



DUCTILITY, OVERSTRENGTH AND RESIDUAL DRIFT IN BUCKLING-RESTRAINED BRACED FRAMES

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Abstract

Buckling-restrained braced frames (BRBF) have become a very popular lateral resisting system due to their balanced, full hysteresis and the ability to tailor both stiffness and strength to meet specific design requirements. This paper reports the results of an analytical investigation on the performance of buckling-restrained braces (BRB) and the global performance of BRBFs with a focus on the ductility and overstrength demands on the braces. Nonlinear analytical models of various three and six-story frames were subjected to a suite of earthquake records to determine the demands on the BRB elements and the overall frame response. The earthquake suites were amplitude scaled to the two seismic hazards and include both near-field and far-field ground motions. The structure variations include the building height, seismic hazard, seismic importance factor (I_e), brace configuration (chevron versus single diagonal), and BRB core yielding length. It was determined that many parameters impact the ductility and force demands on the braces as well as the global performance of the system. The results included story drift, residual drift, roof acceleration, normalized brace force (overstrength), brace strain and multiple ductility metrics. The three ductility metrics are the single cycle ductility demand (maximum inelastic single tension-to-compression or compression-to-tension cycle), reference ductility demand (maximum tension or compression ductility demand with reference to the undeformed configuration) and the cumulative ductility demand. The analysis results indicate that an importance factor of 1.5 reduces the system and brace demands. A shortened brace yielding length has a beneficial effect on both story drift and residual drift but experiences significant increases in acceleration, normalized brace forces, brace strain and all the ductility metrics. The results show that at the mean plus one standard deviation measure of the ratio of the single cycle ductility demand to the reference ductility demand in an actual earthquake is 1.36. Current testing protocol requires braces to undergo a single cycle ductility demand that is two times the reference ductility demand. This is indicative that the brace overstrength capacities which are based on symmetric cyclic testing may be overestimated. A more comprehensive analytical study is needed to identify the best way to relate the overstrength to the brace properties.

Keywords: buckling-restrained brace, ductility in steel structures, overstrength demands, nonlinear analysis

1. Introduction

Buckling-restrained braces (BRB) are an example of an innovation in structural engineering that has had a significant impact on design of steel structures. As opposed to concentrically braced frames that yield in tension and buckle in compression, BRBs have a full and essentially balanced hysteresis. This occurs because the flexural demands are taken by the buckling-restraining element which allows yielding in tension and compression of the core steel. Yielding in both tension and compression allows the development of material limit states in both directions and a greater energy dissipation capacity. In addition, the geometry of the yielding core plate can be tailored to the strength and, to an extent, the stiffness requirements for a given application.

One of the challenges in determining the appropriate design requirements when developing a new lateral resisting system is determining appropriate limitations on code specified design provisions that result in robust and safe structures. An example of this would be allowed inelastic strain levels in a BRB. These limitations must then be linked to an elastic design procedure based on elastic static analysis. Currently, BRBs are designed and

detailed in the United States in accordance with ASCE/SEI Standard 7-10 [1] and AISC/ANSI 341-10 [2]. The provisions with impact on BRB design are the Seismic Performance Factors (R , Ω_o , C_d) and the capacity design provisions. The Seismic Performance Factors relate the elastic analysis model to the expected inelastic response. The capacity design requirements ensure that the other elements in the load path, as well as the casing member and connecting elements of the BRB itself, have sufficient capacity for the maximum inelastic demand required. The current requirement to determine the brace forces at the expected deformations requires a drift that is the larger value of two percent of the story height or twice the design inelastic story drift. The difficulty is that the overstrength depends on the frame geometry frame which can require multiple iterations as section sizes change. One goal of this research is to determine whether the brace demands from a nonlinear analysis can quantify the required overstrength demand as a function of the brace geometry only (i.e. yield deformation or yield force).

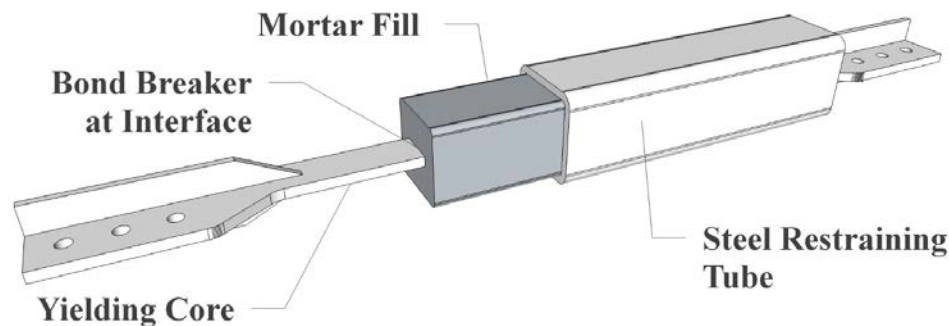


Fig. 1 – Typical U.S. BRB Configuration

The typical configuration of BRBs in US practice today (See Fig. 1) consists of a core plate with a yielding region that is tapered down from the end connection regions. The core plate is covered by a steel tube filled with mortar creating the buckling-restraining mechanism. Between the steel and mortar, an air gap or bond breaker exists to minimize axial load transfer between the core and the restraining system and allow for Poisson effects of the core plate. Significant experimental and analytical research has investigated BRB performance. The original research conducted on a plate debonded from constraining concrete was conducted by Yoshino [3] and Wakabayashi [4]. Many researchers since then have investigated a myriad of different combinations of core plate and buckling restraining mechanisms [5]. While a significant amount of research has been done related to component testing of BRBs, system level research has been less common. A few examples of either experimental or analytical research on system level response include ([6], [7], [8], [9], [10]).

The aim of the research reported in this paper is to add to the data available on system level response of BRBs. A three- and six-story structure, previously used for research on braced frames [8], and based on the SAC Steel Project buildings [11], have been used. The other parameters include seismic hazard, brace configuration, seismic importance factor (I_e) and BRB yielding core length. Two different seismic hazards, Los Angeles and Riverside, California are utilized to examine the effects of seismic hazard and both Near- and Far-Field effects. Both are in the highest seismic design category but there is a significant difference in the spectral accelerations. Single diagonals and chevron (inverted-V) configurations are used to evaluate how the yielding core length difference and a reduced number of braces impacts performance. The seismic importance factor is also investigated by designing for a normal and critical occupancy structure ($I_e = 1$ and $I_e = 1.5$). Lastly, one of the concerns associated with tailoring BRBs for increased stiffness is the impact of having a short yielding core length which results when the BRB stiffness is increased with a shorter core. Two core lengths using the same cross-sectional area are analyzed to study the impact of standard and excessively short yield lengths.

2. Structure Descriptions

All versions of the three- and six-story structures were designed using the equivalent lateral force procedure specified in ASCE 7-10. The gravity loads used for design are the same as those specified by Sabelli [8]. The same gravity system, columns and beams are used for all the versions of the buildings. The only change between the various building versions are the BRBs. A yield stress of 262 MPa (38 ksi) was assumed for the all BRB

designs. The two different seismic hazards used in the analyses are Riverside, CA ($S_{DS} = 1.0$, $S_{D1} = 0.6$) and Los Angeles, CA ($S_{DS} = 1.39$, $S_{D1} = 0.77$). Both locations are considered site class D. The seismic design category for all the structures with normal occupancy is D. For the structures designed with $I_e = 1.5$, the seismic design category is E and F for Riverside and LA, respectively. The building design was completed using SAP 2000 version 15 [12]. In total, 20 building variations were designed, 10 for each building height.

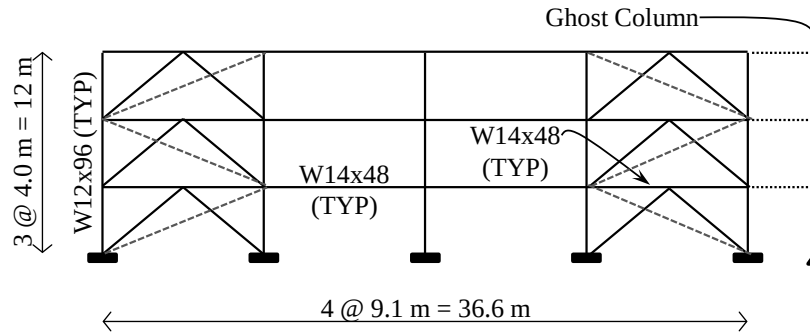


Fig. 2 – Elevation View of Three-Story Structure

2.1 Three-Story Structure

The three story structure is a typical office building with a 4.0 m story height. The plan dimensions are 37.8 m by 56.1 m with 9.1 m square structural bays. The building envelope is 610 mm outside the structural gridlines on all sides. Two bays of perimeter bracing are present on each building face. A building elevation is shown in Figure 2. The columns and beam sizes are consistent for all the different configurations of the structure. Figure 2 shows the chevron bracing in solid lines and the single diagonal configuration in dashed lines. The model names and fundamental periods of vibration are shown in Table 1. The model nomenclature is based on the various set of parameters. Los Angeles (LA) and Riverside (Riv) and the number of stories (3 or 6) are the first component. The two letters after the hyphen indicate either chevron (CH) or single diagonal (SD). The last portion indicates the parameters for increased importance (1.5) or shortened yield length (S). Where no final parameter exists following the brace configuration, a normal yield length and normal importance ($I_e = 1$) were used. Table 2 shows details about the BRB elements in all variations of the three-story structures. The yield length ratio is the ratio of the yielding core length to the working point length of the braces.

Table 1 – Periods of Vibration for Building Models

Models	Fundamental Period (s)	Models	Fundamental Period (s)
LA3-CH	0.52	Riv3-CH	0.57
LA3-CH1.5	0.45	Riv3-CH1.5	0.49
LA3-CHS	0.48	Riv3-CHS	0.52
LA3-SD	0.58	Riv3-SD	0.64
LA3-SDS	0.49	Riv3-SDS	0.53
LA6-CH	1.27	Riv6-CH	1.34
LA6-CH1.5	1.09	Riv6-CH1.5	1.18
LA6-CHS	1.10	Riv6-CHS	1.16
LA6-SD	1.44	Riv6-SD	1.61
LA6-SDS	1.23	Riv6-SDS	1.36

The six story structure is also a typical office building. The first story height is 5.5 m with the remaining stories having a 4.0 m height. The building is square in plan (45.7 m) with 9.1 m square bays. The building envelope is 610 mm outside the structural grid. Figure 3 shows an elevation view of the six-story structure. Three bays of perimeter bracing are used on each face of the building. The dotted lines show the brace orientation of the single diagonal brace configuration. The fundamental periods of vibration for the different configurations of the six-story structure are presented in Table 1. Table 3 shows details about the BRB properties in the six-story models. Naming convention is the same as used for the 3-story building.

Table 2 – BRB Properties for Three-Story Building Models

Model	Story Level	Yield Force (kN)	Yield Length (m)	Yield Length Ratio	Model	Story Level	Yield Force (kN)	Yield Length (m)	Yield Length Ratio
LA3-CH	3 rd	718.4	3.88	0.64	Riv3-CH	3 rd	549.3	4.02	0.66
	2 nd	1098.7	3.52	0.58		2 nd	929.6	3.77	0.62
	1 st	1352.2	3.35	0.55		1 st	1014.1	3.51	0.58
LA3-CH1.5	3 rd	1098.7	3.52	0.58	Riv3-CH1.5	3 rd	845.1	3.85	0.64
	2 nd	1690.2	3.30	0.55		2 nd	1352.2	3.38	0.56
	1 st	1943.8	3.23	0.53		1 st	1521.2	3.32	0.55
LA3-CHS	3 rd	718.4	1.71	0.28	Riv3-CHS	3 rd	549.3	1.69	0.28
	2 nd	1098.7	1.69	0.28		2 nd	929.6	1.70	0.28
	1 st	1352.2	1.66	0.27		1 st	1014.1	1.65	0.27
LA3-SD	3 rd	1183.2	6.86	0.69	Riv3-SD	3 rd	929.6	7.07	0.71
	2 nd	1859.3	6.56	0.66		2 nd	1521.2	6.65	0.67
	1 st	2281.8	6.71	0.67		1 st	1774.8	6.93	0.70
LA3-SDS	3 rd	1183.2	2.06	0.21	Riv3-SDS	3 rd	929.6	2.07	0.21
	2 nd	1859.3	2.06	0.21		2 nd	1521.2	2.05	0.21
	1 st	2281.8	1.99	0.20		1 st	1774.8	1.98	0.20

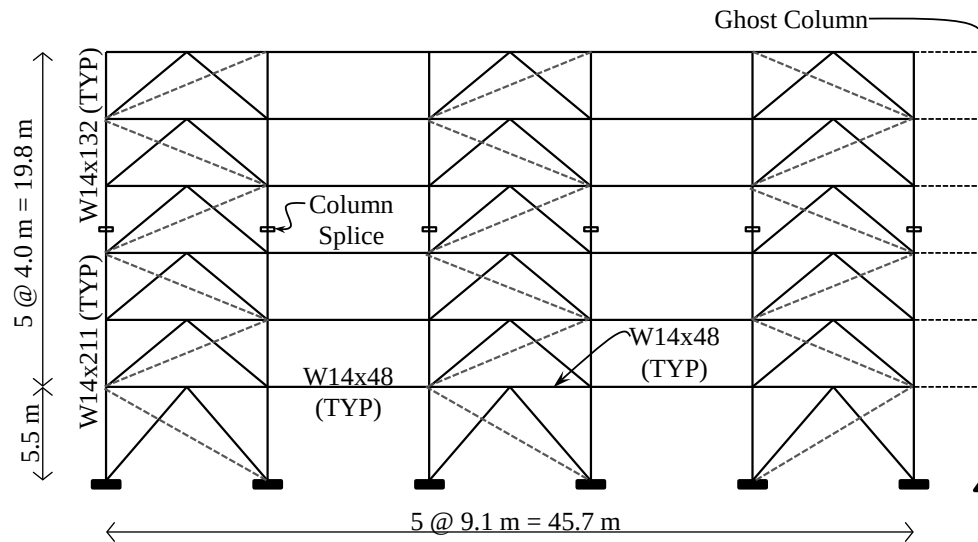


Fig. 3 – Elevation View of Six-Story Structure

3. Modeling and Analysis

The nonlinear dynamic analysis for the models was completed in Perform 3D version 5 [13]. As is shown in Figures 2 and 3, a planar frame model is used for the analyses. In order to capture p-delta effects, a leaning ghost column is used. The ghost column captures the gravity loading and the continuous column effect of the leaning columns. The ghost column is a nonstandard shape with the moment of inertia equal to the sum of the weak axis properties of the tributary gravity columns. An equal displacement constraint is used at each floor to constrain the ghost column to the frame. Gravity loads are applied to the model as both point and distributed loads. Distributed loads are used on the beams except where those loads would induce gravity loads into the BRBs in the chevron configuration. In this case the tributary gravity loads were applied directly to the column. Dead load and 50% of live load are applied to the frame before the earthquake analysis. Tributary horizontal joint masses are applied at all the model nodes.



Table 3 – BRB Properties for Six-Story Building Models

Model	Story Level	Yield Force (kN)	Yield Length (m)	Yield Length Ratio	Model	Story Level	Yield Force (kN)	Yield Length (m)	Yield Length Ratio
LA6-NCh	6 th	253.5	3.71	0.61	Riv6-NCh	6 th	211.3	3.69	0.61
	5 th	338.0	4.11	0.68		5 th	295.8	3.72	0.61
	4 th	464.8	3.72	0.62		4 th	380.3	3.69	0.61
	3 rd	507.1	4.10	0.68		3 rd	422.6	3.68	0.61
	2 nd	549.3	4.10	0.68		2 nd	464.8	3.67	0.61
	1 st	591.6	5.07	0.71		1 st	507.1	5.02	0.70
LA6-NCh1.5	6 th	338.0	4.08	0.67	Riv6-NCh1.5	6 th	295.8	3.72	0.61
	5 th	464.8	3.67	0.61		5 th	422.6	3.68	0.61
	4 th	633.8	3.98	0.66		4 th	549.3	4.02	0.66
	3 rd	718.4	3.88	0.64		3 rd	591.6	4.00	0.66
	2 nd	802.9	3.87	0.64		2 nd	676.1	3.90	0.65
	1 st	845.1	4.84	0.68		1 st	676.1	4.88	0.68
LA6-SCh	6 th	253.5	1.72	0.29	Riv6-SCh	6 th	211.3	1.71	0.28
	5 th	338.0	1.69	0.28		5 th	295.8	1.73	0.29
	4 th	464.8	1.69	0.28		4 th	380.3	1.71	0.28
	3 rd	507.1	1.70	0.28		3 rd	422.6	1.70	0.28
	2 nd	549.3	1.68	0.28		2 nd	464.8	1.69	0.28
	1 st	591.6	1.98	0.28		1 st	507.1	2.02	0.28
LA6-NSD	6 th	338.0	7.42	0.74	Riv6-NSD	6 th	253.5	7.05	0.71
	5 th	507.1	7.37	0.74		5 th	422.6	7.02	0.70
	4 th	676.1	7.24	0.73		4 th	549.3	7.35	0.74
	3 rd	802.9	7.19	0.72		3 rd	591.6	7.33	0.74
	2 nd	845.1	7.18	0.72		2 nd	676.1	7.24	0.73
	1 st	887.4	8.33	0.78		1 st	676.1	8.38	0.79
LA6-SSD	6 th	338.0	2.06	0.21	Riv6-SSD	6 th	253.5	2.06	0.21
	5 th	507.1	2.08	0.21		5 th	422.6	2.08	0.21
	4 th	676.1	2.06	0.21		4 th	549.3	2.08	0.21
	3 rd	802.9	2.06	0.21		3 rd	591.6	2.08	0.21
	2 nd	845.1	2.06	0.21		2 nd	676.1	2.08	0.21
	1 st	887.4	2.61	0.24		1 st	676.1	2.63	0.25

Beams in the unbraced bays are modeled as elastic elements. Beams in the braced bays, specifically for the chevron configuration, were modeled as inelastic beams based on the potential for plastic deformations due to unbalanced brace forces. A yield stress of 345 MPa (50 ksi) was used for the beam elements. All beam column connections were assumed to be pinned as it is expected that a simple connection would be used adjacent to the gusset plate to allow for rotation between the beam and column. Columns adjacent to braced bays were modeled to account for possible inelasticity. Columns not adjacent to braced bays were modeled elastically. Modal damping of 2 percent of critical is used for all the modes. Additionally, a small amount of Rayleigh Damping is specified (0.05%) over the range of important periods.

Inelastic modeling of the BRBs was completed using the BRB compound element. There are three primary components to this compound element. The inelastic component uses the length and cross-sectional area of the BRB core to represent yielding and strain hardening with trilinear behavior. The elastic bar represents the elastic portion of the BRB which includes the length outside the core to the start of the end zone. The end zone is the remaining length between the ends of the brace and the beam-column joint working points. The yield force, initial stiffness, post-yield stiffness, and hardening behavior for the inelastic component as well as the length, equivalent area for the elastic bar component, and end zone multiplier (on the elastic bar area) for the compound element was provided by CoreBrace LLC.



Two different suites of earthquakes were used. The first comes from the SAC ground motion suite for LA with a two percent probability of exceedance in 50 years [14]. The SAC motions were only used for the LA models as they represent primarily near-fault records. The second suite is a selection of ground motions from FEMA P695 [15] including motions from the near- and far-field sets. All ground motions are individually scaled such that the average of the suite is at least 90% of the two percent in 50 years hazard spectrum over the applicable range of structure periods. The ground motion scale factors are shown in Tables 4 and 5.

Table 4 – SAC Ground Motion Scale Factors

Ground Motion	LA3	LA6	Ground Motion	LA3	LA6
LA21	0.89	0.85	LA31	0.80	0.91
LA22	1.05	1.04	LA32	0.79	0.85
LA23	2.02	2.05	LA33	1.31	1.20
LA24	1.49	0.99	LA34	1.23	1.17
LA25	1.13	1.02	LA35	1.20	1.08
LA26	1.17	0.88	LA36	1.24	0.91
LA27	1.55	1.48	LA37	N/A	1.10
LA28	0.80	0.85	LA38	N/A	0.93
LA29	1.42	1.43	LA39	N/A	1.57
LA30	1.08	1.05	LA40	N/A	1.29

Table 5 – FEMA P695 Ground Motion Scale Factors (FF – Far Field, NF – Near Field)

Ground Motion	LA3	Riv3	LA6	Riv6	Ground Motion	LA3	Riv3	LA6	Riv6
FF01-1	2.13	1.49	1.44	1.04	NF09-1	1.14	0.80	0.51	0.58
FF01-2	1.39	0.98	1.46	1.03	NF09-2	1.96	1.38	1.24	1.13
FF02-1	1.91	1.33	3.45	2.47	NF10-1	1.73	1.22	1.40	1.66
FF02-2	2.06	1.45	2.49	2.13	NF10-2	1.13	0.80	0.82	0.82
FF03-1	1.37	0.96	2.05	1.64	NF12-1	2.13	1.86	1.02	0.75
FF03-2	1.65	1.16	1.73	1.43	NF12-2	2.11	1.47	1.14	0.95
FF09-2	2.65	1.86	3.66	2.69	NF15-1	2.16	1.52	1.65	1.31
FF09-2	2.78	1.97	1.67	1.22	NF15-2	1.60	1.13	2.42	1.97
FF16-1	3.42	2.40	3.02	2.19	NF22-1	1.50	1.06	1.43	1.14
FF16-2	4.20	3.00	3.65	2.45	NF22-2	2.26	1.75	2.17	1.74
FF18-1	2.74	1.92	2.46	1.98	NF23-1	1.50	1.05	1.42	1.20
FF18-2	1.43	1.02	2.13	1.72	NF23-2	1.45	1.02	1.65	1.36
FF19-1	3.30	2.88	2.86	2.46	NF24-1	3.22	2.27	3.30	1.90
FF19-2	2.53	1.79	1.77	1.49	NF24-2	1.52	1.07	1.53	1.28
NF02-1	4.20	2.98	2.09	1.69	NF26-1	2.36	1.66	1.46	1.12
NF02-2	2.55	1.79	1.86	1.42	NF26-2	2.08	1.47	1.80	1.34
NF04-1	1.90	1.66	1.05	0.78	NF27-1	0.92	0.81	0.59	0.53
NF04-2	2.72	1.92	2.37	1.66	NF27-2	2.26	1.59	2.06	1.49
NF06-1	2.50	1.75	2.18	1.70	NF28-1	3.36	2.99	1.85	1.34
NF06-2	2.23	1.67	1.32	0.96	NF28-2	2.47	2.16	1.23	0.92
NF07-1	2.14	1.49	2.93	2.50					
NF07-2	1.50	1.04	1.66	1.23					

4. Results and Discussion of Results

A significant volume of data is generated from these analyses. One of the challenges is reducing the data to what is needed to identify the demands. The reported data includes story drift, residual story drift, roof acceleration, normalized brace force, single cycle ductility, reference ductility, brace strain and cumulative ductility. The story and residual story drift represent the maximum drift over the building height. The residual drift is an average of the maximum residual story drift over all stories at the end of the analysis. The roof acceleration is the total horizontal roof acceleration. The data reported for braces represents the maximum magnitude that occurred in tension and compression. To ensure that the maximum response in both directions was obtained, data was taken from braces oriented in both directions. The normalized brace force is the maximum force that occurred in any brace in the structure normalized by the brace yield force. This approximately represents the overstrength that would be used in a capacity design procedure.

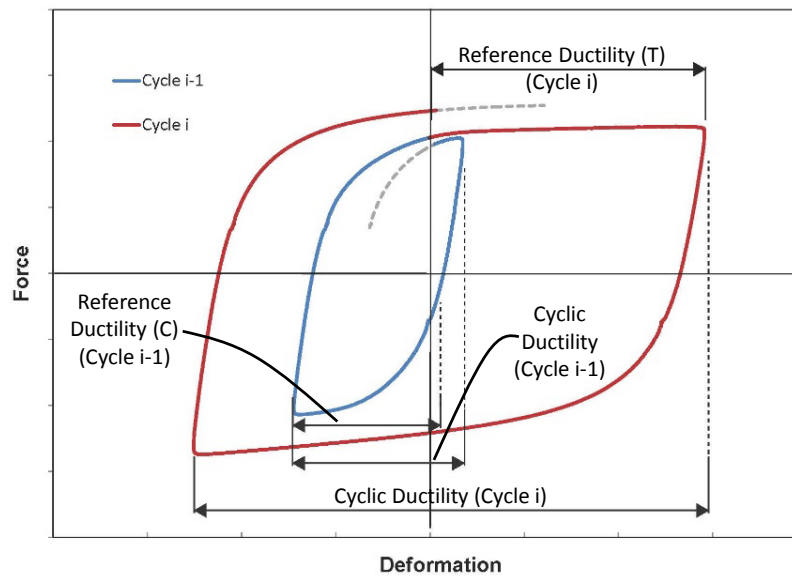


Fig. 4 – Schematic Representation of Ductility Demand Metrics

The three different ductility measures all vary in what they represent. Figure 4 shows a representation of the difference between single cycle and reference ductility. The reference ductility demand is measured from the initial, un-elongated core state (referenced to brace initial state). This measure is consistent with ductility demand limits established in codes such as AISC 341-10 [2] and is the ductility demand associated with the reported core strain values. Single cycle ductility demand represents the largest ductility demand from a negative to positive (or positive to negative) deformation of a single cycle. For symmetrical loading protocols, the single cycle ductility demand would be twice the reference ductility demand. The cumulative ductility demand represents the summation of single cycle excursions in the inelastic range throughout the analysis. The force and displacement data from the brace elements was reduced using subroutines which calculated the single cycle and cumulative ductility. The reference ductility was calculated using the maximum brace deformations in tension or compression.

The analysis data is presented in tabular form and includes the mean and standard deviation for the suite of earthquakes. Table 6 shows the results from the three-story LA model. The LA data set includes both the FEMA P695 and the SAC records. Table 7 shows the results for the three-story Riverside structure, which only includes the FEMA P695 records. The discussion below indicates percent changes in the response of the structure using the normal chevron configuration as the basis unless specifically indicated.

Table 6 – Analysis Results – LA Three-Story Structure

Building Model		Story Drift	Residual Story Drift	Roof Acceleration (g)	Normalized Brace Force	Single Cycle Ductility	Reference Ductility	Brace Strain	Cumulative Ductility
LA3-CH	μ	0.037	0.013	1.78	1.95	25.9	24.2	0.032	104.6
	$\mu+\sigma$	0.051	0.020	2.09	2.25	39.2	34.4	0.045	163.0
LA3-CH1.5	μ	0.028	0.011	1.92	1.77	19.6	19.1	0.025	73.1
	$\mu+\sigma$	0.039	0.017	2.30	1.99	28.9	26.8	0.035	109.5
LA3-CHS	μ	0.027	0.004	1.95	2.48	41.1	33.9	0.044	185.7
	$\mu+\sigma$	0.037	0.006	2.28	2.97	60.2	46.8	0.061	276.5
LA3-SD	μ	0.040	0.018	1.63	1.73	16.4	15.9	0.021	66.7
	$\mu+\sigma$	0.058	0.030	1.91	1.96	24.7	23.1	0.030	101.9
LA3-SDS	μ	0.026	0.004	2.18	2.42	38.2	31.2	0.041	172.9
	$\mu+\sigma$	0.036	0.006	2.53	2.87	56.7	43.3	0.057	256.0

Table 7 – Analysis Results – Riverside Three-Story Structure

Building Model		Story Drift	Residual Story Drift	Roof Acceleration (g)	Normalized Brace Force	Single Cycle Ductility	Reference Ductility	Brace Strain	Cumulative Ductility
Riv3-CH	μ	0.030	0.012	1.16	1.80	21.0	19.6	0.026	85.1
	$\mu+\sigma$	0.044	0.019	1.41	2.14	36.1	33.5	0.044	155.3
Riv3-CH1.5	μ	0.022	0.009	1.31	1.80	14.1	14.1	0.019	52.4
	$\mu+\sigma$	0.032	0.015	1.57	2.14	21.8	21.2	0.028	91.6
Riv3-CHS	μ	0.022	0.005	1.23	2.22	33.2	28.6	0.037	154.1
	$\mu+\sigma$	0.034	0.008	1.46	2.70	53.1	44.2	0.058	272.3
Riv3-SD	μ	0.032	0.015	1.12	1.60	12.6	12.3	0.016	51.0
	$\mu+\sigma$	0.050	0.027	1.33	1.85	20.3	19.3	0.025	90.5
Riv3-SDS	μ	0.022	0.005	1.52	2.15	30.1	25.5	0.033	140.3
	$\mu+\sigma$	0.031	0.007	1.81	2.58	47.4	37.2	0.049	247.8

4.1 Three-story Structure Results

The three-story model results indicate several things based on the differences between the two standard brace configurations. For the typical brace configurations (CH and SD), the single diagonal experiences greater story and residual drifts. The increase in story drifts for the single diagonal compared to the chevron was eight and seven percent for LA and Riverside, respectively. The increase in residual drift for single diagonal braces as compared to a chevron configuration was 38% and 25% for LA and Riverside, respectively. The trade-off is that the normalized brace force, reference ductility, and cumulative ductility are lower for the single diagonal. The decrease in normalized brace force in the single diagonal compared to the chevron is approximately 11%. The decrease in the reference ductility demand and cumulative ductility for the single diagonal is greater than 30% for both locations. The differences are due to the longer brace yielding length and the longer fundamental period of the single diagonal structure. The chevron configuration designed with $I_e=1.5$ results in improved performance in all aspects with the exception of roof acceleration.

The shortened brace length has a significant response impact. This yield length represents an extreme value to investigate the potential impacts and many of these demands may not be achievable in current BRBs without core fracture. It is interesting that the shortened brace length and the $I_e=1.50$ have approximately the



same influence on the fundamental period. The reduction in maximum story drifts for the shortened braces ranges from 27% to 35%. The reduction in residual drifts ranges from 58% to 78% for the various three-story models. All other performance metrics however are increased using the shortened yield length. The largest increase exists in the ductility metrics. The cumulative ductility demand increase ranges between 78% for the LA chevron up to 175% for the Riverside single diagonal. It should be noted that the relative change in yield length is greater for the single diagonal configurations which may be one reason for the larger changes in demands. The reference ductility demand for shortened braces is increased by 46% and 107% for the Riverside chevron and single diagonal respectively. The increases in reference ductility for LA chevron and single diagonal shortened braces are 40% and 96%, respectively. The increases in normalized brace force range between 23% for the LA chevron and 55% for the LA single diagonal.

4.2 Six-story Structure Results

Table 8 shows the analysis results for the LA six-story structures. Table 9 shows the results for the Riverside six-story structures. Many of the same trends seen in the three-story models are also seen in the six-story results. Just as with the three-story model a seismic importance factor of 1.5 decreased the story drift by 14% while also decreasing all the ductility metrics by at least nine percent. The cumulative ductility was decreased by 15%. The shortened yield length braces decreased both the story drift and the residual story drift. However in both cases the shortened yield braces increased all the ductility measures by at least 120% and by as much as 200% and again, are likely not achievable. The normalized brace force (overstrength) increased by 18% for the chevron and 56% for the single diagonal. The increases were greater for the single diagonal as the relative shortening of the single diagonal was much greater than for the chevron configuration.

4.3 Comparison of Six- and Three-Story Response

The six-story structures on average experienced an increase in maximum story drift over their three-story counterparts. For the LA buildings the increase ranged from one percent for the single diagonal to 33% for the short yield length chevron with the three-story as the basis. The Riverside structure exhibited a six percent decrease for the single diagonal max story drift while all the other configurations increased for the six-story structure by between nine and 24%. The residual drifts were a mixed comparison. For LA, the six-story structures had lower residual drifts for all cases with the exception of the shortened chevron. The residual drift for the six-story shortened yield chevron structure was nearly double the three-story version. For the Riverside structures all the residuals decreased with the exception of the chevron which increased by 45%. The roof accelerations decreased for the six-story buildings for all cases by at least 30%.

The metrics representing the brace demands also changed from the three to six-story buildings. For LA, the normalized brace force increased for all cases except the shortened yield chevron which decreased by six percent. The increases ranged from two to 16%. An increase in the normalized brace force occurred for all the Riverside six-story configurations. These increases ranged from one to eight percent. The ductility metrics also generally increased. The most substantial increases were seen in both shortened yield length configurations. The LA chevron configuration showed the same single cycle ductility demand and a 10% decrease for the six-story in the reference ductility demand and brace strain. The chevron configuration in Riverside showed an eight percent decrease for the single cycle ductility, reference ductility and the brace strain. The cumulative inelastic ductility demand for the chevron increased by three percent for LA and remained constant for Riverside. The chevron with a 1.5 importance factor and the single diagonal experienced similar trends. Double digit percentage increases (12% to 46%) were seen for the normalized brace force and the cumulative inelastic ductility demand for both LA and Riverside. The reference ductility demand and brace strain increased from two to eight percent for both brace configurations in both locations. The ductility metrics for the shortened yield length braces all increased by at least 20%. The maximum increases were over 50% which occurred in the single cycle ductility demand for the LA shortened chevron and the cumulative inelastic ductility demand for the Riverside shortened single diagonal.



Table 8 – Analysis Results – LA Six-Story Structure

Building Model		Story Drift	Residual Story Drift	Roof Acceleration (g)	Normalized Brace Force	Single Cycle Ductility	Reference Ductility	Brace Strain	Cumulative Ductility
LA6-CH	μ	0.040	0.010	0.87	1.98	25.8	21.7	0.028	108.2
	$\mu+\sigma$	0.058	0.017	1.08	2.30	38.6	31.5	0.041	162.0
LA6-CH1.5	μ	0.034	0.011	0.99	1.90	23.5	19.6	0.026	91.9
	$\mu+\sigma$	0.049	0.017	1.27	2.17	34.5	27.9	0.037	136.3
LA6-CHS	μ	0.036	0.008	0.93	2.33	64.4	48.5	0.064	271.4
	$\mu+\sigma$	0.052	0.012	1.18	2.71	95.1	70.0	0.092	406.3
LA6-SD	μ	0.040	0.013	1.00	1.81	19.5	17.0	0.022	82.2
	$\mu+\sigma$	0.059	0.023	1.25	2.08	29.5	25.1	0.033	123.0
LA6-SDS	μ	0.034	0.004	1.20	2.81	52.9	41.7	0.055	249.6
	$\mu+\sigma$	0.050	0.006	1.49	3.54	75.7	62.8	0.082	364.0

Table 9 – Analysis Results – Riverside Six-Story Structure

Building Model		Story Drift	Residual Story Drift	Roof Acceleration (g)	Normalized Brace Force	Single Cycle Ductility	Reference Ductility	Brace Strain	Cumulative Ductility
Riv6-CH	μ	0.033	0.017	0.640	1.81	19.3	18.0	0.024	84.9
	$\mu+\sigma$	0.048	0.031	0.824	2.10	29.5	26.5	0.035	136.8
Riv6-CH1.5	μ	0.027	0.008	0.729	1.81	17.5	15.2	0.020	76.6
	$\mu+\sigma$	0.037	0.014	0.959	2.10	25.2	20.8	0.027	119.6
Riv6-CHS	μ	0.025	0.005	0.738	2.41	39.8	32.1	0.042	185.7
	$\mu+\sigma$	0.035	0.007	0.974	2.90	58.2	46.2	0.060	290.1
Riv6-SD	μ	0.030	0.010	0.757	1.63	14.1	12.6	0.017	69.9
	$\mu+\sigma$	0.044	0.019	1.004	1.86	22.0	18.5	0.024	113.4
Riv6-SDS	μ	0.026	0.003	0.886	2.29	42.7	32.8	0.043	220.0
	$\mu+\sigma$	0.039	0.005	1.148	2.87	62.7	48.4	0.063	337.1

4.4 Brace Strain and Normalized Brace Force (Overstrength)

A graphical look at the distribution of the data related to the overstrength (normalized brace force) and brace strain is shown in Fig. 5. These graphs show the maximum normalized tension and compression forces and brace strains that occurred simultaneously. The results shown include two braces on the first story, one in each orientation. The top graph in Fig. 5 shows the impact of the importance factor for the three-story LA chevron. Both the maximum brace strains and the overstrength have been reduced. For the $I_e = 1.5$ chevron the concentration of data points in the first quadrant has moved down and left indicating a reduced demand on the braces which also reduces the demand on the structure. The bottom figure shows the impact of the yielding core shortening on the six-story single diagonal in Riverside. This is a more extreme case and it shows the shortened single diagonal experiencing a strain of about 0.10. This is well beyond the tested range for BRBs indicating that the modeling procedure may not be applicable for this type of brace. It also shows the potential issues of shortening the yield length of the brace on both the material strain and the axial force demands of the braces experiencing an overstrength demand of nearly 4.

4.5 Summary of Analysis Results

One of the primary goals of this study was to determine a multiplier on brace yield deformation that would simplify the BRB seismic design process in place of the currently specified 2 percent story drift (similar to the 2x factor on the story drift that is also currently checked). Reference Ductility is the metric presented to develop this multiplier. If we look at the normal chevron configuration, the three-story model average reference ductility is 20 for Riverside and 24 for LA. For the six-story model the values for Riverside and LA are 18 and 22, respectively. It is clear that the importance factor of 1.5 does have an impact. For the LA three- and six-story structures the average reference ductility is 19 and 20. Both of these are reduced as compared to the normal structure but by different ratios. The variability of the reference ductility value for the different variations is too complex for a simple multiplier. A more comprehensive study of building designs with varying hazard and geometry would be required to have a reasonable and reliable multiplier based on the important parameters.

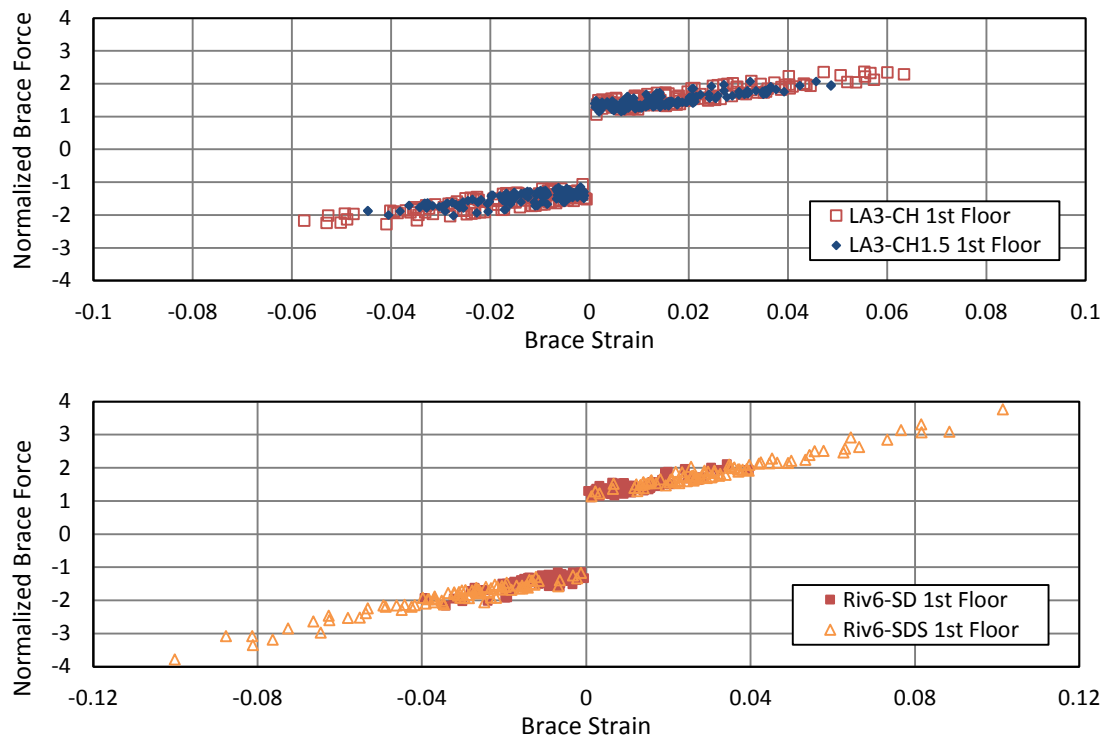


Fig. 5 –Brace Strain vs. Overstrength. Top: LA Three-Story Chevron, Bottom: Riverside Six-Story Single Diagonal

Another interesting discussion is the difference between the single cycle and the reference ductility. Current testing requirements use a symmetric protocol. This symmetric protocol results in a single cycle ductility that is double the reference ductility. The data presented here shows that the average ratio ranges from 1.0 to 1.36. This indicates that the hardening model based on a symmetric cyclic loading may be greater than what occurs during an actual earthquake due to the less-than symmetric nature of the loading. As such, when comparing reference ductility demands indicated in this research, which are seemingly high, to those obtained in symmetrical BRB qualification testing, it should be taken into account that the lower reference strains obtained in tests are associated with higher single-cycle strains.

5. Conclusions

This paper used two different high seismic hazard sites and two structural heights coupled with a single diagonal and a chevron brace configuration along with several other parameters to investigate the system performance, brace force demands and ductility demands of buckling-restrained braced frames. The 2-D nonlinear dynamic analyses were completed with a large suite of earthquakes that included both near-field and far field records. The important findings and conclusions include:



- Many parameters have an influence on the ductility and force demands in BRBs including the brace configuration, importance factor, seismic hazard and brace yield length.
- The importance factor has a beneficial effect on brace forces, ductility demands and story drift. In most cases it reduces residual drifts. However, it does increase the roof acceleration.
- The shortened yield length braces experienced smaller story and residual story drifts. However, this is coupled with significant increases in acceleration, normalized force demands and all measures of brace ductility demand. Limits on how short the yield length of braces can be should be considered to avoid the potential for large forces or other potential failure methods.
- A simple multiplier on yield deformation to determine the maximum brace deformation and subsequently the overstrength demand is not feasible due to the numerous important parameters. A more comprehensive study is needed to solve this problem.
- The ratio of the single cycle to reference ductility demand is much lower than what results from the symmetric testing protocols for BRBs. This indicates that the forces due to analytical hardening rules determined from testing results may be too high.

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