Preliminary Study of the Strongback System: Preventing the Soft-Story Mechanism

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Introduction

Braced frame systems resist lateral loads and limit story drift by dissipating energy through tension yielding and/or compression buckling in the braces. Technological improvements in the design of earthquake resistant buildings has seen an evolution from use of special moment frames (SMFs) (Figure 1a) to special concentrically braced frames (SCBFs) (Figure 1b) and more recently buckling restrained braced frames (BRBFs) (Figure 1c).

Figure 1a: Moment frame connection (Source: AISC)

Figure 1b: SCBF in a X configuration (Source: AISC)

Figure 1c: 2-story BRBF (Source: AISC)

While SCBFs have proven more efficient than special moment frames in opposing lateral effects, one very limiting shortcoming of this type of system is the severe decrease in brace stiffness and capacity once it buckles, leading to premature failure. The BRB was developed to balance the compression capacity and tension capacity by acting as a two part system that inhibits buckling by encasing the steel core (Figure 2).

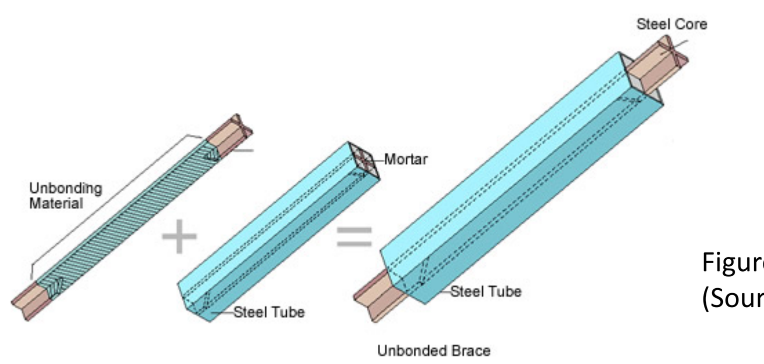


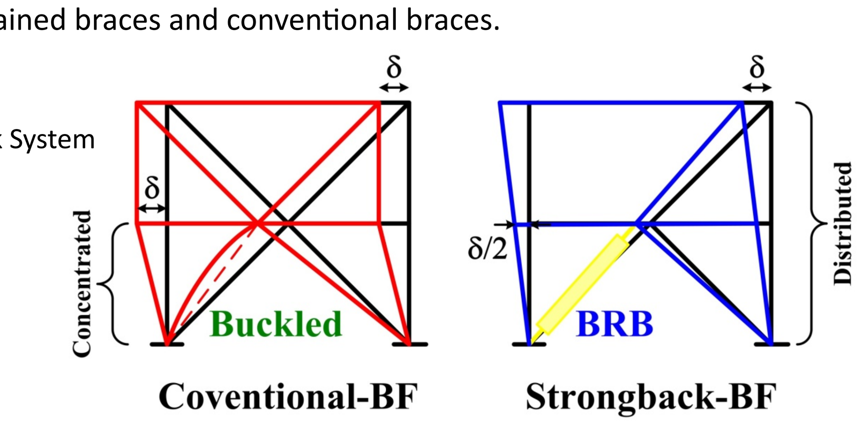
Figure 2: The BRB Components (Source: Nippon Steel)

While BRBs have shown strong performance, they are still vulnerable to deformation and failure at the gusset plates, and they have shown concentration of lateral deflection at lower stories, which can lead to increased damage and in extreme cases, soft story collapse (Figures 3a and 3b).

Figure 3a and 3b: The Soft-story Mechanism (Source: NISEE)

A strongback system (Figure 4) can theoretically prevent the soft story mechanism with the buckling restrained braces dissipating energy and yielding first allowing the conventional braces to distribute the lateral displacement. For such a new idea, the dual system has very little experimental testing and design procedures. The design of structures using BRBFs is done primarily using requirements for SCBFs, which BRBFs have shown they can outperform. This project aims at determining the most effective ratios of sizes, shapes, and orientations of both buckling-restrained braces and conventional braces.

Figure 4: The Strongback System (Source: xxx)



Methods

The model building was selected to be a simple two-story office building in downtown Berkeley. The dimensions were decided to be 120 feet by 180 feet with 30 foot wide bays and 13 foot tall stories, with one set of braces per story contained in one outer bay of each side of the building (Figure 5).

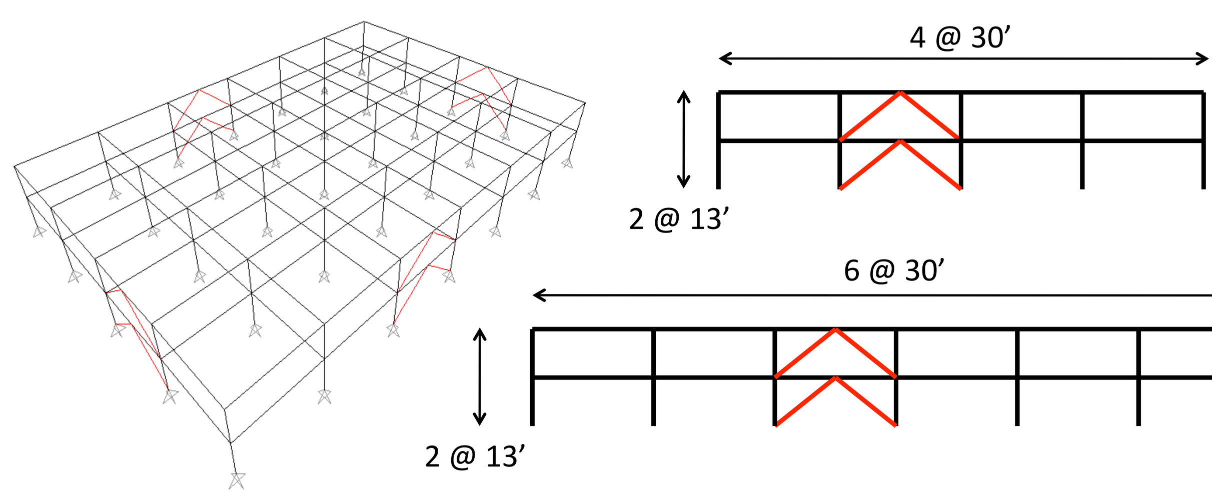


Figure 5: The Model Building

Using AISC-360-05, the loading was calculated for this 2 story building. Earthquake loading was determined with Equivalent Lateral Force Analysis, with seismic base shear from FEMA-450 Provisions equation 5.2-1 equaling 656 kips. This force was rounded and distributed 400 kips at the top floor and 260 kips at the bottom floor. The dead load was calculated based on loading assumptions from a similar previous test (Lai 2009) and was applied as a point load at each of the four column-beam connections. The dead load from member weight was not accounted for in calculations because the analysis program, SAP2000, was set to account for this weight during analysis. The braces were arranged in a chevron design and pinned at both ends with the BRB on the left and the conventional brace on the right (Figure 6a). Three different brace length configurations were considered and given the names *25/75*, *50/50*, and *75/25* for reference (Figure 6).

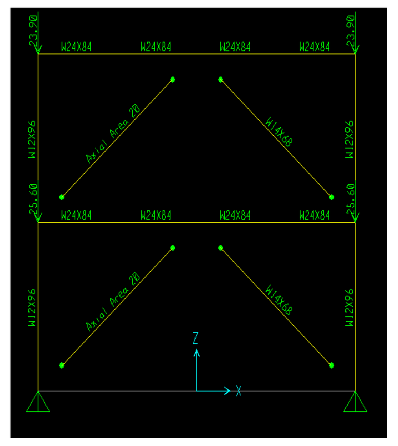


Figure 6a: *50/50* Configuration before analysis with dead load shown

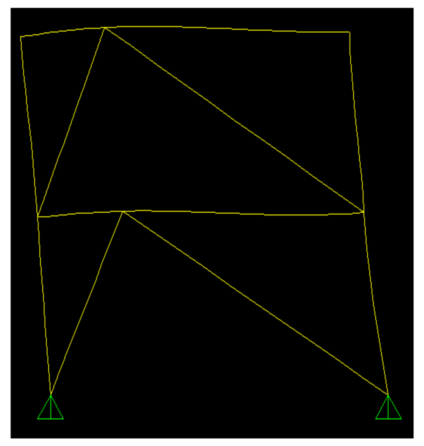


Figure 6b: *25/75* configuration after analysis of right to left earthquake loading

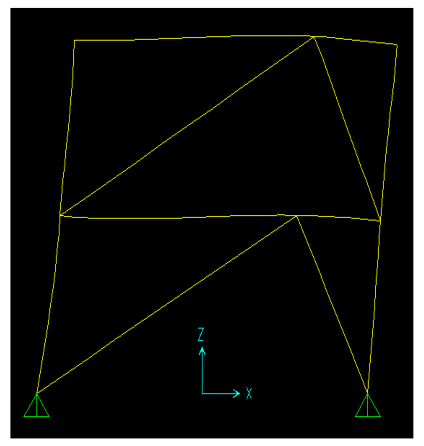


Figure 6c: *75/25* Configuration after analysis of left to right earthquake loading

During analysis, the load combination of interest was 1.2D+1.0EQ. The analysis was performed in the elastic range of brace response, so in order to simplify the procedure, BRBs were modeled as solid sections with varying axial areas under the assumption that BRB failure would only be caused by exceeding the yielding capacity and not by buckling.
Earthquake loading was applied from left to right (Figure 6c) and right to left (Figure 6b), resulting in two sets of values for each of the 48 different brace configurations. After the analyses were carried out in SAP 2000 , deflections, axial forces of the frames, and shear forces in the columns were recorded in Microsoft Excel, where this data was used to calculate inter-story drift ratios, and axial deformation of the BRBs.

Results

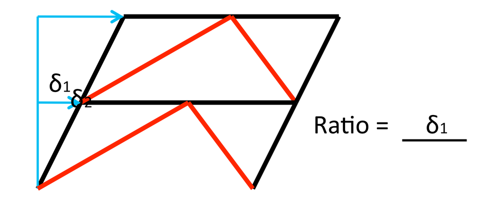


Figure 7: Inter-story drift ratio calculation

Lateral deflection was measured at the joints at which earthquake loading was applied. The inter-story drift ratio calculation is shown in Figure 7. Ideally, this ratio would be equal to 1, indicating the structure's deflection is uniformly distributed.

50 / 50 Configuration

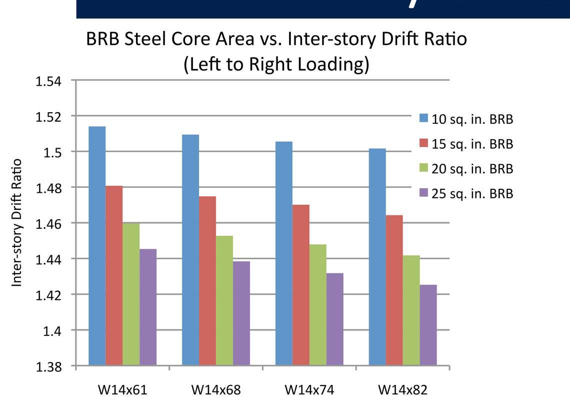


Figure 8a: Left to right loading of 50/50 configuration

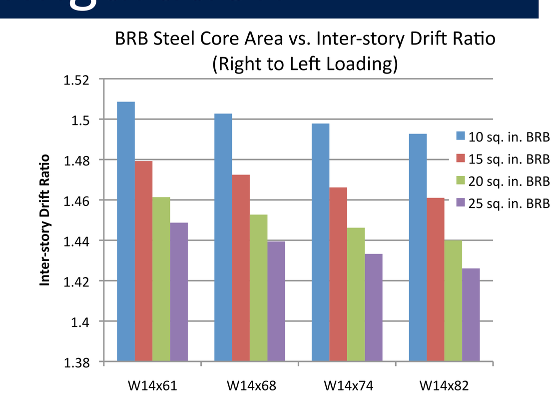


Figure 8b: Right to left loading of 50/50 configuration

25 / 75 Configuration

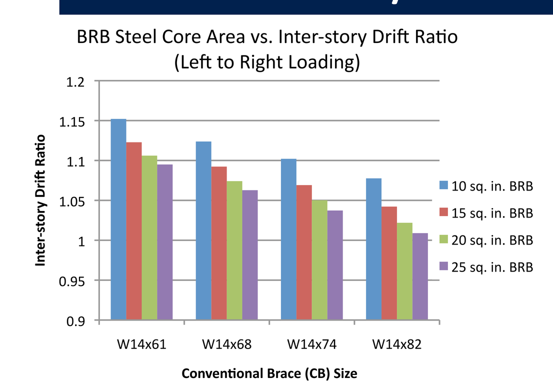


Figure 9a: Left to right loading of 25/75 configuration

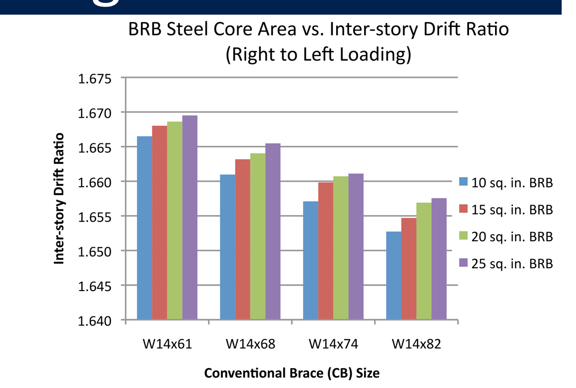


Figure 9a: Right to Left loading of 25/75 configuration

75 / 25 Configuration

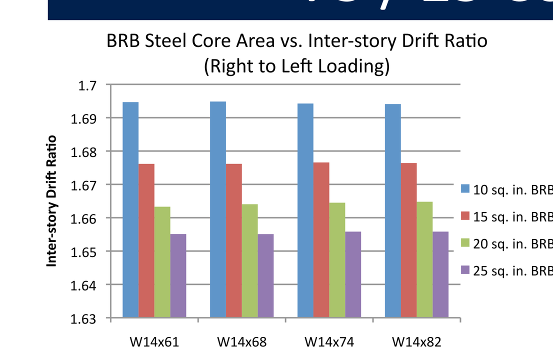


Figure 10b: Left to right loading of 75/25 configuration

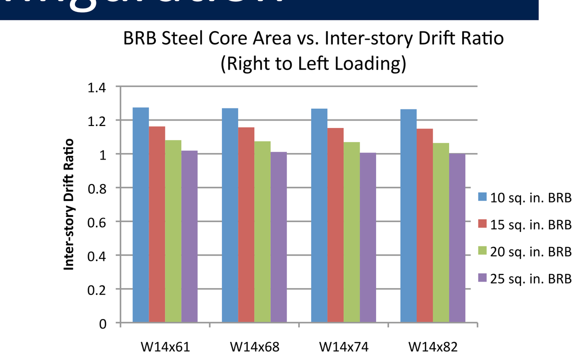


Figure 10b: Right to Left loading of 75/25 configuration

BRB Axial Deformation

		25/75	50/50	75/25
BRB 10	Axial Deformation (in.)	0.20	0.34	0.58
	Strain	0.11%	0.14%	0.19%

		25/75	50/50	75/25
BRB 20	Axial Deformation (in.)	0.11	0.18	0.30
	Strain	0.06%	0.07%	0.10%

		25/75	50/50	75/25
BRB 15	Axial Deformation (in.)	0.14	0.23	0.40
	Strain	0.08%	0.10%	0.13%

		25/75	50/50	75/25
BRB 25	Axial Deformation (in.)	0.09	0.14	0.24
	Strain	0.05%	0.06%	0.08%

Table 1: Average Deformation and Strain of BRB with Left to Right Loading

Conclusions

In nearly all cases, an increase in brace size (axial area) reduced inter-story drift. There were two specific conditions when this trend was not followed. Right to left loading of the 25/75 configuration (Figure 11a) saw an increase in inter-story drift with increase in BRB size, while left to right loading of the 75/25 configuration (Figure 11b) saw mostly increases in the inter-story drift with increase in conventional brace size. These cases are uniquely similar in that there is no brace resisting the lateral load on the second floor until ¾ of the way across the beam. It is estimated that the increased stiffness of the shorter braces reduces these braces' axial shortening, resulting in a higher level of vertical displacement at the brace intersection which, in turn, causes a greater axial load on the column nearest the shorter braces. Notably, in the opposite load case of these two conditions, the inter-story drift ratio was close to 1 (Figures 9a and 10b), although the longer braces were more susceptible to failure.

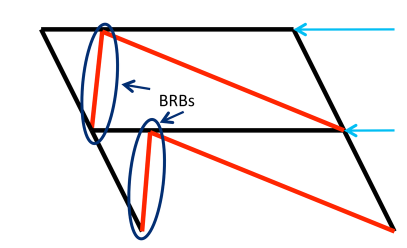


Figure 11a: Right to left loading of 25/75

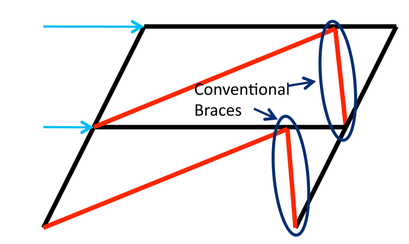


Figure 11b: Left to right loading of 75/25

Because this analysis was done in the elastic range, some of the advantages the strongback system offers over conventional or buckling restrained brace systems were not apparent and would only be exhibited once the braces were pushed into the inelastic range. However some strengths of the strongback system were clearly displayed. Many of the systems performed well, meeting the loading demand without any members failing. In addition, some brace configurations contained BRBs that would have buckled if they were conventional braces, while other configurations contained locations at which either a BRB or conventional brace would be adequate. The strongback system exhibits the distinct advantage of having a lower cost than a dual BRB system, due to the lower number of expensive BRBs. Also, with optimal design of BRB and conventional brace combination, it is able to outperform conventional brace systems which are at risk of buckling failure.
The full possibilities of strongback system performance could be explored more fully with non-linear analysis of its response in the inelastic range. It is expected that in the inelastic range, the conventional brace will serve as an elastic truss and distribute the inter-story drift more uniformly while the BRB yields.

Future Work

- Non-linear analysis of the strongback system
- Study on the cost and constructability of strongback system compared to the conventional systems
- Further study on taller frames and more complicated floor plans utilizing strongback systems (Figure 12)
- Experimental testing of this innovative system
- Study on the brace combinations differing from floor to floor to optimize the distribution of the inter-story drift

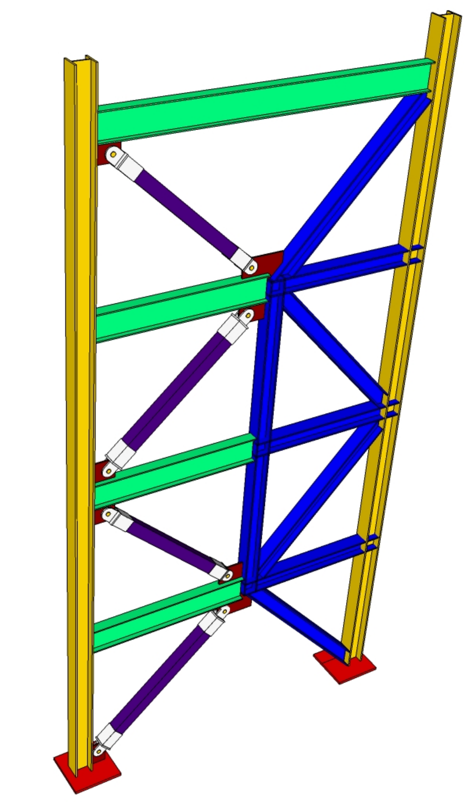


Figure 12: 4 story strongback system design

Literature Cited

1.) American Institute of Steel Construction Inc. [2006] *Seismic Design Manual,* Structural Steel Educational Council.
2.) SEAOC. [2008]. *SEAOC Blue Book – Seismic Design Recommendations: Concentrically Braced Frames*. Retrieved from http://www.seaoc.org/bluebook/sample_pdfs/803050ConcentricBracedFrames_smpl1.pdf
3.) Sabelli, R. and López, W. [2004] "Design of Buckling-Restrained Braced Frames," *Modern Steel Construction.*
4.) Ko, E. and Field, C. [n.d.] *The Unbonded Brace by Eric Ko and Caroline Field.* Retrieved from http://www.arup.com/_assets/_download/download172.pdf
5.) Uriz, P. [2005] "Towards Earthquake Resistant Design of Concentrically Braced Steel Structures," Ph.D. thesis, Civil Engineering Dept., University of California, Berkeley, California
6.) Merrit, S., Uang, C.-M., and Benzoni, G. [2003]. "Subassemblage Testing of Corebrace Buckling-Restrained Braces." *Report no. TR-2003/01*, University of California, San Diego, La Jolla, California.
7.) Sabelli, R., Mahin, S., and Chang, C. [2001] *Seismic Demands on Steel Braced Frame Buildings with Buckling-Restrained Braces.* Retrieved from http://nisee.berkeley.edu/library/bracedframes.pdf
8.) Lai, Jiun-Wei. [2009] *NEESR-SG International Hybrid Simulation of Tomorrow's Steel Braced Frame.* Retrieved from http://research.eerc.berkeley.edu/projects/tomorrows_bracedframes/cbf1/About_The_Project.html

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