EFFECTS OF DIFFERENT CORE PLATE PROPERTIES ON GLOBAL RESPONSE OF BRBFs

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1. ABSTRACT

Steel buckling restrained braced frames (BRBFs) are one of the most preferred lateral load resisting systems in seismic prone regions due to their high elastic stiffness and high ductility. Buckling restrained braces (BRBs) utilize a core segment which is used as a fuse element to provide a high level of energy dissipation without loss of inherent axial load carrying capacity. Only the yielding part of the entire core segment is subjected to inelastic deformation during a destructive earthquake. Therefore, yield strength and yielding length of the core plates are the most important parameters that influence story drifts and inelastic behavior of BRBs. In this study, four chevron 6-story BRBF archetypes having BRBs with different yield strength and yielding length were designed according to ASCE7-10 and AISC341-10 provisions. Non-linear time history analysis of the archetypes were conducted by considering 44 far-field ground motions defined in FEMA P695 and scaled to Maximum Considered Earthquake (MCE) for Seismic Design Category D_{max}. Story drifts and brace axial strains obtained from time history analyses are reported. The axial strain demands obtained from inelastic time history analyses are compared with the demands recommended by AISC341-10.

2. INTRODUCTION

Even though buckling restrained braced frames (BRBFs) are relatively new among lateral load resisting systems, they have been investigated and used in the steel buildings for 30 years in the United States and Japan. BRBFs are composed of beams, columns and concentrically connected buckling restrained braces (BRBs). The most distinguishing feature of the BRBs, as opposed to concentrically braced frames (CBFs) is their behavior showing yielding under both tension and compression. BRBFs are designed as per AISC 341-10 Seismic Provisions for Structural Steel Buildings (AISC 341-10) [1] in the United States. According to this specification, braces shall be designed, tested and detailed to accommodate expected deformations. Expected deformations are those corresponding to a story drift of at least 2% of the story height or two times the design story drift, whichever is larger. In addition to that, the design of braces shall be based upon qualifying cyclic tests in accordance with the procedures and acceptance criteria of AISC 341-10. BRB members shall be subjected to the loading protocol defined in AISC 341-10 which requires that BRB members show adequate performance up to axial deformation corresponding to 2 times the design story drift and cumulative inelastic axial deformation of the BRB members shall be at least 200 times the yield deformation.

All requirements concerning BRB members mentioned above emerged from numerous analyses and experiments conducted in the United States where American steel materials are used such as A36 and A992. In this study, four archetypes composed of chevron BRBFs having different steel materials which are S235 and S355 available in European market and different yielding lengths equal to two thirds and one half of the total BRB length were designed in accordance with ASCE7-10 Minimum Design Loads for Buildings and Other Structures [2], AISC 360-10 Specification for Structural Steel Buildings [3] and AISC 341-10 Seismic Provisions for Structural Steel Buildings [1]. After sections of beams, columns and BRB members of each four archetypes were obtained, nonlinear time history analyses were conducted in OPENSEES [4] program by taking into account 44 far-field ground motions defined in FEMA P695 Quantification of Building Seismic Performance Factors [5]. These ground motions were scaled to the Maximum Considered Earthquake (MCE) for Seismic Design Category D_{max}. Finally, interstory drifts, story drifts and brace axial strains obtained from time history analyses are reported and compared herein.

3. OVERVIEW OF THE FEMA P695 METHODOLOGY

The Methodology requires nonlinear collapse simulation on the selected archetype models. Collapse simulation is conducted using a far field record set that consists of 22 pairs of ground motions that are defined in FEMA P695 [5]. All 44 ground motion records must be individually applied to an archetype in cases where a two dimensional analysis is performed. The ground motion records are scaled twice. The first scaling is required to anchor the median spectrum of the far field record set to the Maximum Considered Earthquake (MCE) response spectra at the fundamental period of the archetype. The second scaling is applied successively to all far field ground motions until 50 percent of the archetypes exhibit collapse. The amount of scaling that results in the collapse of 50 percent of the archetypes is compared with a variable named the Adjusted Collapse Margin Ratio (ACMR). The target ACMR values are tabulated in the FEMA P695 [5] document and depend on the total system collapse uncertainty (β_{TOT}), and collapse probability. Two conditions must be satisfied for acceptable performance. The average value of ACMR for each performance group should meet the target ACMR for 10 percent collapse probability ($ACMR_{10\%}$). Furthermore, individual values of ACMR for each index archetype within a performance group should meet the target ACMR for 20 percent collapse probability ($ACMR_{20\%}$). While successive scaling approach can be adopted for new structural systems, scaling of all ground motions using a pre-calculated scaling factor is sufficient for evaluation of existing systems. Because individual archetypes are considered in this study, the 20 percent probability of collapse was adopted as a criterion for ACMR (i.e. $ACMR_{20\%}$).

The total system collapse uncertainty (β_{TOT}) depends on various factors such as record-to-record collapse uncertainty, design requirements-related collapse uncertainty, test data-related collapse uncertainty, and modelling-related collapse uncertainty. The methodology enables to use non-simulated collapse models for collapse failure modes that cannot be explicitly modelled. Non-simulated collapse modes can be indirectly evaluated using alternative limit state checks on structural response quantities measured in the analysis.

4. DESIGN AND SELECTION OF ARCHETYPES

Different Seismic Design Categories (SDC) can be adopted in the Methodology in order to represent the variation in seismic hazard. In the present study only one seismic design category namely SDC D_{max} was considered which represents the highest seismic hazard level. The MCE, 5 percent damped, spectral response acceleration parameter at short periods adjusted after site class effects (S_{MS}) was taken as 1.50g. The MCE, 5 percent damped, spectral response acceleration parameter at a period of 1 sec adjusted after site class effects (S_{M1}) was taken as 0.90g.

Two geometrical configurations can be adopted for BRBFs where the first one employs single diagonal braces and the second one employs chevron type braces. In the present study performance of only chevron type BRBFs was evaluated.

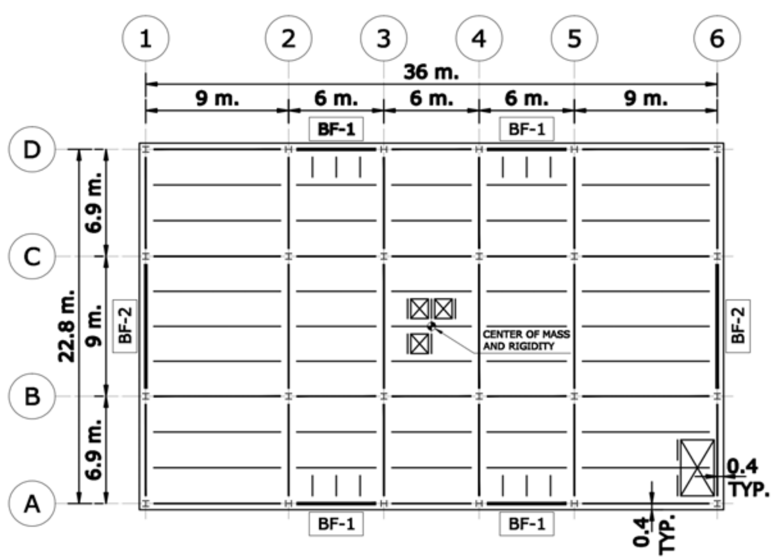

Fig. 1: Floor plan used for the study

Only one type of floor plan shown in Fig. 1 was considered. The floor plan is rectangular with side dimensions of 36 meters and 22.8 meters. There are a total of four bays with single diagonal BRBs in the long direction of the floor plan which are indicated as BF-1 in Fig. 1. A total of two bays with chevron type BRBs are employed in the short direction of the floor plan which are indicated as BF-2 in Fig. 1. Only BF-2 type frames were designed as a part of this study. All beam-to-column connections of the BRBF were considered simple connections with no moment transfer. A dead load of 5 kN/m^2 and a live load of 2 kN/m^2 which are typical for steel office buildings were considered as loading. Story height was taken as 3.5 meters for all stories except the first story where the height was equal to 3.8 meters. In order to take into account variations in structural periods, 3, 6, and 9 story BRBFs were considered.

AT	MT	BR	ST	Column	Beam	Brace (mm^2)	DSD %	DAS %	MSD %	MAS %
1	S235	2/3	1	W14x132	W16x50	4075	0.82	1.50	3.46	2.48
			2	W14x132	W16x50	3550	0.93	1.46	3.13	2.12
			3	W14x68	W16x50	3275	0.97	1.46	2.31	1.54
			4	W14x68	W16x50	2900	1.01	1.46	1.48	0.95
			5	W14x48	W16x50	2375	1.01	1.47	1.07	0.64
			6	W14x48	W16x50	1725	0.91	1.46	0.83	0.49
2	S355	2/3	1	W14x132	W16x50	2800	1.23	1.85	3.84	2.82
			2	W14x132	W16x50	2600	1.41	2.06	3.09	2.09
			3	W14x132	W16x50	2575	1.53	2.24	2.37	1.56
			4	W14x132	W16x50	2450	1.63	2.37	2.05	1.31
			5	W14x68	W16x50	2300	1.68	2.45	1.64	1.03
			6	W14x68	W16x50	2100	1.17	2.52	1.29	0.73
3	S235	1/2	1	W14x132	W16x50	4075	0.69	2.00	3.28	3.43
			2	W14x132	W16x50	3550	0.79	1.94	3.10	3.21
			3	W14x68	W16x50	3275	0.85	1.94	2.40	2.45
			4	W14x68	W16x50	2900	0.88	1.94	1.58	1.53
			5	W14x48	W16x50	2375	0.90	1.94	1.13	1.02
			6	W14x48	W16x50	1725	0.82	1.94	0.77	0.68
4	S355	1/2	1	W14x132	W16x50	2825	0.92	2.00	3.57	3.34
			2	W14x132	W16x50	2425	1.04	2.01	3.14	3.21
			3	W14x68	W16x50	2225	1.09	2.12	2.49	2.52
			4	W14x68	W16x50	1975	1.12	2.17	1.67	1.62
			5	W14x48	W16x50	1625	1.18	2.29	1.27	1.13
			6	W14x48	W16x50	1175	0.92	1.94	1.03	0.90

MT: Material, BR: Brace yielding length ratio to brace total length, ST: Story, DSD: Design interstory drift, DAS: Design brace axial strain, MSD: Median interstory drift, MAS: median brace axial strain.

Table 1: Member sizes of archetypes and response quantities

S355 and S235 steel grades with a yield strength of 355 and 235 MPa respectively were considered for the core plates of BRBs, whereas S355 grade steel was considered for columns and beams of all four archetypes. Different BRBs in terms of different yielding length equal to two thirds and one half of the total BRB length were used separately for each archetype where different steel grades were considered. Designs were conducted according to ASCE 7-10, AISC 341-05, and AISC 360-05. Archetypes were designed by minimizing the weight of the framing. Beam, column and brace members of four archetypes are given in Table 1. Archetype properties and scaling factors are given in Table 2.

AT	MT	BR	N	Mass (ton)	T (sec)	SF_1	μ_T	β_{RTR}	β_{TOT}	AC	SSF	CMR (SF_2)	SF
1	S235	2/3	6	10.55	1.032	2.57	4.52	0.400	0.436	1.443	1.33	1.08	2.78
2	S355	2/3	6	10.03	1.032	2.57	3.89	0.400	0.436	1.443	1.31	1.10	2.84
3	S235	1/2	6	10.55	1.032	2.57	3.26	0.400	0.436	1.443	1.27	1.13	2.90
4	S355	1/2	6	10.03	1.032	2.57	4.39	0.400	0.436	1.443	1.34	1.08	2.78

MT: Material, BR: Brace yielding length ratio to brace total length, T: fundamental period of vibration, SF_1: First scaling factor for anchoring far-field record set to MCE spectral demand, μ_T: period-based ductility of an index archetype model, β_{RTR}: Record-to-record collapse uncertainty, β_{TOT}: total system collapse uncertainty, SSF: Spectral shape factor, CMR: Collapse margin ratio, SF: Ultimate scaling factor, AC: $ACMR_{20\%}$, N: Number of story.

Table 2: Archetype properties and scaling factors

5. NUMERICAL MODELLING DETAILS AND ANALYSIS RESULTS

Performances of the designed archetypes were evaluated by making use of numerical analysis. The OPENSEES [4] computational framework was used for numerical simulations. Two-dimensional finite element models were used to model the archetypes. The beams and columns of the archetypes were modelled with nonlinear beam column elements and the braces were modelled with non-linear truss elements. In general, one of the BRBF bays was modelled and the tributary mass was added to two of the nodes at every story. Leaner columns carrying gravity loads were linked to the frame to simulate P-Δ effects.

The total system collapse uncertainty is dependent on four factors, three of which requires judgment. These factors depend on the knowledge level and modelling capabilities about the system of interest. BRBFs have been studied for over 15 years and have been implemented in the practice. Therefore, high quality level was assigned to design requirements-related collapse uncertainty (β_{DR}=0.1), test data-related collapse uncertainty (β_{TD}=0.1), and modelling-related collapse uncertainty (β_{MDL}=0.1). The fourth factor that needs to be considered is the record-to-record collapse uncertainty (β_{RTR}) which depends on the period based ductility (μ_T). The μ_T values were determined by conducting nonlinear static (pushover) analysis in accordance with ASCE41-13 [6] and are reported in Table 2. Resulting β_{TOT} and $ACMR_{20\%}$ are reported alongside Spectral Shape Factors (SSF) and ultimate scaling factors (SF) for each archetype in Table 2. The archetypes were subjected to 44 ground motion records and the records were scaled by the ultimate scaling factors. A two percent mass and stiffness proportional damping was used in time history analysis.

Interstory drift ratios and brace axial strains were investigated in detail. Design demands and median demands obtained from time history analysis are indicated in Table 1. Variation of interstory drift ratios and brace axial strains along the height are given in Fig. 2 and Fig. 3. The median of response quantities were used for assessment purposes. In Figures 2 and 3 the responses obtained from time history analyses are shown in black while the values considered in design are shown in red. The design values include an amplification of the response quantities by a factor of two as recommended in AISC341-10 [1]. The comparisons indicate that the response considered at the design stage is very different than the response obtained from time history analyses. In general, significant amount of interstory drifts and brace axial strains were observed for lower stories whereas the demands are much less in upper stories. The design values display the opposite.

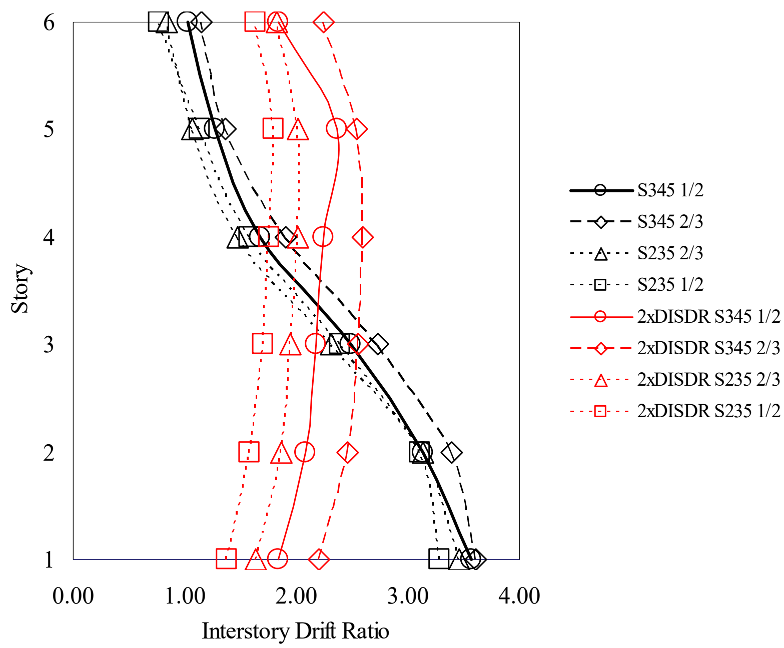

Fig. 2: Interstory drift ratio response of archetypes

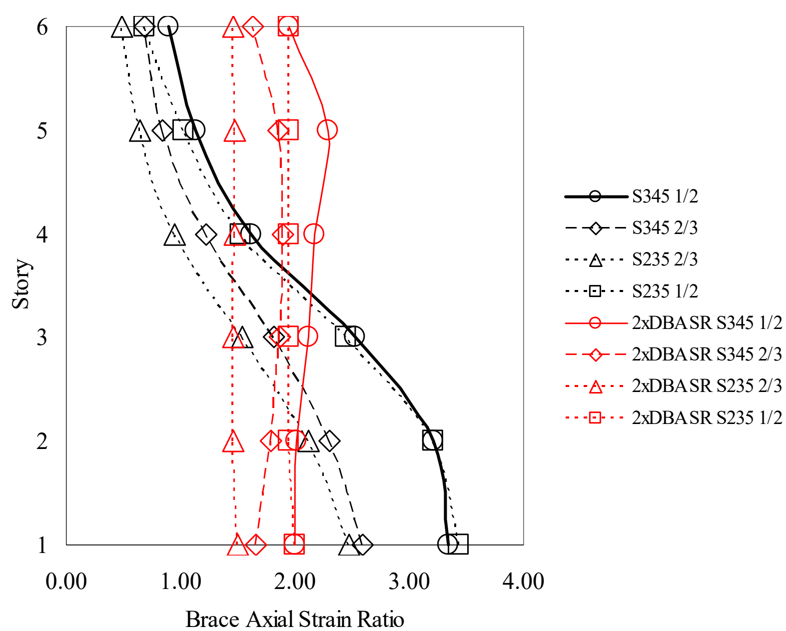

Fig. 3: Brace axial strain response of archetypes

6. EVALUATION OF DISPLACEMENT AMPLIFICATION FACTOR

Analysis results indicate that calculated interstory drifts and design drifts have different variations along the height. The calculated interstory drifts at MCE level ground motions is expected to be 1.5 times the design interstory drifts which are determined considering design based earthquake. Calculated interstory drifts are significantly higher than the design interstory drifts for lower stories. The differences are more pronounced as yielding length of the BRB member decreases. On the other hand, for upper stories the calculated interstory drifts are observed to be less than the design interstory drifts. The differences observed at the lower stories can be attributable to the differences between the response modification (R=8) and displacement amplification (C_d=5) factors adopted in design. According to Newmark's equal displacement rule the displacement amplification (C_d) factor should be taken equal to the response modification R factor to be able to accurately estimate the inelastic demands. For BRBFs, however, the displacement amplification (C_d) factor is taken lower than the response modification (R) factor. It should be emphasized that the design of all BRBF archetypes were governed by strength requirements. Considering a displacement amplification (C_d) factor equal to the response modification (R) factor would result in significant over-design of BRBFs which may adversely affect the cost of this system. One alternative would be to develop displacement amplification (C_d) factors for BRBFs that vary over the height as it was developed for eccentrically braced frames by Kuşyılmaz and Topkaya [7].

Excessive interstory drifts which concentrate to bottom stories resulted in brace axial strains that exceeded the expected strains. The analysis results revealed that the expected deformations of a BRB should be determined by considering an interstory drift of at least 4 percent for the archetypes where material grade of 235 MPa and 355 MPa are utilized for core plates of BRBs.

7. CONCLUSIONS

A numerical study on seismic performance factors of BRBFs with different yielding strength and different yielding length has been presented. The Methodology outlined in FEMA P695 [5] was applied to BRBFs to evaluate the response factors. Nonlinear time history analyses were conducted for four archetypes and the structures were subjected to a set of ground motions in excess of the Maximum Considered Earthquake (MCE) ground motions.

The analysis results indicate that there are marked differences between the calculated interstory drifts and design interstory drifts. These difference stem from the fact that different values are assigned to the deflection amplification factor (C_d) and response modification factor (R). Yielding of BRBs was observed to be non-uniform along the height and significantly higher demands are produced at the bottom stories when compared with top stories. In the past, deflection amplification factors (C_d) that vary over the height of the structure were developed for other lateral load resisting systems [7] and a similar approach can be taken to arrive at BRBF behavior that results in more uniform yielding along the height. Future research should focus on developing relationships between response modification factor (R) and deflection amplification factor (C_d) for BRBFs with different yielding length and different yielding length that vary over the height of the structure.

Brace strain demands are calculated using the interstory drifts at the design stage. Any underestimation of interstory drifts would result in an underestimation of the brace strain demands. In order to safeguard against underestimations the AISC341-10 Specification [1] provides a minimum brace strain demand that corresponds to 2 percent interstory drift. Analysis results showed that the maximum strain in the bottom story of the archetype is higher than the design strains in spite of the minimum demand that corresponds to 2 percent interstory drift. The differences can exceed 100 percent for the archetypes which indicate a potential weakness in the design of buckling-restrained braces. Until further research it is recommended to calculate the minimum strain demand based on 4 percent interstory drift.

When the yielding strength and yielding length of the BRB members are compared, the archetype where the yielding segment is two thirds of the total BRB length showed better performance than the archetype where the yielding segment is one half of the total BRB length in terms of interstory drift ratio and brace axial ratio.

8. REFERENCES

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