., Sause, R., Garlock, M. and Zhao, C. (2001), "Posttensioned seismic-resistant connections for steel frames", *J. Struct. Eng*., **127**, 113-121. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:2(113).

Rojas, P., Ricles, J. and Sause, R. (2005), "Seismic performance of posttensioned steel moment resisting frames with friction devices", *J. Struct. Eng.*, **131**, 529-540. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:4(529).

Sabelli, R., Mahin, S. and Chang, C. (2003), "Seismic demands on steel braced frame buildings with buckling restrained braces", *Eng. Struct*., **5**, 655-66. https://doi.org/10.1016/S0141-0296(02)00175-X.

Sarno, D., Elnashai, L. and Nethercot, D. (2006), "Seismic retrofitting of framed structures with stainless steel", *J. Constr. Steel Res.*, **62**, 93-104. https://doi.org/10.1016/j.jcsr.2005.05.007.

Seismosoft, SeismoMatch (2016), A Computer Program for Spectrum Matching of Earthquake Records, www.seismosoft.com.

Tremblay, R., Lacerte, M. and Christopoulos, C. (2008), "Seismic response of multistory buildings with self-centering energy dissipative steel braces", *J. Struct. Eng*., **134**, 108-120. https://doi.org/10.1061/(ASCE)0733-9445(2008)134:1(108).

Wu, C., Loh, C., Yang, Y. and Lin, C. (2004), "Consideration of collapse and residual deformation in reliability-based performance evaluation of buildings", *Proceedings of the 13th World Conference on Earthquake Engineering*, Canadian Association for Earthquake Engineering (CAEE), Vancouver, Canada.

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