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Response modification factor of the frames braced with reduced yielding segment BRB

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Abstract. In this paper, overstrength, ductility and response modification factors are calculated for frames braced with a different type of buckling restrained braces, called reduced yielding segment BRB (Buckling Restrained Brace) in which the length of its yielding part is reduced and placed in one end of the brace element in comparison with conventional BRBs.Forthermore,these factors are calculated for ordinary BRBF and the results are compared. In this regard incremental dynamic analysis (IDA) method is used for studying 17 records of the most known earthquakes happened in the world. To do that, the considered buildings have different stories and two bracing configurations: diagonal and inverted *V* chevron, the most ordinary configurations of BRBFs. Static pushover analysis, nonlinear incremental dynamic analysis and linear dynamic analysis have been performed using OpenSees software. Considering the results, it can be seen that, overstrength, ductility and response modification factors of this type of BRBF(Buckling Restrained Braced Frame) is greater than those of conventional types and it shows better seismic performance and also eliminates some of conventional BRBF's disadvantages such as low post-yield stiffness.

Keywords: response modification factor; ductility factor; overstrength factor; reduced length BRB; IDA

1. Introduction

Design of steel buildings for seismic loads is generally based on two performance objectives: 1) elastic response during minor to moderate earthquakes; 2) collapse prevention during extreme (rare) earthquakes. Regarding the former, the buildings are designed with enough lateral stiffness to limit large displacements and for the latter, with enough ductility to survive large inelastic displacements and prevent collapse during extreme earthquakes. Such designs are often achieved by ductile braced frame systems. These systems have both high lateral stiffness, provided by a bracing element and ductility, usually provided by an inelastic mechanism. This mechanism is specially designed in order to isolate the frame from damaged area during overloading (Prinz 2010). One of the most common types of ductile braced frame systems is buckling-restrained braced frames (BRBFs).

Buckling restrained braces have been substituted for conventional ones in concentric braced frames due to their better seismic performances. BRBs have higher energy absorption capacities in

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Table 1 Summary of some studies on BRB with reduced core length (Shemshadian *et al*. 2011a)

Researcher	Year	Location	*Lc/L*	Model	Max Strain
Temblay *et al.*	2006	Canada	25%	Experimental & Analytical	3.40%
Mirghaderi and Ahlehagh	2008	Iran	35%	Analytical	4.30%
Ma *et al*.	2009	China	20%	Experimental	3.40%
Mazzolani *et al.*	2009	Italy	40%	Experimental	3.50%
Razavi and Mirghaderi	2009	Iran	20-40%	Experimental & Analytical	3-4%
Di Sarno and Manfredi	2010	Italy	20%	Analytical	1.50%

comparison with normal braces due to their symmetric and stable hysteretic behaviors. Nevertheless, the stiffness of BRB frames are highly degraded in case of yielding core segments; in other words their post-yield stiffness are low.

2. Reduced yielding segment BRB

Reducing core length (yielding segment) leads in developing the overstrength in the structure and increasing the post-yield stiffness of braces. Therefore, the lack of high post-elastic stiffness of conventional BRBs could be covered.

The above advantages raised the interest of many researchers to investigate the possibility of reducing core length in BRBs. The majority of these studies have been carried out in recent years. Table 1 summarizes some of these studies.

Reduced yielding segment BRB, is a BRB proposed by Shemshadian et.al (2011b) in which the length of yielding part is reduced and therefore smaller than that of conventional one. Moreover, this segment is placed in one end of the brace element while in conventional BRBs it is in the middle of the brace. The mentioned segment acts as a structural fuse and in certain conditions, after severe earthquakes, only the damaged fuse is replaced with a new one (only at the end of the brace) and not the entire brace length. In this BRB, each brace element has two parts: 1) yielding segment; 2) elastic part or non yielding segment. The former, as a displacement control part is a small BRB (yields in both tension and compression) and restrained against buckling and its core cross section is smaller than that of the elastic part. About the latter its cross section is greater, comparing to the yielding segment, and not restrained against buckling. It is expected to remain elastic so it is force controlling part. One of the main criteria in designing such systems is to prevent the brace from global buckling without using any restraining mechanism in the non-yielding part (Shemshadian *et al*. 2011b)

The scheme of reduced yielding segment BRB is shown in Figs. 1-2.

They also proposed a design procedure for their recommended BRBF system. According to their results the suggested BRB makes no significant difference in designing a common BRBF. Furthermore, the recommended system showed high potential in reducing residual drifts due to its proper inelastic stiffness. Here, nonlinear behavior of BRBFs using suggested BRB is compared with that of ordinary BRBFs. The obtained results showed that reducing in the yielding part causes more elastic and inelastic stiffness. Consequently, the brace yielding are taken place sooner and the intervals are smaller. In such system, *X*-shaped bracing can be applied, another advantage of

BRB with reduced core length, which is not practical in conventional BRB systems (Fig. 3) (Razavi *et al*. 2011).

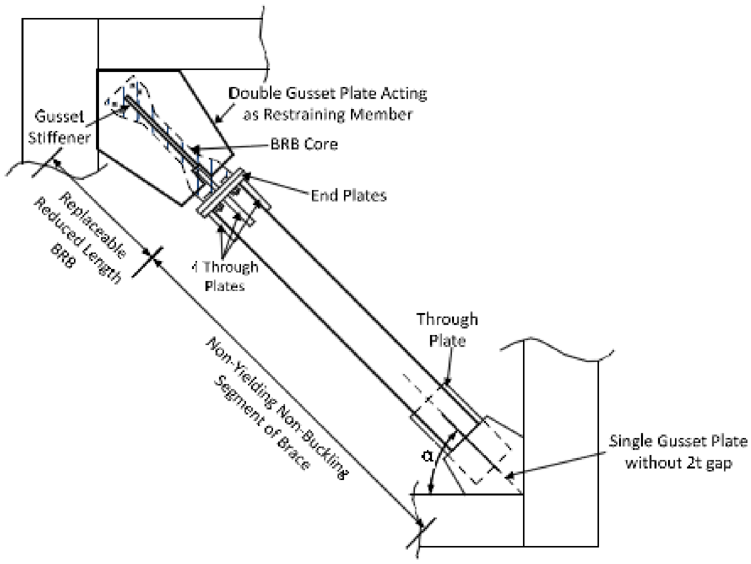


Fig. 1 Recommended BRB with reduced yielding segment (Razavi *et al.* 2011)

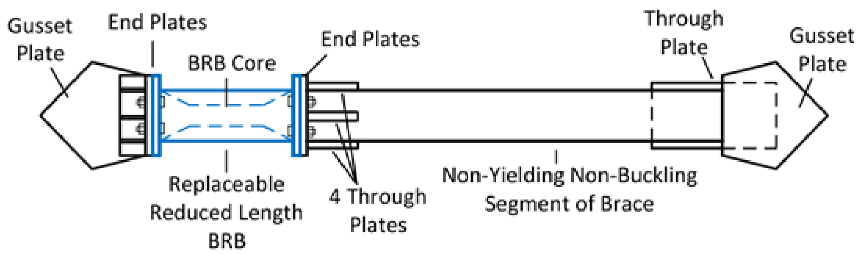


Fig. 2 Typical details of reduced yielding segment BRB (Shemshadian *et al.* 2011b)

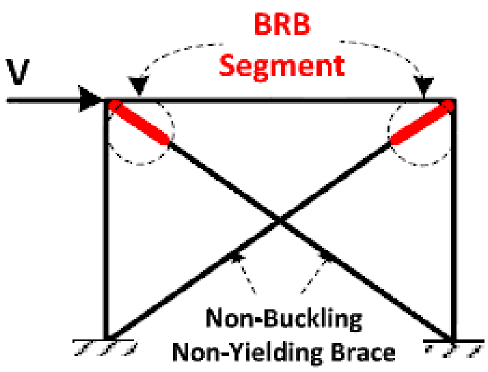


Fig. 3 Implementation of *X*-shaped bracing in the BRBs with reduced yielding length

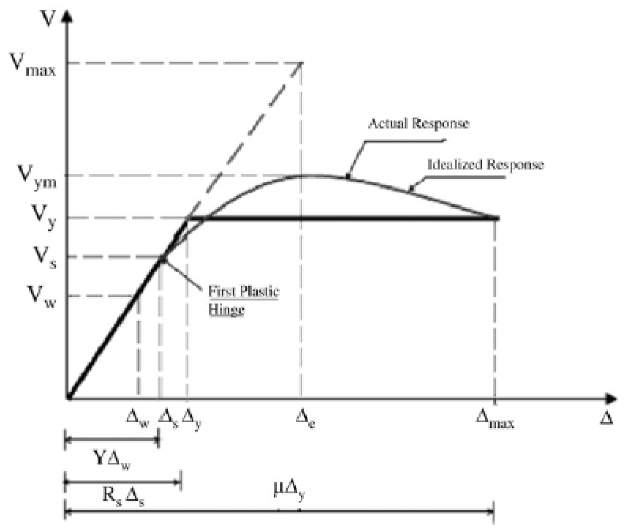


Fig. 4 General response of structure

Response modification factor (*R*) is an important structural seismic response against earthquake forces. In fact, this factor explains the ability of structural system in dissipating earthquake energy and creating nonlinear deformation without collapse of the structure. In this study, overstrength and response modification factors are calculated for both conventional and Reduced length BRBFs in order to evaluate the seismic performance of this new BRB; the obtained results are compared. To do this, nonlinear static analysis, linear dynamic analysis and incremental dynamic analysis (IDA) have been conducted on the frames with 3, 6, 9 and 12 stories using “OpenSees” software.

3. Response modification factor

Many seismic codes permit reduction in design loads as the structures possess significant reserve strength (overstrength) and capacity to dissipate energy (ductility). Overstrength and ductility are incorporated in the structural design through force reduction factor or response modification factor. The response modification factor represents the ratio of the forces that would be developed under certain ground motion where the structure behaves elastically to the prescribed design forces at the strength limit state. Such designing concept is based on the assumption that well-detailed structures can develop lateral strength in excess of their design strength and sustain large inelastic deformation without collapse. Force reduction factor plays significant role in designing earthquake load-resisting elements (Kim and Choi 2004).

Response modification factor was first proposed in ATC3-06 (1978) and then it was calculated in ATC-19 (1995) and ATC-34 (1995) as the product of three factors: Over-Strength factor, Ductility factor, and Redundancy factor. Response modification factor should be relatively computed for buckling restrained braced frames. In this regard the system should be defined according to its ductility and performance in such a way to be consistent with the factors already established for other structural systems such as: ordinary braced frames, eccentrically braced frames, and moment-resisting frames. The provision for buckling restrained braced frame design has been recommended in Seismic provisions of American institute of steel construction (AISC). Accordingly, response modification factor (*R*) has been proposed 7 (*R*=7) for simple connection of beam-column.

In this study, response modification factor is calculated using Uang's ductility factor method (Uang 1991) in which real nonlinear behavior is usually idealized by a bilinear elasto perfectly plastic relation, Fig. 4. (Abdollahzadeh *et al.* 2013)

In this figure, V_y is corresponded to the yield force, Δ_y yield displacement and V_e ($V_{\max}$) elastic response strength of the structure. The maximum base shear is V_y in an elasto perfectly plastic behavior. Force reduction factor is the ratio of maximum base shear considering elastic behavior (V_e) to maximum base shear in elasto perfectly plastic behavior (V_y) and defined as

$$R_\mu = \frac{V_e}{V_y} \tag{1}$$

Overstrength factor is the ratio of maximum base shear in actual behavior (V_y) to the first significant yield strength of structure (V_s), defined as

$$R_s = \frac{V_y}{V_s} \tag{2}$$

In the allowable stress method, design load is reduced from V_s to V_w by allowable stress factor (Y) as follows

$$Y = \frac{V_s}{V_w} \tag{3}$$

This factor is considered here as 1.44 (Uang 1991).

Response modification factor is accounted for ductility and overstrength of the structure and the difference of stresses is considered in designing the structure, expressed as follows

$$R = \frac{V_e}{V_s} = \frac{V_e}{V_y} \times \frac{V_y}{V_s} = R_\mu \times R_S \tag{4}$$

$$R_w = \frac{V_e}{V_w} = \frac{V_e}{V_y} \times \frac{V_y}{V_s} \times \frac{V_s}{V_w} = R_\mu \times R_S \times Y \tag{5}$$

Seismic response modification factor is expressed as Eq. (4) in the load and resistance factor design method and as Eq. (5) in allowable stress design method (Uang 1991).

Nonlinear static analysis (pushover) and IDA (incremental dynamic analysis) are conducted on 2D frames, braced with conventional BRBs and new BRBs, for obtaining overstrength factor, and IDA and linear dynamic analysis for ductility factor. Then, final response modification factors of the frames are evaluated through statistic methods.

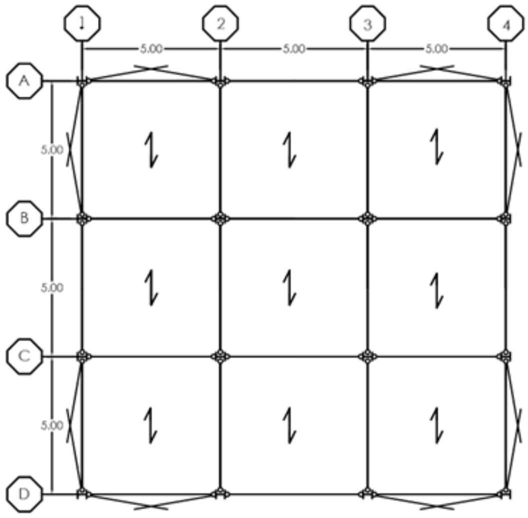


Fig. 5 Plan of the frames

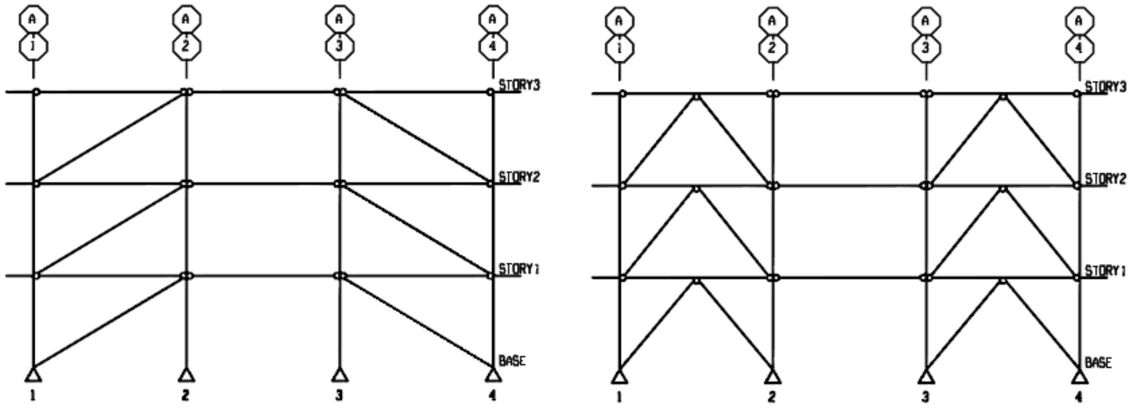


Fig. 6 Brace configurations

4. Design of model structures

In this research, overstrength, ductility, and response modification factors of buckling restrained braced frames have been evaluated. In this regard, 3, 6, 9 and 12 story buildings with 5 m bay length and two different bracing types (chevron-inverted *V* and diagonal Types) are designed according to the requirements of Iranian Earthquake Resistant Design Code (2005) and Iranian National Building Code, part 10, steel structure design (2006). Fig. 5 and Fig. 6 show the model frames' plane and typical configuration of the brace.

The story height of the models is considered as 3 m. The equivalent lateral static forces are applied on all story levels for the member design subjected to earthquake. These forces are calculated according to the provisions stated in Iranian Earthquake Code Standard No. 2800 (2005).The dead and live loads are considered as 600 kg/m^2 and 200 kg/m^2 respectively for the floors and 550 kg/m^2 and 150 kg/m^2, respectively, for the roof. Moreover, the dead load, caused by

Table 2 Brace design details of 6 story frame braced with reduced yielding segment inverted V BRB

No. Story	non-yielding part Pipe (outer diameter×thickness) (cm)	ratio of yielding part length to whole brace length	yielding core cross section (cm^2)
6	18×0.64	0.25	6.5
5	22×0.68	0.25	12.9
4	22×0.68	0.25	12.9
3	22×0.68	0.25	16.1
2	22×0.7	0.25	19.3
1	22×0.7	0.25	19.3

peripheral walls, is considered as 800 kg/m for outside of the frames.

The design base shear is computed as follows

$$V = CW, \quad C = \frac{ABI}{R} \tag{6}$$

where, V is base shear, C is seismic coefficient, W is equivalent weight, A is design base acceleration, B is response coefficient, I is importance factor and R is response modification factor of the structure. In designing the frame, the importance factor (I), is considered as *1*, preliminary response modification factors (R) as 7 and design base acceleration (A) as 0.35. It is assumed that braces are pinned at both ends. Allowable stress design method is used to design the frame members based on the part 10 of Iranian National Building Code. This code has been used to design vertical bracing columns in order to ensure that they have enough strength to resist the forces transferred from bracing elements and expressed as follows

(a) Axial compression according to: $$P_{DL} + P_{LL} + \Omega_0 P_E \leq F_a.A \tag{7}$$

(a) Axial compression according to: $$P_{DL} + \Omega_0 P_E \leq 0.6F_y.A \tag{8}$$

where, F_a is allowable compressive stress, F_y is the yield stress, A is cross section area of the column. P_{DL}, P_{LL}, P_E are axial load from dead, live and earthquake load, respectively, and Ω_0 is overstrength factor of structure.

Furthermore, new BRB elements have been designed based on the procedure presented by Razavi *et al*. (2011).

They considered the ratio of yielding core length to whole brace length as 0.15 to 0.35 in order to save the structure from low-cycle fatigue failure effects. In this research, this ratio is assumed as 0.25. The brace design details of 6 story frame, braced with reduced yielding segment BRB in inverted *V* shape, are shown in Table 2.

5. Modeling the structures

The structures have been modeled using OpenSees (Mazzoni 2007), a finite element software applied specifically in designing the structures under earthquakes. Here, 2D frame corresponding to *A* axis is modeled in OpenSees in order to perform IDA and pushover analyses. The

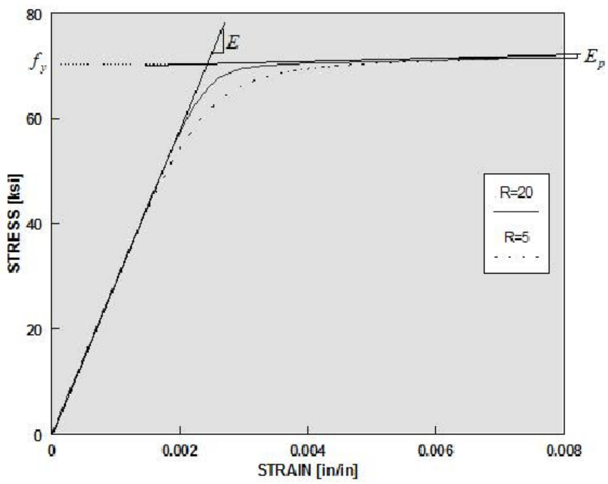


Fig. 7 Steel 02 material

assumptions considered for modeling the members in nonlinear range of deformation are discussed in the following.

5.1 Columns and beams modeling assumptions

The column and beam elements as well as the sections are modeled using nonlinear beam-column element and fiber section. The steel 02 bilinear kinematic stress_strain curve, from the library of materials introduced in OpenSees, is assigned to model the behavior of the mentioned elements, Fig. 7.

In this research, ASTM A992 material is considered for designing the beams and columns. Therefore, yielding stress and elasticity modulus of this material are assumed as 3515.3 kg/cm^2 (50 ksi) and 2038902 kg/cm^2 (29000 ksi), respectively. The strain hardening of 1% is considered for the member's behavior in the inelastic range. The imperfection of 0.001 of each column's height is assumed in its middle to consider the potential of buckling.

5.2 Brace modeling assumptions

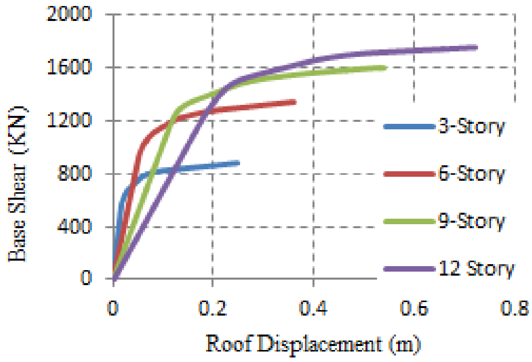
The assumptions of brace modeling are divided into conventional BRB and reduced yielding segment BRB due to the two different types of BRB brace elements.

5.2.1 Conventional BRB

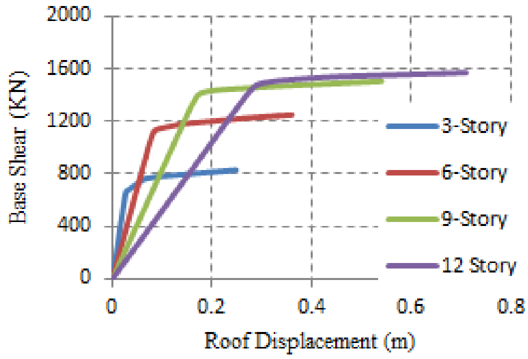
This brace is modeled by one equivalent element using corotational truss element and steel02 material. The ASTM A36 material is used to design BRBs. The yielding stress and elasticity modulus of this material are assumed as 2531 kg/cm^2 (36 ksi) and 2038902 kg/cm^2 (29000 ksi), respectively; the strain hardening is considered as 1%.

5.2.2 Reduced yielding segment BRB

Two elements, yielding part and non-yielding part, are used for modeling each brace. The

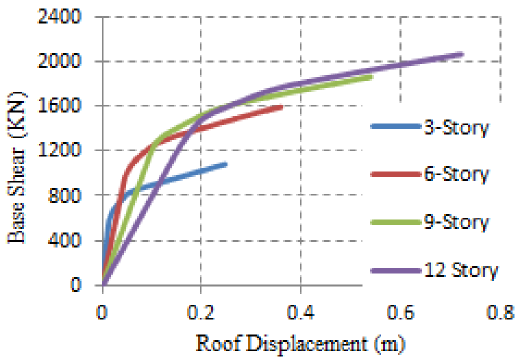


(a) Inverted V BRBs

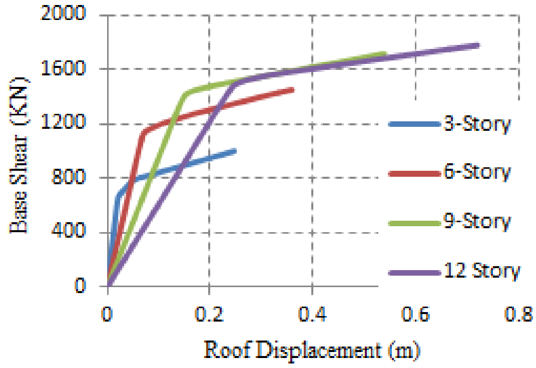


(b) Diagonal BRBs

Fig. 8 Roof displacement-base shear curves of the conventional BRBFs



(a) Inverted V BRBs



(b) Diagonal BRBs

Fig. 9 Roof displacement-base shear curves of the reduced length BRBFs

former is modeled with steel02 material (same as conventional BRB) and the elastic part by hysteretic material to define buckling limitation point in pressure. The elements of both parts are nonlinear beam-columns.The corotational coordinate transformation (CorotCrdTransf) object is used for all elements.

6. Pushover analysis

Pushover analysis is carried out by progressively increasing the lateral forces in the inverted triangular shape in order to obtain the base shear related to the first plastic hinge formation in the structure $V_{b(St,y)}$. It means that the linear ultimate limit of structure has been considered the same in nonlinear static and nonlinear dynamic analyses. The results obtained by pushover analysis are presented in Figs. 8 and 9 and the base shear related to the first plastic hinge formation ($V_{b(St,y)}$) in Table 3.

Considering the results obtained from the pushover analyses, reduced yielding segment BRBFs exhibited more stiffness comparing with those of conventional BRBFs in all cases. This difference is mainly observable after formation of first plastic hinge.

Table 3 The base shear related to the first plastic hinge formation

Bracing type	Number of stories	$V_{b(St,y)}$ (KN)	Bracing type	Number of stories	$V_{b(St,y)}$ (KN)
(a) conventional BRBFs			(b) reduced yielding segment BRBFs		
Inverted-V	3	571.82	Inverted-V	3	554.83
	6	940.45		6	904.53
	9	1174.91		9	1136.98
	12	1220.85		12	1187.31
Diagonal	3	658.80	Diagonal	3	645.16
	6	1101.78		6	1074.55
	9	1391.74		9	1343.98
	12	1470.35		12	1418.02

Table 4 Ground motions used in IDA analysis

Earthquake	Station	Date	PGA (g)
Cape Mendocino	1806, Rio Dell Overpass FF	4/25/1992	0.549
Chi-Chi-, Taiwan	CHY080	9/20/1999	0.968
Coyote Lake	Gilroy Array 3	8/6/1979	0.434
Kobe	KJMA	1/16/1995	0.821
Kocaeli, Turkey	Sakarya	8/17/1999	0.376
Landers	Coolwater	6/28/1992	0.417
Loma Prieta	Corralitos	10/18/1989	0.644
Morgan Hill	Anderson Dam	4/24/1984	0.423
N. Palm Springs	N. Palm Springs	7/8/1986	0.694
Northridge	Santa Monica	1/17/1994	0.883
Parkfield	Temblor Pre-1969	6/28/1966	0.357
San Fernando	Lake Hughes #12	2/9/1971	0.366
Superstition Hills	Usgs Station 5051	11/24/1987	0.455
Victoria, Mexico	Unam/Ucsd Station 6604	6/9/1980	0.621
Whittier Narrows	Obregon Park	10/1/1987	0.45
Tabas	Tabas, LN	9/16/1978	0.836
Bam	Bam	26/12/2003	0.799

7. Calculating response modification factor using IDA analysis results

7.1 Overstrength factor (R_S) calculation

Incremental dynamic analysis (IDA) is a parametric analysis method that has recently emerged in several different forms to estimate the structural performance under seismic loads more thoroughly. It involves a structural model subjected to one (or more) ground motion record(s), each of which scaled to multiple intensity levels. Therefore, one (or more) curve(s) are plotted for the response (s) versus intensity (Vamvatsikos *et al*. 2002).

Calculating overstrength factor by nonlinear static analysis has limitations such as lateral loading pattern. On the other hand, overstrength phenomenon is more important when earthquake occurs. Therefore, it can be calculated using incremental dynamic analysis. In the method,

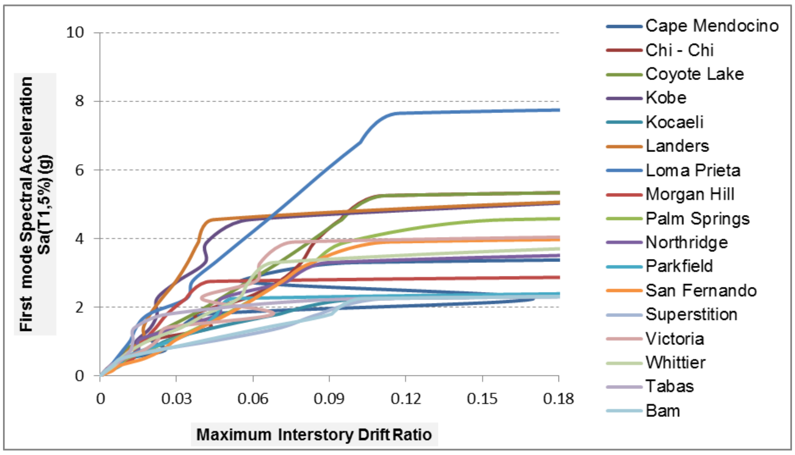


Fig. 10 IDA curves for 6 story frames, braced with reduced yielding segment inverted V BRB

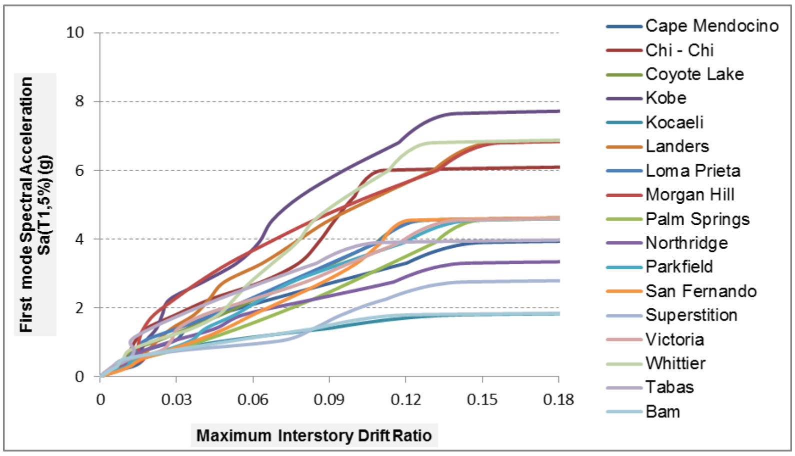


Fig. 11 IDA curves for 6 story frames, braced with conventional inverted V BRB

introduced by Mwafy and Elnashai (2002), $V_{b(Dyn,u)}$ is calculated conducting incremental nonlinear dynamic analysis on the models subjected to strong ground motions matching with the design spectrum . In this regard 17 earthquake records have been used (Table 4).

Their spectral accelerations (S_a) have been changed with several trial and error processes using Hunt & Fill algorithm to gain the time history in which the structure meets the failure criteria presented by Eqs. (9)-(10). The maximum nonlinear base shear of this time history is the inelastic base shear of structure (i.e., $V_{b(Dyn,u)}$)

The maximum relative story displacement limit is selected based on the Iranian Standard Code No. 2800 as follows

(a) For the frames with the fundamental period less than 0.7 s: $\Delta_m < 0.025H$ (9)

(b) For the frames with the fundamental period more than 0.7 s : $\Delta_m < 0.02H$ (10)

where, H is story height. Overstrength factor is calculated as follows

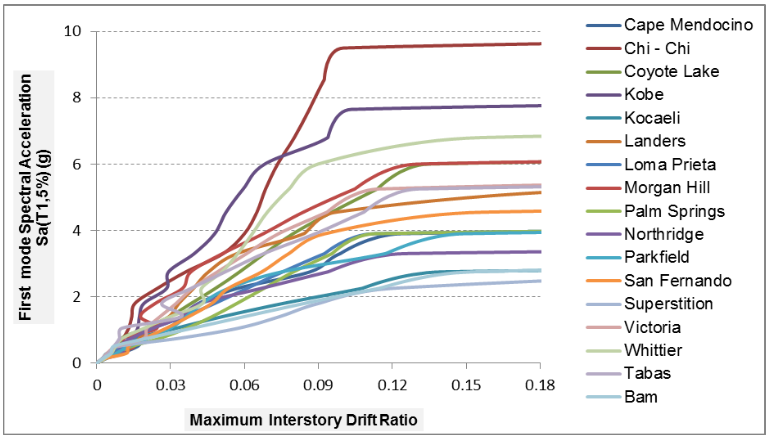


Fig. 12 IDA curves for 6 story frames, braced with reduced yielding segment diagonal BRBs

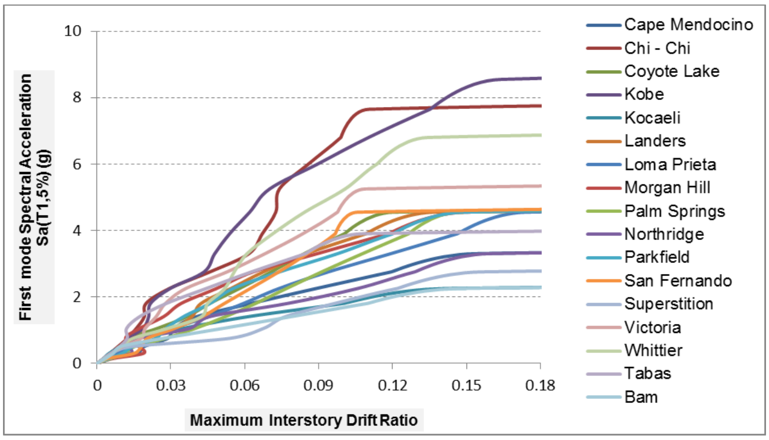


Fig. 13 IDA curves for 6 story frames, braced with conventional diagonal BRBs

$$R_S = \frac{V_{b(Dyn,u)}}{V_{b(St,y)}} \tag{11}$$

IDA curves have been plotted for 6 story frames, braced with reduced yielding segment and conventional BRBs in term of maximum interstory drift- spectral acceleration corresponding to first mode shape and shown in Figs. 10-13, as examples.

7.2 Ductility factor (R_μ) calculation

R_μ is calculated through nonlinear and linear dynamic analyses. Nonlinear dynamic analysis and trial and error are applied on S_a of earthquake records in order to calculate nonlinear base shear $V_{b(Dyn,u)}$, as described earlier. Then, maximum linear base shear $V_{b(Dyn,e)}$ is calculated by conducting linear dynamic analysis of the structure under the same time history; finally, the ductility reduction factor is evaluated as follows (Asgarian and Shokrgozar 2009, Mwafy and Elnashai 2002)

Table 5 Overstrength, ductility and response modification factors of 6 story frame, braced with reduced yielding segment inverted V BRB

Records	DM Max Drift	IM $Sa(T1,5\%)$	$V_{b(Dyn,u)}$ (KN)	$V_{b(St,y)}$ (KN)	$V_{b(Dyn,e)}$ (KN)	R_s	R_μ	R_{LRFD}	R_{ASD}
Cape Mendocino	0.025	1.56	1644.18		4100.66	1.82	2.49	4.53	6.53
Chi-Chi, Taiwan	0.025	1.92	1166.06		3411.07	1.29	2.93	3.77	5.43
Coyote Lake	0.025	0.83	1609.62		4567.99	1.78	2.84	5.05	7.27
Kobe	0.025	1.78	1492.18		5861.61	1.65	3.93	6.48	9.33
Kocaeli, Turkey	0.025	0.39	1527.57		3566.73	1.69	2.33	3.94	5.68
Landers	0.025	1.17	1540.51		7693.55	1.70	4.99	8.51	12.25
Loma Prieta	0.025	1.15	1613.68		7433.78	1.78	4.61	8.22	11.83
Morgan Hill	0.025	0.27	1641.80		6838.92	1.82	4.17	7.56	10.89
N. Palm Springs	0.025	0.40	1625.05	904.53	4327.86	1.80	2.66	4.78	6.89
Northridge	0.025	0.51	1437.75		8055.01	1.59	5.60	8.91	12.82
Parkfield	0.025	0.17	1607.51		4901.17	1.78	3.05	5.42	7.80
San Fernando	0.025	0.14	1619.37		6714.35	1.79	4.15	7.42	10.69
Superstition Hills	0.025	0.98	1614.91		2994.93	1.79	1.85	3.51	4.77
Victoria, Mexico	0.025	0.50	1492.58		4084.84	1.65	2.74	4.52	6.50
Whittier Narrows	0.025	0.26	1625.99		5453.76	1.80	3.35	6.03	8.68
Tabas	0.025	1.56	1541.93		7763.36	1.70	5.03	8.58	12.36
Bam	0.025	0.99	1589.92		3022.26	1.76	1.90	3.34	4.81
Average						**1.72**	**3.45**	**5.90**	**8.50**
σ						0.13	1.12	1.90	2.74
C.V.						0.07	0.32	0.32	0.32

$$R_\mu = \frac{V_{b(Dyn,e)}}{V_{b(Dyn,u)}} \tag{12}$$

7.3 Results

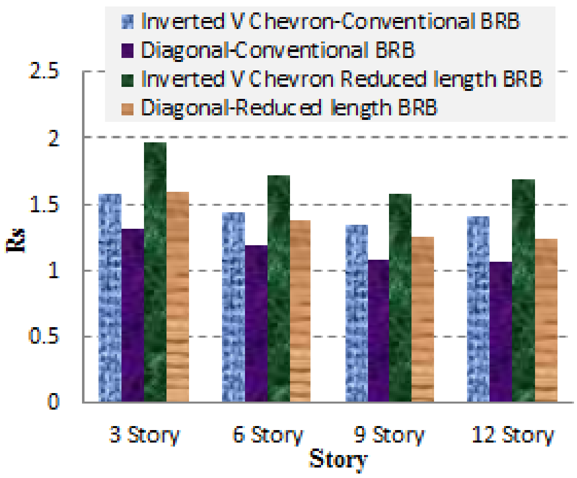
Overstrength, ductility and response modification factors of 6 story frames, braced with inverted *V* braces, are shown in details in Tables 5-6 (for instance). In addition, the values of average, variance (σ) and coefficient of variation (C.V.) are presented to evaluate the results dispersal.

The results are plotted in Figs 14 and 15 for better comparing the conventional and Reduced length BRBFs.

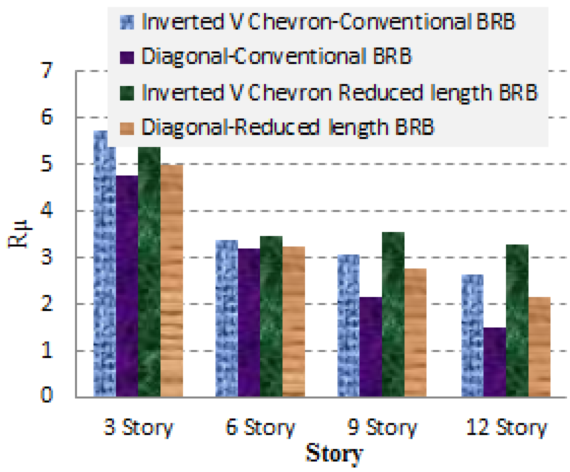
Response modification factor is calculated statistically after eliminating the irrelevant data from the results. Overstrength, ductility and response modification factors are calculated for different number of stories and different bracing types through statistical procedure and presented in Tables 7-10. In these tables, variance (σ) and coefficient of variation (C.V.) are presented for response modification factor in ASD method.

Table 6 Overstrength, ductility and response modification factors of 6 story frame, braced with conventional inverted V BRB

Records	DM Max Drift	IM $Sa(T1,5\%)$	$V_{b(Dyn,u)}$ (KN)	$V_{b(St,y)}$ (KN)	$V_{b(Dyn,e)}$ (KN)	R_s	R_μ	R_{LRFD}	R_{ASD}
Cape Mendocino	0.02	0.42	1404.06		4531.08	1.49	3.23	4.82	6.94
Chi-Chi, Taiwan	0.02	2.60	1090.82		2850.57	1.16	2.61	3.03	4.36
Coyote Lake	0.02	0.81	1379.79		3711.21	1.47	2.69	3.95	5.68
Kobe	0.02	1.87	1315.96		4826.90	1.40	3.67	5.13	7.39
Kocaeli, Turkey	0.02	0.34	1425.87		3981.61	1.52	2.79	4.23	6.10
Landers	0.02	0.76	1268.20		4477.16	1.35	3.53	4.76	6.86
Loma Prieta	0.02	0.74	1396.06		6456.08	1.48	4.62	6.86	9.89
Morgan Hill	0.02	0.30	1400.90		8696.02	1.49	6.21	9.25	13.32
N. Palm Springs	0.02	0.34	1399.78	940.45	4151.87	1.49	2.97	4.41	6.36
Northridge	0.02	0.48	1341.51		5303.26	1.43	3.95	5.64	8.12
Parkfield	0.02	0.15	1403.28		4045.78	1.49	2.88	4.30	6.19
San Fernando	0.02	0.13	1402.13		5120.06	1.49	3.65	5.44	7.84
Superstition Hills	0.02	0.99	1397.99		3447.11	1.49	2.47	3.67	5.28
Victoria, Mexico	0.02	0.45	1318.31		2885.55	1.40	2.19	3.07	4.42
Whittier Narrows	0.02	0.29	1410.81		5086.17	1.50	3.61	5.41	7.79
Tabas	0.02	1.52	1352.64		6328.34	1.44	4.68	6.73	9.69
Bam	0.02	1.05	1379.38		2646.23	1.47	1.92	2.81	4.05
Average						**1.44**	**3.39**	**4.91**	**7.07**
σ						0.08	1.03	1.57	2.26
C.V.						0.06	0.30	0.32	0.32

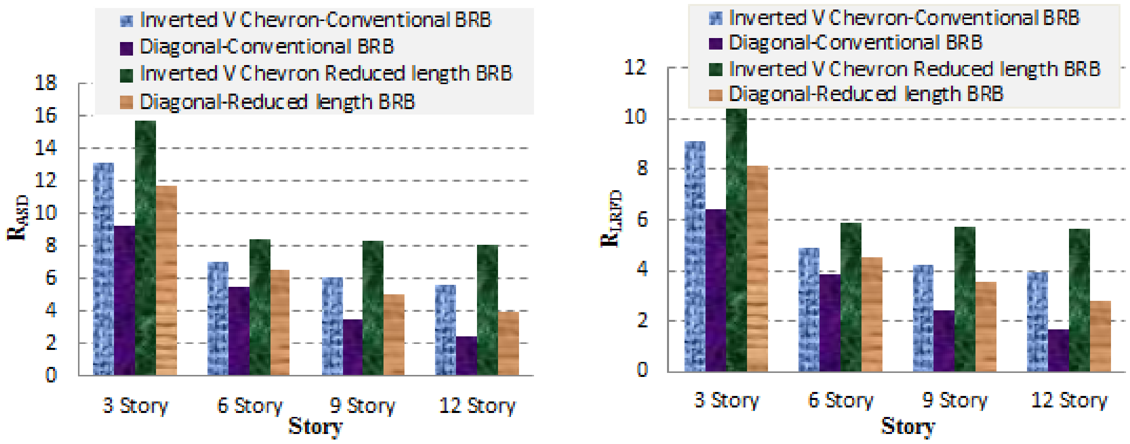


(a) Overstrength factor



(b) Ductility factor

Fig. 14 Overstrength and ductility factors of the frames



(a) ASD method (b) LRFD method

Fig. 15 Response modification factors of the frames

Table 7 Average values of ductility, overstrength and response modification factors for conventional inverted V BRB

No. Story	Conventional BRB in inverted *v* configuration							
	R_S	R_μ	R_{ASD}	σ	C.V.	R_{LRDF}	σ	C.V.
3	1.60	5.43	12.50	6.63	0.53	8.68	4.60	0.53
6	1.44	3.39	7.07	2.26	0.32	4.91	1.57	0.32
9	1.39	2.98	6.00	1.57	0.26	4.17	1.09	0.26
12	1.45	2.55	5.43	2.48	0.46	3.77	1.72	0.46
Average	1.47	3.59	7.75	3.23	0.39	5.38	2.25	0.39

Table 8 Average values of ductility, overstrength and response modification factors for conventional diagonal BRB

No. Story	Conventional BRB in diagonal configuration							
	R_S	R_μ	R_{ASD}	σ	C.V.	R_{LRDF}	σ	C.V.
3	1.33	4.45	8.54	3.34	0.39	5.93	2.32	0.39
6	1.20	3.18	5.54	1.67	0.30	3.85	1.16	0.30
9	1.11	2.08	3.35	1.17	0.35	2.33	0.81	0.35
12	1.06	1.47	2.29	0.86	0.37	1.59	0.59	0.37
Average	1.18	2.80	4.93	1.76	0.35	3.42	1.22	0.35

Table 9 Average values of ductility, overstrength and response modification factors for reduced yielding segment inverted V BRB

No. Story	Reduced length BRB in inverted *V* configuration							
	R_S	R_μ	R_{ASD}	σ	C.V.	R_{LRDF}	σ	C.V.
3	2.00	5.12	14.75	6.48	0.44	10.24	4.50	0.44
6	1.72	3.45	8.50	2.74	0.32	5.90	1.90	0.32
9	1.61	3.34	7.79	2.37	0.30	5.41	1.64	0.30
12	1.71	3.13	7.76	2.50	0.32	5.39	1.74	0.32
Average	1.76	3.76	9.70	3.52	0.35	6.74	2.44	0.35

Table 10 Average values of ductility, overstrength and response modification factors for reduced yielding segment diagonal BRB

No. Story	Reduced length BRB in diagonal configuration							
	R_S	R_μ	R_{ASD}	σ	C.V.	R_{LRDF}	σ	C.V.
3	1.62	4.81	11.23	5.77	0.51	7.80	4.01	0.51
6	1.39	3.26	6.52	1.69	0.26	4.53	1.17	0.26
9	1.27	2.72	5.00	1.71	0.34	3.47	1.19	0.34
12	1.27	2.11	3.95	1.70	0.43	2.75	1.18	0.43
Average	1.39	3.23	6.68	2.72	0.39	4.64	1.89	0.39

Table 11 Final values of ductility, overstrength and response modification factors

BRB type	R_S	R_μ	R_{ASD}	R_{LRDF}
Inverted V, Conventional	1.47	3.59	7.75	5.38
Diagonal, Conventional	1.18	2.80	4.93	3.42
Inverted V, Reduced length	1.76	3.76	9.70	6.74
Diagonal, Reduced length	1.39	3.23	6.68	4.64

8. Conclusions

To evaluate seismic performance of reduced length BRB whose yielding segment is placed at the end of brace length and also is shortened in comparison with conventional BRB, overstrength, ductility and response modification factors are evaluated for 16 buckling-restrained braced frames with various stories and bracing types. These factors are computed through static pushover, linear dynamic and incremental nonlinear dynamic analyses as well. As it can be seen in Table 11, the values of response modification, ductility and overstrength factors of reduced yielding segment BRBFs are greater than those of conventional ones. It means that new BRBs have higher capacities in absorbing earthquake energy and can be replaced by common BRBs in the future.

The results obtained in this study can be summarized as follows:

• Response modification factor values are 7.75 and 4.93 for conventional buckling restrained braced frames in inverted *V* and diagonal configurations , respectively, in allowable stress design method.

• Response modification factor values are 9.70 and 6.68 for reduced yielding segment buckling restrained braced frames in inverted *V* and diagonal configurations, respectively, in allowable stress design method. The values are greater than those of conventional types.

• Overstrength factor values are 1.76 and 1.39 for for reduced yielding segment buckling restrained braced frames in inverted *V* and diagonal configurations, respectively. The values are greater than those of conventional types which are 1.47 and 1.18, respectively.

• Ductility factor values are 3.76 and 3.23 for reduced yielding segment buckling restrained braced frames in inverted *V* and diagonal configurations, respectively. These values are greater than those of conventional types which are 3.59 and 2.80, respectively.

• The values of overstrength and ductility factors are decreased as the number of stories increases.

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