PRELIMINARY STUDY OF THE STRONGBACK SYSTEM: PREVENTING THE SOFT STORY MECHANISM

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Abstract

With advances in braced frame technology, new systems with increasingly better earthquake resistance are coming into existence. This project consists of a series of preliminary analyses on an innovative dual structural system – the strongback system. A regular two-story model building was developed in a widely used commercial software, and elastic analysis was performed to investigate the elastic behavior of the proposed system. Different steel core areas of buckling restrained braces and conventional wide flange braces were selected to examine the effects on system lateral stiffness. Brace-to-beam intersection points were varied to analyze the performance of different configurations. Axial deformations of the conventional bucking braces and the buckling restrained braces were also reviewed. Due to the strongback system's potential of uniformly distributing interstory drift, this drift was the primary result of note. Preliminary elastic analysis results show that the proposed dual system deformed uniformly along the height of the building if designed properly. Further nonlinear analysis on this new system is suggested, and it is expected that the inelastic behavior of the strongback system has higher potential than systems in use today to prevent the soft-story mechanism under extreme loading events.

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1. Introduction

1.1 Research Background and Literature Review

Special concentrically braced frame (SCBF) systems resist lateral loads and limit story drift by dissipating energy through tension yielding and/or compression buckling in the braces (AISC, 2006). The main differences between SCBFs and ordinary concentrically braced frame (OCBF) systems involve requirements on ductility, slenderness, and brace capacity (SEAOC, 2008). While SCBFs have proven more efficient than special moment frames (SMF) 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 buckling restrained brace (BRB) was developed to balance the low compression capacity and high tension capacity by inhibiting this buckling tendency. Early forms of the BRB were tested as far back as 1976 (Kimura et al., 1976), but the modern incarnation wasn't developed until the 1980s. This BRB acts as a two part system, the steel core and steel tube sleeve, in contact with encasing mortar and a slip surface (Sabelli and López, 2004; Uriz, 2005). In past experiments, buckling restrained braced frame (BRBF) systems have shown smooth, stable, and reliable hysteretic performance when subjected to various loadings (Uriz, 2005; Merrit et al., 2003).

Testing has shown the BRB's low-cycle fatigue life capacity to exceed established demands (Sabelli and López, 2004), and in multiple cases, BRBFs have outperformed SCBFs when subjected to seismic loading (Sabelli and López, 2004; Uriz, 2005).

Preliminary experimental testing was done on BRBFs at the University of California, Berkeley in 2005 with a single-story single-bay frame and another single bay frame with two stories. In both cases, lateral loading was applied at a single joint at the top story (Uriz, 2005). More recent research at Berkeley has expanded on these early experiments, and experimental testing of a two story BRBF with lateral loading at first and second story joints is pending (Lai, 2009).

However, with all the potential BRBFs have shown, they have shown weaknesses such as deformation and failure at the gusset plates and have still exhibited concentrations of lateral deflection at lower stories (Sabelli et al., 2001), which can result in increased damage and in extreme cases soft story collapse. The deflective response of these structures exhibits a soft story mechanism, so a more uniform distribution of drift is desired.

A dual system can theoretically distribute the interstory drift more evenly with the conventional brace sections responding elastically and the BRB sections yielding first. The inelastic response of the BRB sections would dissipate the energy, and the conventional braces would deform uniformly with a lower threat of buckling failure. The BRB system acts as a spine or mast for the structure, leading some to call it the "strongback" system (Mahin, 2010). For such a new idea, the strongback 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. Also, the most effective ratios of sizes, shapes, and orientations of the differing braces are still largely unknown. Additional research into these topics is essential.

1.2 Objectives

Due to the limited research conducted on the strongback system, a series of preliminary studies were proposed and summarized below:

(1) Analyze the trends of the strongback system’s response in the elastic range by altering cross sectional areas of braces.
(2) Analyze the braces’ performance when the conventional brace and the BRB meet at an offset position ¼ and ¾ of the beam’s length (which allows potential for doors, windows, and other architectural aspects of design).
(3) Analyze axial deformation of the BRB and capacity of both conventional braces and BRBs.
(4) Provide a preliminary foundation of strongback research from which additional research can be conducted.

2. Methods

2.1 Model Building Selection

The model building was selected to be a simple two-story office building in downtown Berkeley. The building footprint is 120 feet by 180 feet with a basic 30 foot grid column line layout in the N-S and E-W directions. There are two 13 foot high stories with no basement or penthouse, and there is one set of braces per story contained in one outer bay of each side of the building. 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 2.1). The building was modeled to be very regular and uncomplicated, but it is also in a style that would not be out of place in the downtown Berkeley area.

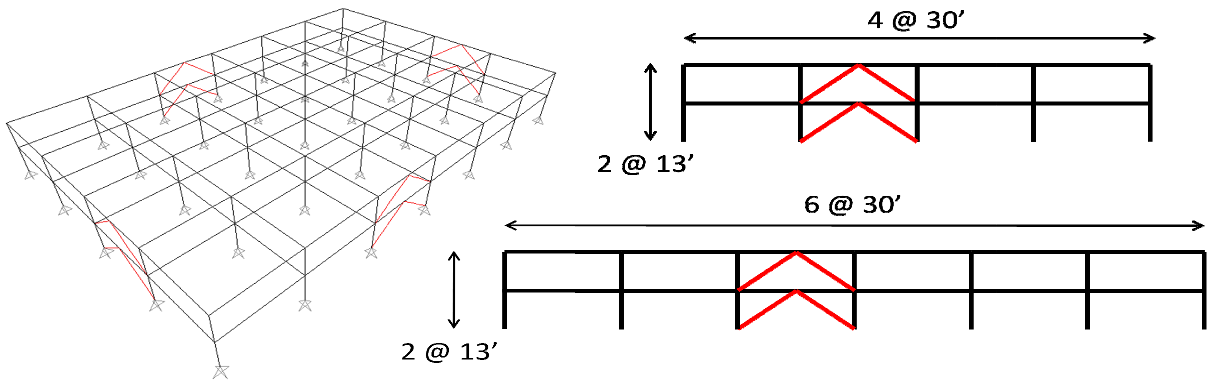

Figure 2.1: Three-Dimensional and profile views of model building

2.2 Modeling

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. The conventional braces were modeled by simply utilizing the pre-existing wide flange sections in SAP2000. SAP2000's "Steel Frame Design Check" was used to check failure of conventional braces.

2.3 Loading

Using AISC-360-05, the loading was calculated for this two-story building. Earthquake loading was determined with equivalent lateral force (ELF) 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 2.2a). Three different brace length configurations were considered and given the names *25/75*, *50/50*, and *75/25* for reference (Figures 2.2a, 2.2b, 2.2c).

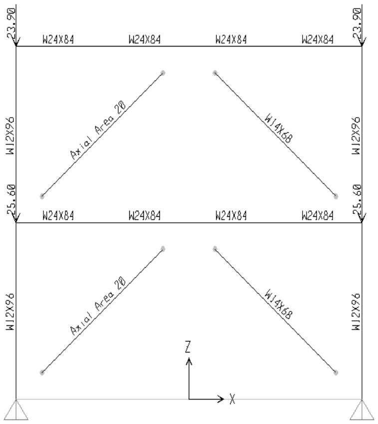

Figure 2.2a: *50/50* Configuration before analysis with dead load shown

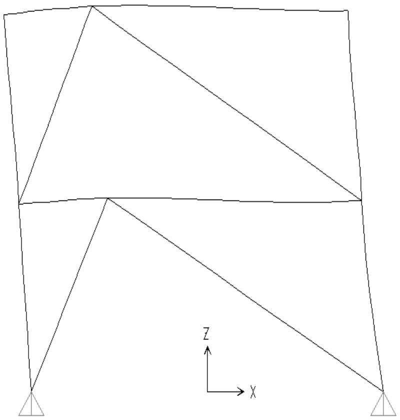

Figure 2.2b: 25/75 configuration after analysis of right to left earthquake loading

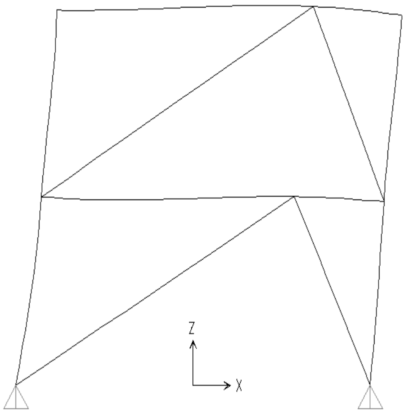

Figure 2.2c: *75/25* configuration after analysis of left to right earthquake loading

Earthquake loading was applied from left to right (Figure 2.2c) and right to left (Figure 2.2b), resulting in two sets of values for each of the 48 different brace configurations.

After the analyses were carried out in SAP2000, deflections, axial forces of the frames, and shear forces in the columns were recorded in Microsoft Excel. Lateral deflection was measured at the joints at which earthquake loading was applied. The inter-story drift ratio calculation is shown in Figure 2.3. Ideally, this ratio would be equal to 1, indicating the structure's deflection is uniformly distributed. Axial deformations of the BRBs on both floors were determined by simply using the distance formula and measuring the coordinates of the BRBs' endpoints before and after loading.

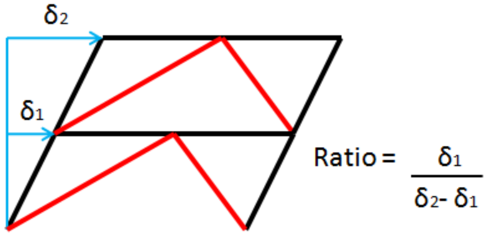

Figure 2.3: Definition of the inter-story drift ratio

3. Results

3.1 The 50/50 Configuration

The results of the 50/50 configuration are shown in Figures 3.1a and 3.1b.

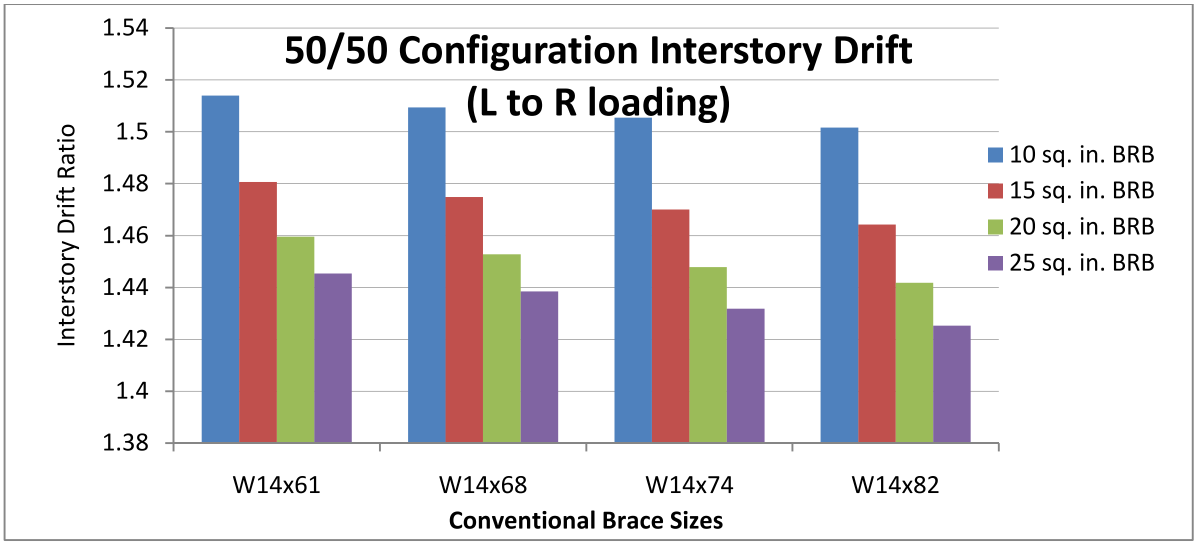

Figure 3.1a: Inter-story drift ratios of brace combinations in 50/50 configuration with left to right loading

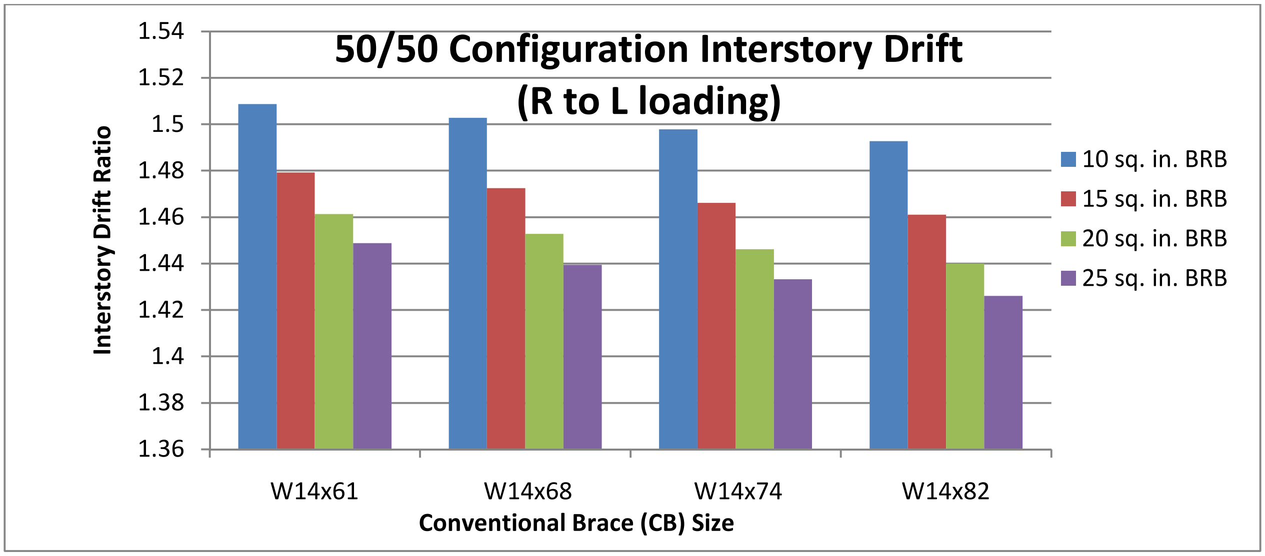

Figure 3.1b: Inter-story drift ratios of brace combinations in 50/50 configuration with right to left loading

3.2 The 25/75 Configuration

The results of the 25/75 configuration are shown in Figures 3.2a and 3.2b.

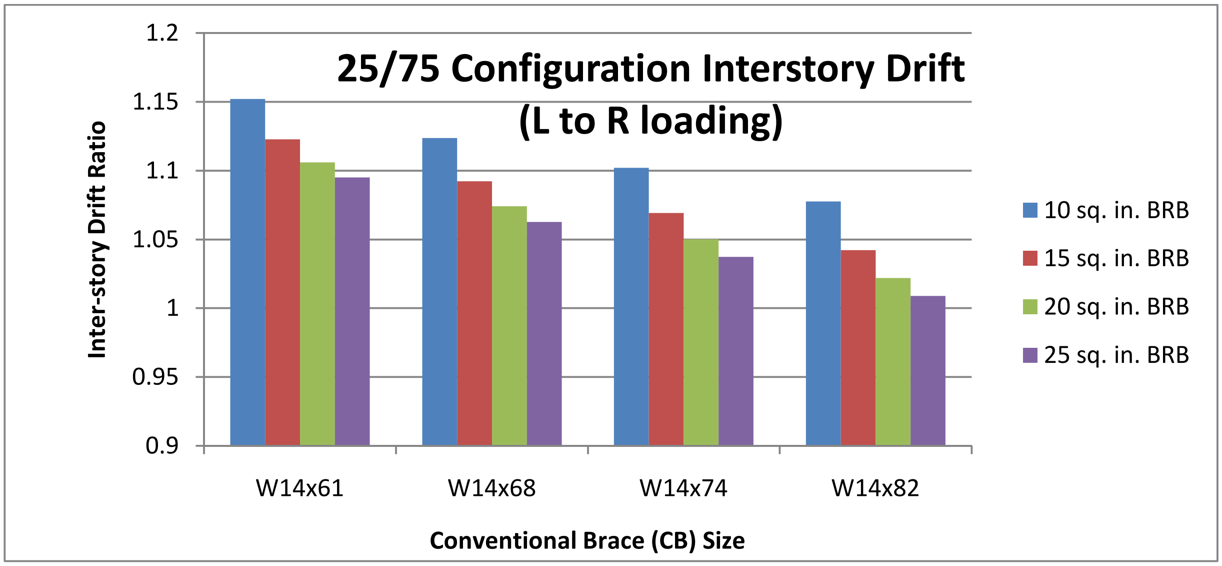

Figure 3.2a: Inter-story drift ratios of brace combinations in 25/75 configuration with left to right loading

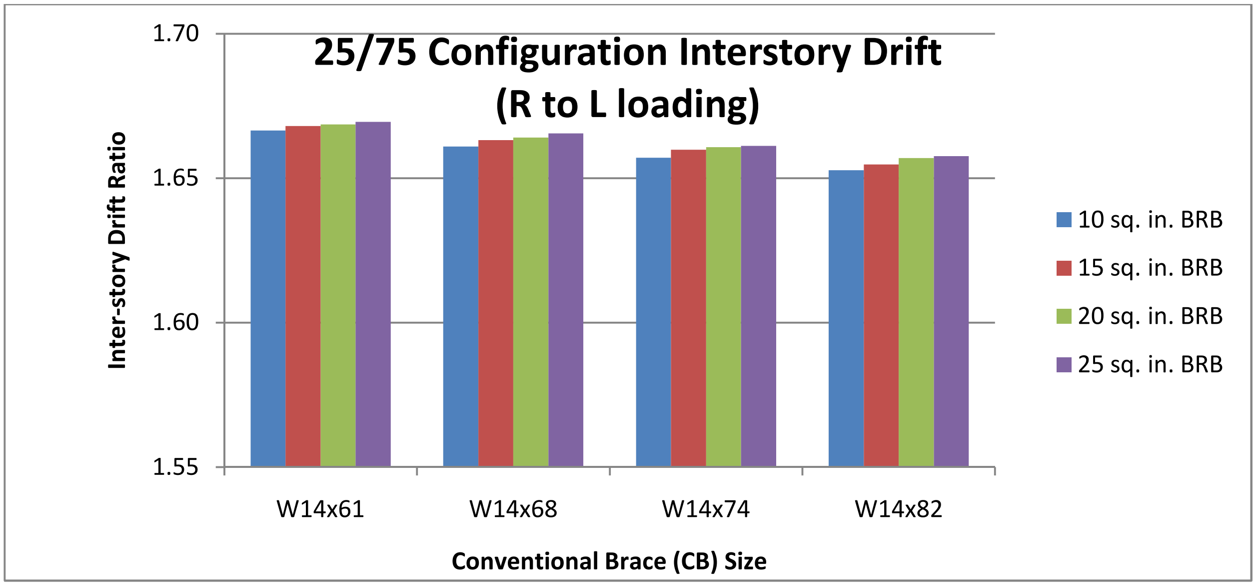

Figure 3.2b: Inter-story drift ratios of brace combinations in 25/75 configuration with right to left loading

3.3 The 75/25 Configuration

The results of the 50/50 configuration are shown in Figures 3.3a and 3.3b.

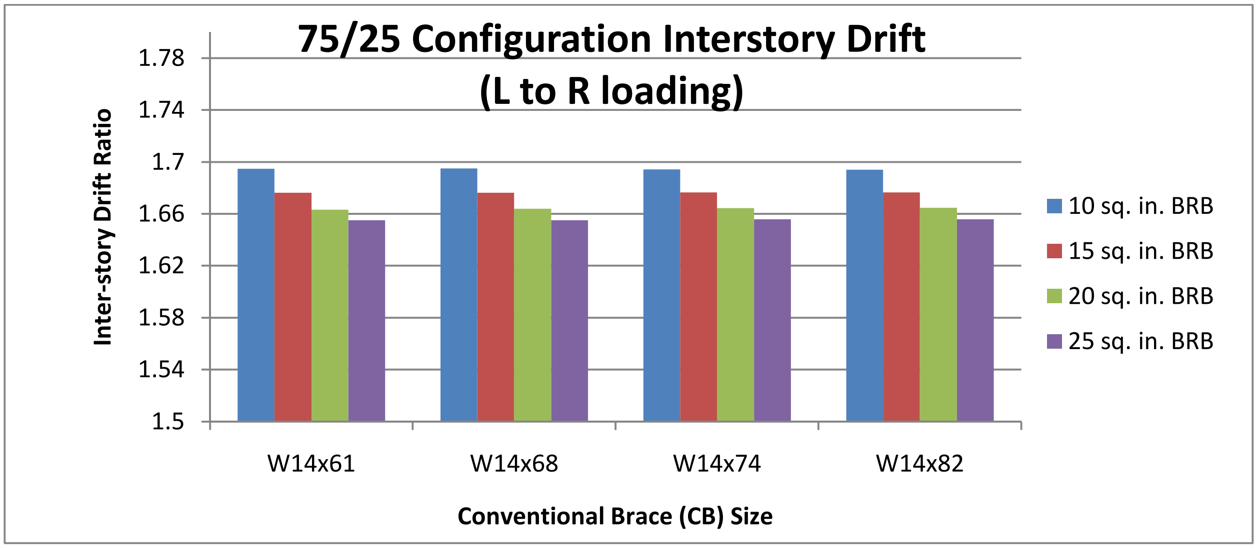

Figure 3.3a: Inter-story drift ratios of brace combinations in 75/25 configuration with left to right loading

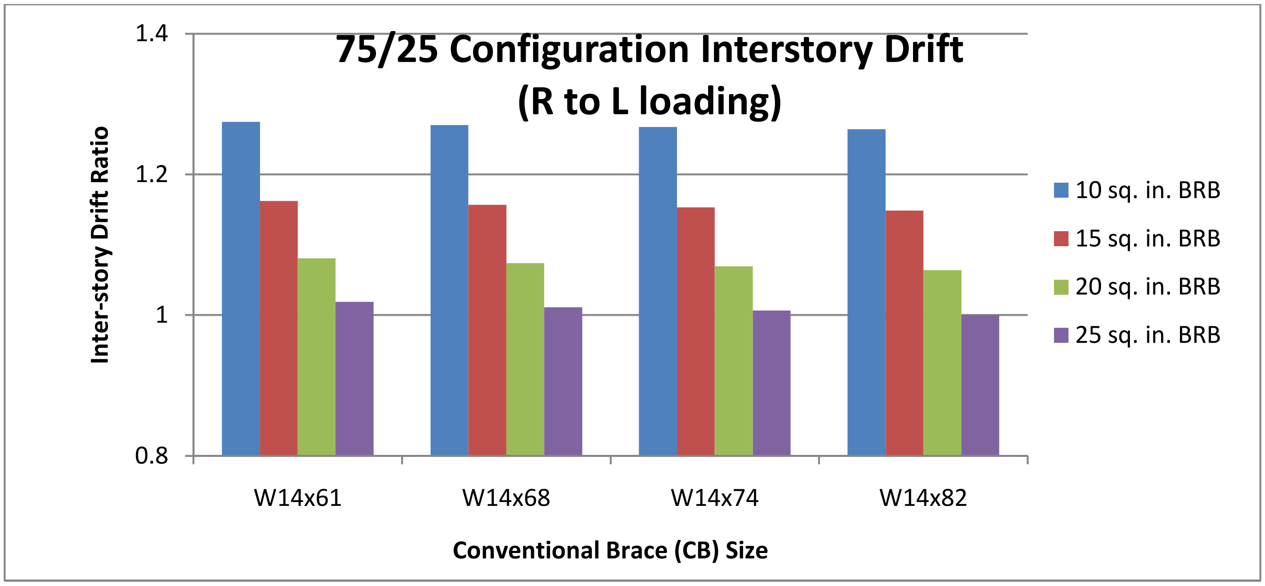

Figure 3.3b: Inter-story drift ratios of brace combinations in 75/25 configuration with right to left loading

3.4 Brace Failures

Table 3.1a and 3.1b show the occasions on either floor in which failure occurs in the conventional and buckling restrained braces, respectively.

Table 3.1a: Failures of conventional braces under all loading directions

		W14x61			W14x68			W14x74			W14x82		
	Load	50/50	75/25	25/75	50/50	75/25	25/75	50/50	75/25	25/75	50/50	75/25	25/75
BRB 10	L to R	1F	None	1F 2F	None	None	1F 2F	None	None	1F 2F	None	None	1F 2F
	R to L	None	None	None	None	None	None	None	None	None	None	None	None
BRB 15	L to R	1F	None	1F 2F	None	None	1F 2F	None	None	1F 2F	None	None	1F
	R to L	None	None	None	None	None	None	None	None	None	None	None	None
BRB 20	L to R	1F	None	1F 2F	None	None	1F 2F	None	None	1F 2F	None	None	1F
	R to L	None	None	None	None	None	None	None	None	None	None	None	None
BRB 25	L to R	1F	None	1F 2F	None	None	1F 2F	None	None	1F 2F	None	None	1F
	R to L	None	None	None	None	None	None	None	None	None	None	None	None

Table 3.1b: Failures of BRBs under all loading directions

		W14x61			W14x68			W14x74			W14x82		
	Load	50/50	75/25	25/75	50/50	75/25	25/75	50/50	75/25	25/75	50/50	75/25	25/75
BRB 10	L to R	None	1F	None	None	None	None	None	None	None	None	None	None
	R to L	None	1F	None	None	None	None	None	None	None	None	None	None
BRB 15	L to R	None	1F	None	None	None	None	None	None	None	None	None	None
	R to L	None	1F	None	None	None	None	None	None	None	None	None	None
BRB 20	L to R	None	1F	None	None	None	None	None	None	None	None	None	None
	R to L	None	1F	None	None	None	None	None	None	None	None	None	None
BRB 25	L to R	None	1F	None	None	None	None	None	None	None	None	None	None
	R to L	None	1F	None	None	None	None	None	None	None	None	None	None

3.5 Axial Deformations of BRBs

The lengths of the BRBs were recorded in the unloaded state and then the loaded state and compared to determine the degree of axial deformation in the member. In most cases, these deformations were very slight. Table 3.2 displays the deformations for the BRBs in different configurations as well as their strains. The values are from the left to right loading condition only because of the similarity shown in the values of the right to left loading condition.

Table 3.2: Axial deformation and strain of BRBs under right to left loading

		25/75	50/50	75/25
BRB 10	Axial Deformation (in.)	0.20	0.34	0.58
	Strain	0.11%	0.14%	0.19%
BRB 15	Axial Deformation (in.)	0.14	0.23	0.40
	Strain	0.08%	0.10%	0.13%
BRB 20	Axial Deformation (in.)	0.11	0.18	0.30
	Strain	0.06%	0.07%	0.10%
BRB 25	Axial Deformation (in.)	0.09	0.14	0.24
	Strain	0.05%	0.06%	0.08%

4. 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 2.2b) saw an increase in inter-story drift with increase in BRB size, while left to right loading of the 75/25 configuration (Figure 2.2c) 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, although the longer braces were more susceptible to failure.

Few members failed under the loading of this test. 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.

5. Future Work

This research project has provided a strong foundation of preliminary knowledge of the strongback system in the elastic range. The results of this project can be used by future researchers in order to more fully understand and utilize the strongback system and its capabilities. Potential future projects include:

(1) Non-linear analysis of the strongback system.

(2) Study on the cost and constructability of strongback system compared to the conventional systems.

(3) Further study on taller frames and more complicated floor plans utilizing strongback systems.

(4) Experimental testing of this innovative system.

(5) Study on different brace combinations from floor to floor to optimize the distribution of the inter-story drift.

6. References

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,"* 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. Mahin, S. [2010] Personal Communication.
9. 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
10. Kimura, K., Takeda, Y., Yoshioka, K., Furuya, N., and Y. Takemoto. [1976] "An experimental study on braces encased in steel tube and mortar," *Proc. Annual Meeting of the Architectural Institute of Japan*, Japan (in Japanese).

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8. Appendices

Loading spreadsheet

LOADS			
Roof DL (ksf)	0.055	Assumed	
Ext. Wall Cladding (ksf)	0.025	Assumed	
Roof slab (kips)	1221.22		
Walls (kips)	53.2		
Columns	43		
Total roof DL	1317.42		
Floor	1388		
Walls	198		
Columns	130		
Total Floor Load	1716		
Building Weight	3033		
Materials			
E (ksi)	29000		
Fy (ksi	50		
Cs	0.216		
Seismic Base Shear V (kips)	656		
			Totals
Floor level	RF	2F	
wx (kips)	1317	1716	3033
hx (ft)	26	13	
wx*hx^k	34253	22308	56561
Cvx	0.61	0.39	1.00
Fx (kips)	397	259	656
Vfloor (kips)	397	656	656

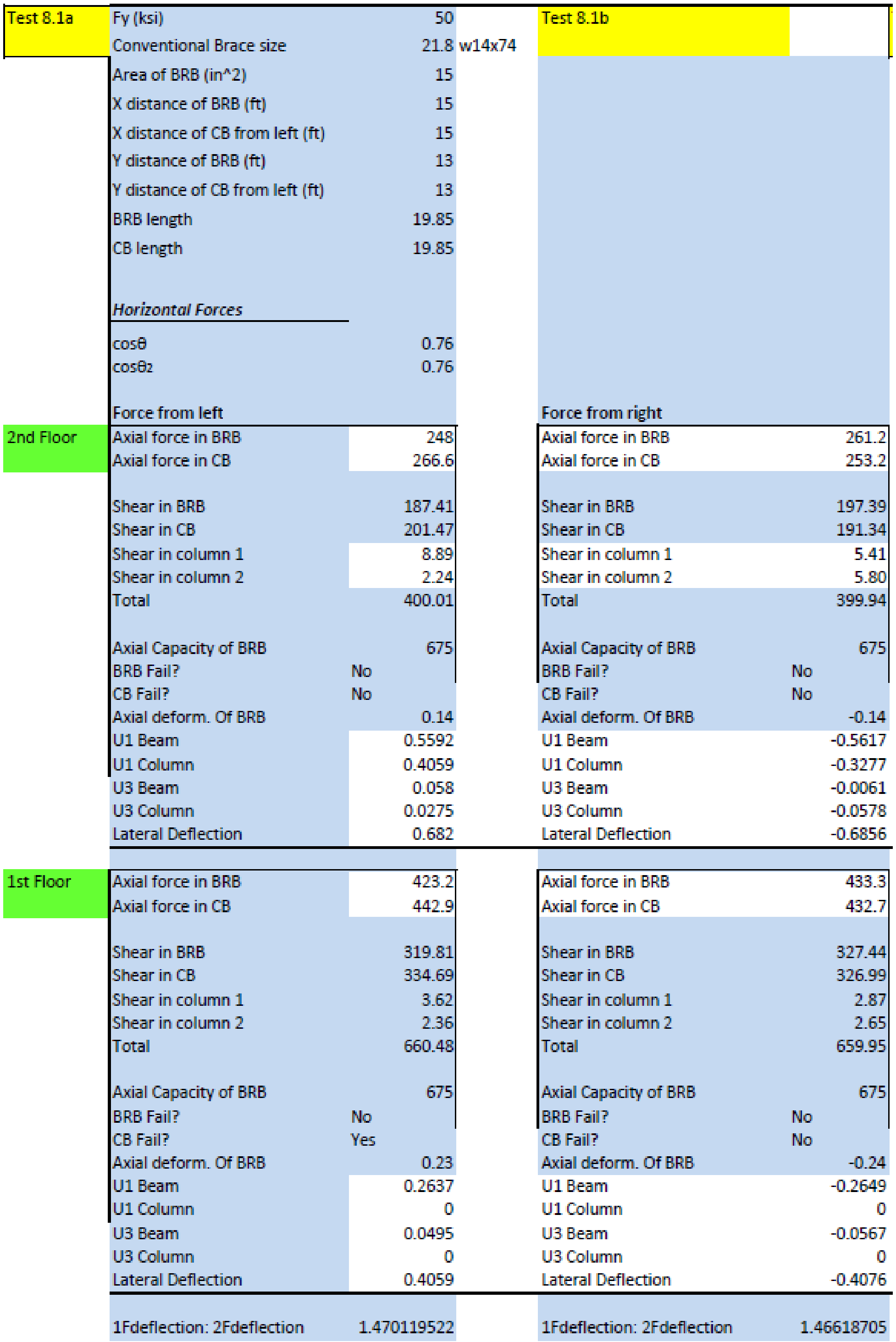
Point Load Calculations

Floor by Floor point loads (per column)	
Roof DL (ksf)	0.055
Floor DL (ksf)	0.0625
Roof Tributary Area	480
Floor Tributary Area	450
Beam weight (klf)	0.084
beam length (feet)	30
Beam weight (kips)	2.52
Roof Level point load (kips)	26.4
1st floor level point load (kips)	28.125
Roof final	23.88
1F final	25.605

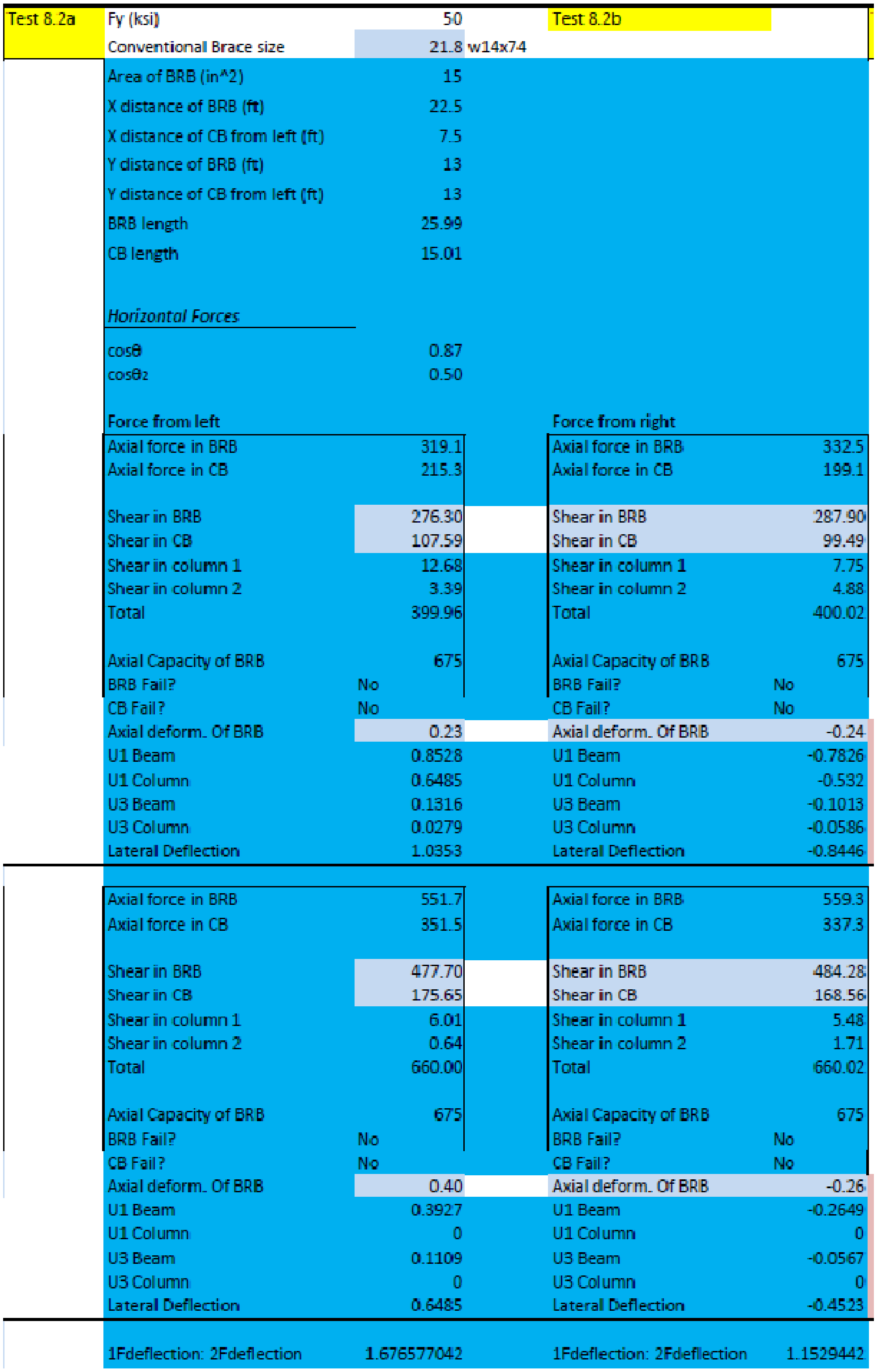
Spreadsheet for the Analysis Case 15xW14x74

All Tests are run with loads applied from one side at a time only. For example a 400 kip load applied at the top left joint rather than 200 applied at top left and 200 at top right.

The following pages show the tables from 50/50, 75/25, and 25/75 configurations, respectively.



Test 8.1a	Fy (ksi)	50		Test 8.1b	
	Conventional Brace size	21.8	w14x74		
	Area of BRB (in^2)	15			
	X distance of BRB (ft)	15			
	X distance of CB from left (ft)	15			
	Y distance of BRB (ft)	13			
	Y distance of CB from left (ft)	13			
	BRB length	19.85			
	CB length	19.85			
	Horizontal Forces				
	cosθ	0.76			
	$\cos\theta_2$	0.76			
	Force from left			Force from right	
2nd Floor	Axial force in BRB	248		Axial force in BRB	261.2
	Axial force in CB	266.6		Axial force in CB	253.2
	Shear in BRB	187.41		Shear in BRB	197.39
	Shear in CB	201.47		Shear in CB	191.34
	Shear in column 1	8.89		Shear in column 1	5.41
	Shear in column 2	2.24		Shear in column 2	5.80
	Total	400.01		Total	399.94
	Axial Capacity of BRB	675		Axial Capacity of BRB	675
	BRB Fail?	No		BRB Fail?	No
	CB Fail?	No		CB Fail?	No
	Axial deform. Of BRB	0.14		Axial deform. Of BRB	-0.14
	U1 Beam	0.5592		U1 Beam	-0.5617
	U1 Column	0.4059		U1 Column	-0.3277
	U3 Beam	0.058		U3 Beam	-0.0061
	U3 Column	0.0275		U3 Column	-0.0578
	Lateral Deflection	0.682		Lateral Deflection	-0.6856
1st Floor	Axial force in BRB	423.2		Axial force in BRB	433.3
	Axial force in CB	442.9		Axial force in CB	432.7
	Shear in BRB	319.81		Shear in BRB	327.44
	Shear in CB	334.69		Shear in CB	326.99
	Shear in column 1	3.62		Shear in column 1	2.87
	Shear in column 2	2.36		Shear in column 2	2.65
	Total	660.48		Total	659.95
	Axial Capacity of BRB	675		Axial Capacity of BRB	675
	BRB Fail?	No		BRB Fail?	No
	CB Fail?	Yes		CB Fail?	No
	Axial deform. Of BRB	0.23		Axial deform. Of BRB	-0.24
	U1 Beam	0.2637		U1 Beam	-0.2649
	U1 Column	0		U1 Column	0
	U3 Beam	0.0495		U3 Beam	-0.0567
	U3 Column	0		U3 Column	0
	Lateral Deflection	0.4059		Lateral Deflection	-0.4076
	1Fdeflection: 2Fdeflection	1.470119522		1Fdeflection: 2Fdeflection	1.46618705



Test 8.2a	Fy (ksi)	50		Test 8.2b	
	Conventional Brace size	21.8	w14x74		
	Area of BRB (in^2)	15			
	X distance of BRB (ft)	22.5			
	X distance of CB from left (ft)	7.5			
	Y distance of BRB (ft)	13			
	Y distance of CB from left (ft)	13			
	BRB length	25.99			
	CB length	15.01			
	Horizontal Forces				
	$\cos\theta$	0.87			
	$\cos\theta_2$	0.50			
	Force from left			Force from right	
	Axial force in BRB	319.1		Axial force in BRB	332.5
	Axial force in CB	215.3		Axial force in CB	199.1
	Shear in BRB	276.30		Shear in BRB	287.90
	Shear in CB	107.59		Shear in CB	99.49
	Shear in column 1	12.68		Shear in column 1	7.75
	Shear in column 2	3.39		Shear in column 2	4.88
	Total	399.96		Total	400.02
	Axial Capacity of BRB	675		Axial Capacity of BRB	675
	BRB Fail?	No		BRB Fail?	No
	CB Fail?	No		CB Fail?	No
	Axial deform. Of BRB	0.23		Axial deform. Of BRB	-0.24
	U1 Beam	0.8528		U1 Beam	-0.7826
	U1 Column	0.6485		U1 Column	-0.532
	U3 Beam	0.1316		U3 Beam	-0.1013
	U3 Column	0.0279		U3 Column	-0.0586
	Lateral Deflection	1.0353		Lateral Deflection	-0.8446
	Axial force in BRB	551.7		Axial force in BRB	559.3
	Axial force in CB	351.5		Axial force in CB	337.3
	Shear in BRB	477.70		Shear in BRB	484.28
	Shear in CB	175.65		Shear in CB	168.56
	Shear in column 1	6.01		Shear in column 1	5.48
	Shear in column 2	0.64		Shear in column 2	1.71
	Total	660.00		Total	660.02
	Axial Capacity of BRB	675		Axial Capacity of BRB	675
	BRB Fail?	No		BRB Fail?	No
	CB Fail?	No		CB Fail?	No
	Axial deform. Of BRB	0.40		Axial deform. Of BRB	-0.26
	U1 Beam	0.3927		U1 Beam	-0.2649
	U1 Column	0		U1 Column	0
	U3 Beam	0.1109		U3 Beam	-0.0567
	U3 Column	0		U3 Column	0
	Lateral Deflection	0.6485		Lateral Deflection	-0.4523
	1Fdeflection: 2Fdeflection	1.676577042		1Fdeflection: 2Fdeflection	1.1529442

Test 8.3a	Fy (ksi)		50		Test 8.3b		
	Conventional Brace size		21.8	w14x74			
	Area of BRB		15				
	X distance of BRB (ft)		7.5				
	X distance of CB from left (ft)		22.5				
	Y distance of BRB (ft)		13				
	Y distance of CB from left (ft)		13				
	BRB length		15.01				
	CB length		25.99				
	Horizontal Forces						
	cosθ		0.50				
	cosθ2		0.87				
	Force from left				Force from right		
	Axial force in BRB		190.4		Axial force in BRB		206.6
	Axial force in CB		337.8		Axial force in CB		324.2
	Shear in BRB		95.15		Shear in BRB		103.24
	Shear in CB		292.49		Shear in CB		280.71
	Shear in column 1		8.14		Shear in column 1		6.80
	Shear in column 2		4.21		Shear in column 2		9.21
	Total		399.99		Total		399.97
	Axial Capacity of BRB		675		Axial Capacity of BRB		675
	BRB Fail?	No			BRB Fail?	No	
	CB Fail?	YES			CB Fail?	No	
	Axial deform. Of BRB		0.08		Axial deform. Of BRB		-0.08
	U1 Beam		0.6478		U1 Beam		-0.7237
	U1 Column		0.3665		U1 Column		-0.3265
	U3 Beam		-0.0443		U3 Beam		0.0742
	U3 Column		0.0269		U3 Column		-0.0562
	Lateral Deflection		0.7093		Lateral Deflection		-0.9078
	Axial force in BRB		321.9		Axial force in BRB		336.1
	Axial force in CB		569		Axial force in CB		561.4
	Shear in BRB		160.86		Shear in BRB		167.96
	Shear in CB		492.68		Shear in CB		486.10
	Shear in column 1		2.46		Shear in column 1		1.42
	Shear in column 2		3.99		Shear in column 2		4.51
	Total		659.99		Total		659.98
	Axial Capacity of BRB		675		Axial Capacity of BRB		675
	BRB Fail?	No			BRB Fail?	No	
	CB Fail?	YES			CB Fail?	No	
	Axial deform. Of BRB		0.14		Axial deform. Of BRB		-0.14
	U1 Beam		0.3098		U1 Beam		-0.3095
	U1 Column		0		U1 Column		0
	U3 Beam		-0.0249		U3 Beam		0.0179
	U3 Column		0		U3 Column		0
	Lateral Deflection		0.3665		Lateral Deflection		-0.5665
	1Fdeflection: 2Fdeflection		1.069136523		1Fdeflection: 2Fdeflection		1.65983006