Structural Cost Comparison
Utilizing Buckling Restrained Braces

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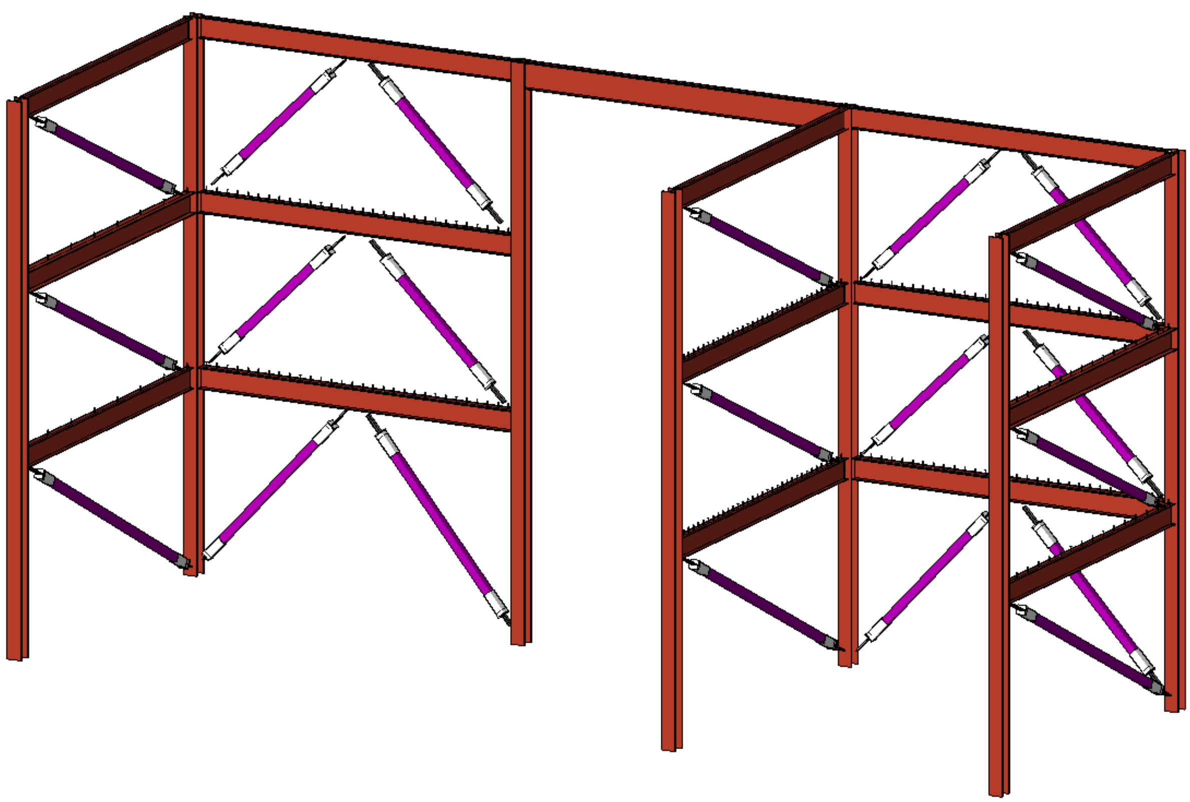

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Introduction

The use of Buckling Restrained Braces has increased significantly in recent years. The innovation of this product is to prevent global buckling of the brace, which typically controls the design of concentrically braced frame systems. The extensive testing of this bracing system reveals consistent, predictable, ductile behavior in seismic events.

Buckling Restrained Braces Frames have been recognized by model Codes as an acceptable Seismic Force-Resisting System: in the 2005 edition of the AISC Seismic Provisions (AISC 341); in the 2005 edition of ASCE 7; and in the 2006 edition of IBC.

The purpose of this study is to compare the structural costs of four distinct office buildings near the Charleston, South Carolina area. This location was selected because it is representative of the maximum seismic activity in the Eastern United States. The building types are:

1. Three-story building using Special Concentric Braced Frames (SCBF)
2. Three-story building using Buckling Restrained Braced Frames (BRBF)
3. Five-story building using SCBF
4. Five-story building using BRBF

Design Assumptions

The structural analysis, design, and cost comparison for these buildings is based on the following design assumptions:

Building Code: 2012 International Building Code
ASCE 7-10
AISC 341-10 and 360-10

Risk Category: II (IBC Table 1604.5, ASCE 7-10, Table 1.5-1)

Wind: 140 mph, Exposure B

Seismic: Equivalent Lateral Force Analysis & Modal Response Spectrum Analysis
S_S=1.701, S_1=0.580
S_{DS}=1.134, S_{D1}=0.580
Site Class D; Design Category D; T_L=8.0
Redundancy Factor=1.3 (ASCE 7-10, 12.3.4.2)
Coefficients and Factors:

Bracing System	Response Modification Factor, R	Overstrength Factor, Ω_o	Deflection Amplification Factor, C_d	Building Period Coefficient, C_T
SCBF	6.0	2.0	5.0	0.020
BRBF	8.0	2.5	5.0	0.030

Geotechnical: Often the typical soil conditions in the Charleston, South Carolina will require a Site Response Analysis due to the possibility of liquefaction. It has been our experience that the resulting Design Response Spectrum graph will yield results very similar to Site Class D. Also the soil conditions often dictate the use of a soil improvement system such as Geopiers. Therefore our analysis is based on Site Class D, using Geopiers with an allowable bearing capacity of 8,000 psf under transient loading, such as the braced frames.

Building Description

Three-story building: 77,500 sf
Five-story building: 130,000 sf

The architectural layout of these office buildings is typical for structures in this region. There are many window openings for natural lighting, so the perimeter walls are not available for brace locations. The floor-to-floor height is 14 ft at all levels.

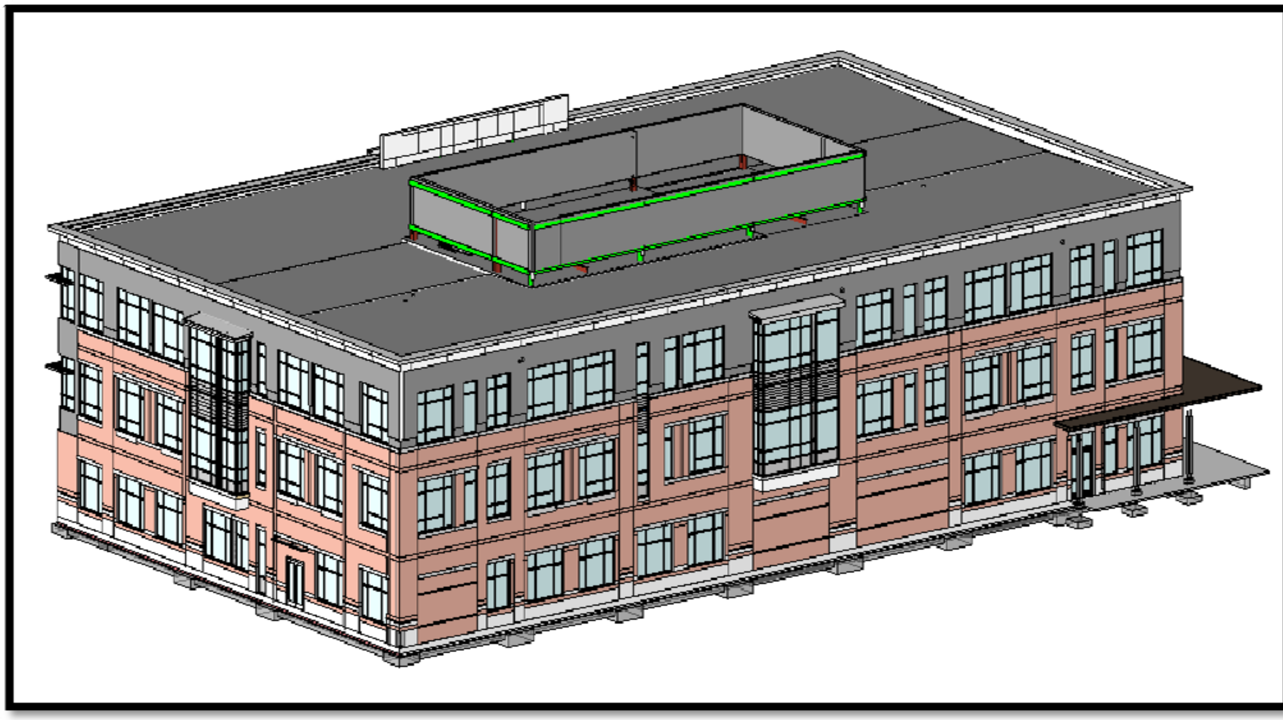

Figure 1: Isometric of 3-Story Building

The core area of the building accommodates two stairs, two elevators, Men's and Women's restrooms, an HVAC chase, and an electrical room. Since the owner and architect desire open areas for optimum leasable square footage, this core area is the location typically made available for braced frames. The architectural layout requires a corridor adjacent to column line B which means the braces along lines 3, 4, 5, and 6 must be high at that end, passing above the corridor. Further, the braces along lines B and C must allow access to the elevator lobby and restrooms midway between columns. Hollow structural sections (HSS) are used for the SCB frames.

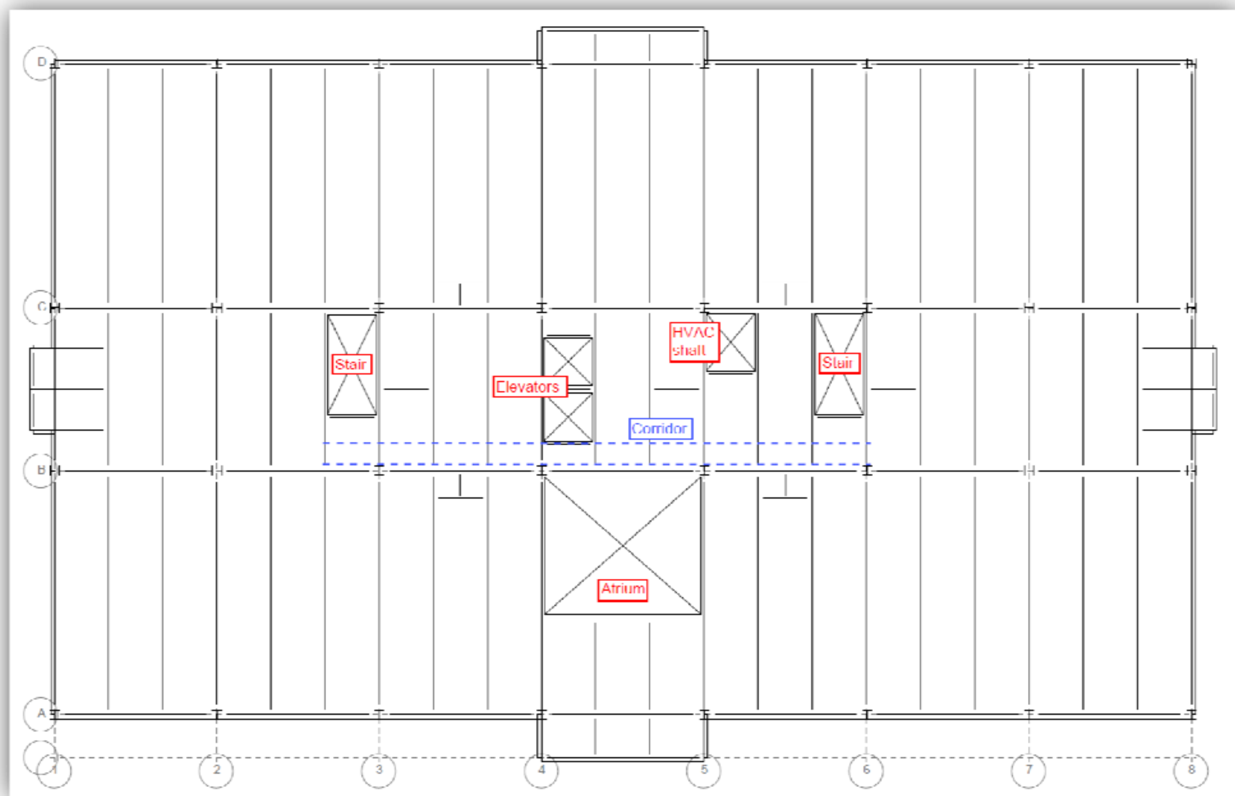

Figure 2: Second Floor Framing Plan

The floors are concrete topping on 3” composite steel deck, total thickness of 6.5” for the three-story buildings and 7.5” for the five-story buildings. The roof area above the core also has a concrete topping on steel deck for sound attenuation. The exterior walls are light gauge steel studs with brick veneer and metal panels. The brick does not extend up to the top of parapet, but stops at the highest floor for both building heights.

For the 3-story buildings, the columns are continuous with no splices. For the 5-story buildings, all columns are spliced above the 3rd floor.

Discussion

The architectural requirements described above limit the acceptable bracing configuration possibilities. BRBFs are allowed as a single diagonal in a framing line, whereas SCBFs are not (AISC 341-10, F2.4a). These limitations require many of the SCBFs to be chevrons or V-braces. In order to accommodate the steeper angle of the V-braces in the SCBF option at the main corridor, the hallway width must be narrower and the ceiling height must be lower than desired by the architect.

The beams in SCB chevron frames are penalized compared to BRBF beams because of the significant difference between tension and compression capacities of conventional bracing members (see Commentary AISC 341-10, F4.4a). The design requirements for beams in these SCB frames lead to heavy members relative to those in BFBFs.

The limiting width-to-thickness values of highly ductile members in Table D1.1 of AISC 341 have been reduced approximately 15% in the 2010 edition. Consequently, many of the larger HSS shapes are not allowed, thus limiting the seismic force the frame can withstand. In both of the SCBF buildings in this study, the seismic demand exceeded the brace strength of our initial bracing layout, so additional frames were required. Figures 3 through 6 show the final designed bracing layout.

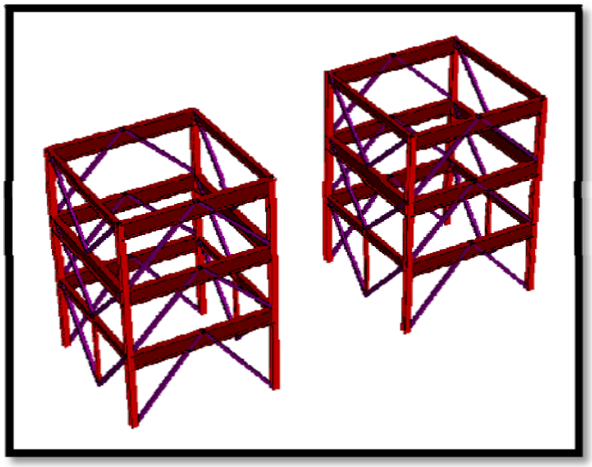

Figure 3: 3-Story SCBF

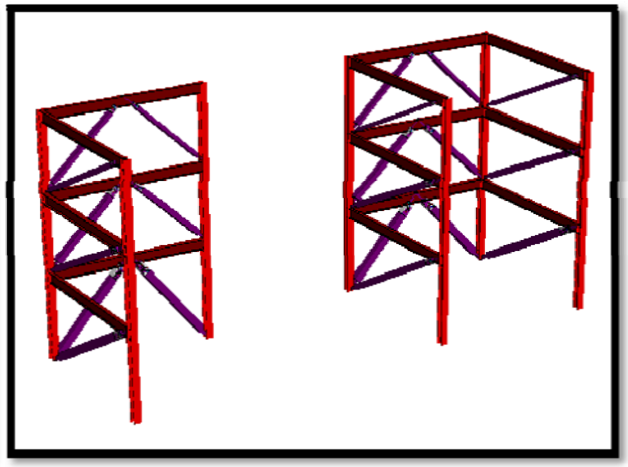

Figure 4: 3-Story BRBF

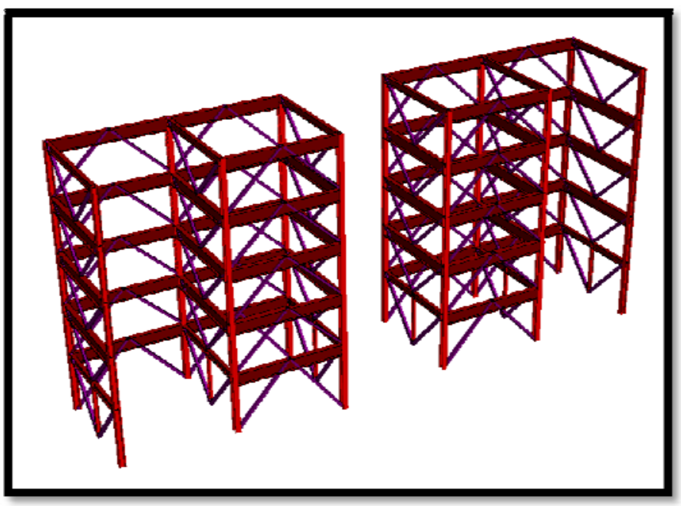

Figure 5: 5-Story SCBF

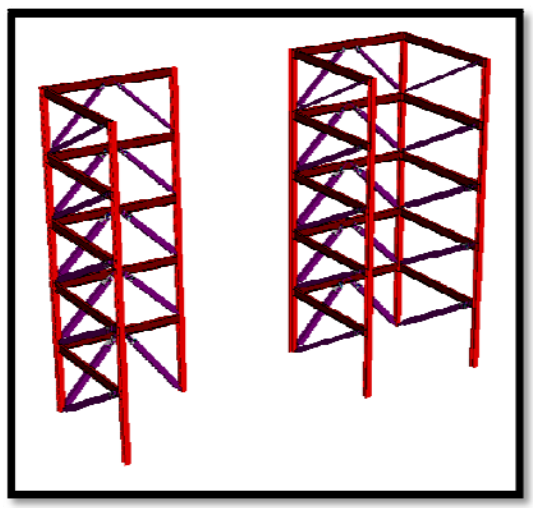

Figure 6: 5-Story BRBF

All of these bracing configurations were torsionally irregular, so a Modal Response Spectrum Analysis was performed for each. Brace sizes were adjusted to satisfy story drift limitations.

One of the greatest advantages found in the design of BRBFs is the higher corresponding Response Modification Factor (R). Using an R=8 instead of an R=6 yields an immediate 25% reduction in the seismic base shear.

Also, the use of the fundamental period based on structural analysis instead of the approximate fundamental period can further reduce the demand. The lateral stability systems of buildings may be "tuned" by adjusting the member sizes to allow for greater drift of the building (within acceptable limits), thus creating a longer fundamental period. BRBFs are more sensitive to these adjustments because of the smaller area of steel required to provide adequate strength.

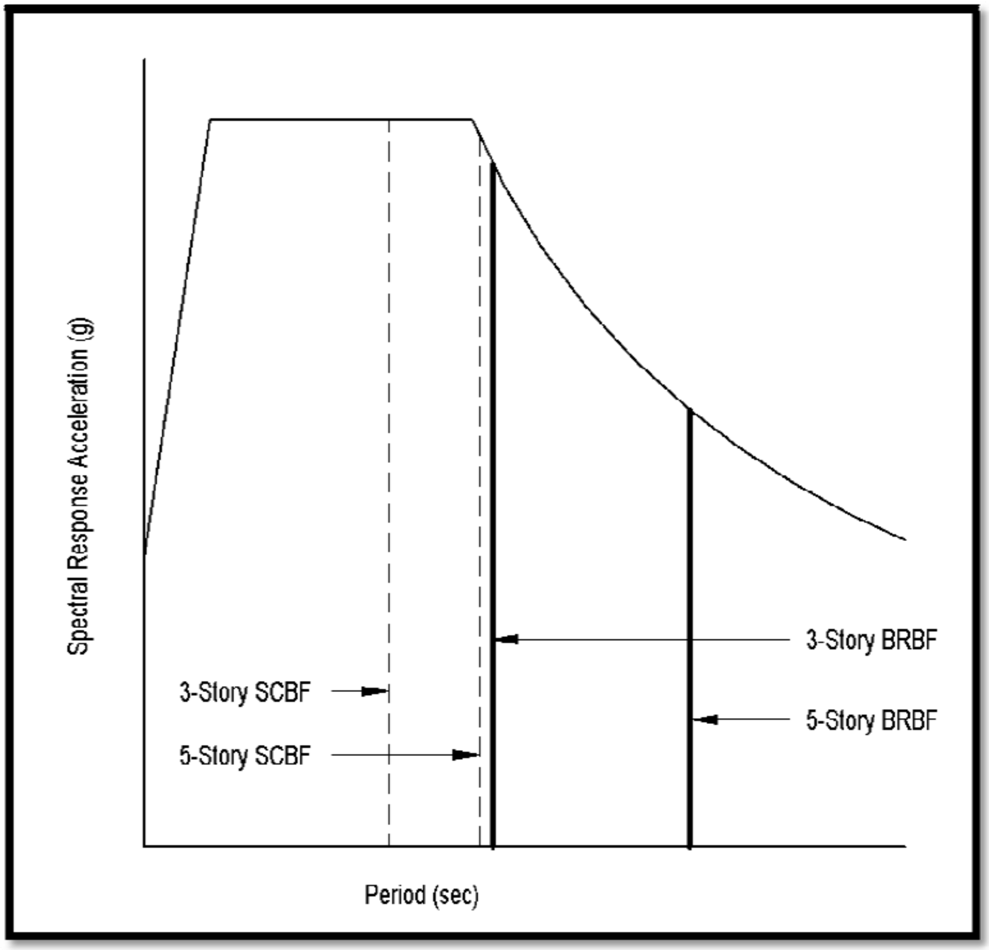

Figure 7: Design Response Spectrum

For graphical simplicity, the plotted values are the average of Tx and Ty.

Table 1: Three-Story Base Shears using Equivalent Lateral Force Analysis (ELFA)

Building Type	Fundamental Period (sec)		$Ts=S_{D1}/S_{DS}$ (sec)	Response Coefficient		ELFA Base Shear (kips)	
	Tx	Ty		C_sx	C_sy	Vx	Vy
SCBF 3-story	0.377	0.386	0.511	0.189	0.189	1,126	1,126
BRBF 3-story	0.501	0.586	0.511	0.142	0.124	821	717

The values above indicate calculated fundamental periods based on analysis, not approximate fundamental periods.

Table 2: Five-Story Base Shears using Equivalent Lateral Force Analysis (ELFA)

Building Type	Fundamental Period (sec)		$Ts=S_{D1}/S_{DS}$ (sec)	Response Coefficient		ELFA Base Shear (kips)	
	Tx	Ty		C_sx	C_sy	Vx	Vy
SCBF 5-story	0.497	0.549	0.511	0.189	0.176	2,129	1,985
BRBF 5-story	0.788	0.913	0.511	0.092	0.079	982	848

The values above indicate calculated fundamental periods based on analysis, not approximate fundamental periods.

Cost Comparison

The intention of this study is to quantify the difference in cost between these sample buildings which directly results from the type of bracing system selected. Therefore, the following costs do not attempt to capture total structural building cost, but merely to serve as a cost comparison.

We have evaluated the structural cost differences between the four building types with the assistance of SteelFab, Inc., a highly respected fabricator, one of the nation's largest suppliers of fabricated structural steel, but also very knowledgeable in the regional labor market and the current connection requirements of the seismic provisions. Tables 3 and 4 summarize the cost analysis.

Table 3: 3-Story Cost Comparison

	3-Story SCBF		3-Story BRBF		BRBF Savings Unit Cost
	Weight (tons)	Cost ($)[1]	Weight (tons)	Cost ($)[1]	
Gravity Beams	229.8		240.1		
Gravity Columns	26.0		27.7		
Frame Beams	92.6		19.1		
Frame Columns	45.8		20.8		
Braces	28.6				
Subtotal	422.7	401,577	307.7	292,339	
Detailing/Misc[2]	84.5	92,997	40.0	44,005	
Tonnage Total	507.3		347.7		
Shop Labor Cost[3]		380,442		226,024	
BRB members[4]			56.6	79,500	
Foundation Cost[5]		120,000		152,000	
Total Cost		$995,016		$793,868	$2.60 / sf

Footnotes:

1. Units costs used are $950/ton for main material, $1,100/ton for Detailing/Misc, and $50/manhour for shop labor. These unit costs are subject to market fluctuations.
2. Detailing/Misc includes the cost of all connection material, angles, bent plates, base plates, outriggers, and braced frame gusset plates. This is a percentage of the Subtotal main member tonnage. Based on

SteelFab's experience with similar projects this is taken as 20% for SCBF and 13% for BRBF. Gusset plates are significantly larger for SCBFs.

3. Shop Labor Cost is 15 manhours/ton for SCBF and 13 manhours/ton for BRBF, based on SteelFab's experience with similar projects. Gusset plates are significantly larger for SCBFs, with more welding. The labor rate is taken as $50/manhour.
4. The weight shown for the BRBs includes the weight of the steel core, HSS casing, concrete, and collar. The cost is provided by Star Seismic.
5. Foundation Cost includes the footings for the braced frame foundations, designed as combined foundations resisting downward, horizontal and uplift forces. As the SCBFs utilize more columns, the foundations for these same gravity columns in the BRBF option have been included. The unit cost of concrete, rebar, and installation has been taken as $300/yd^3.

Table 4: 5-Story Cost Comparison

	5-Story SCBF		5-Story BRBF		BRBF Savings Unit Cost
	Weight (tons)	Cost ($)[1]	Weight (tons)	Cost ($)[1]	
Gravity Beams	401.4		417.1		
Gravity Columns	38.9		52.3		
Frame Beams	257.7		34.9		
Frame Columns	141.9		45.3		
Braces	71.9		----		
Subtotal	911.8	866,193	549.5	522,021	
Detailing/Misc[2]	164.1	180,533	60.4	66,489	
Tonnage Total	1,075.9		609.9		
Shop Labor Cost[3]		806,928		396,461	
BRB members[4]		----	80.9	131,750	
Foundation Cost[5]		240,000		276,000	
Total Cost		$2,093,654		$1,392,721	$5.39 / sf

Footnotes:

1. Same as for Table 3.
2. Detailing/Misc includes the cost of all connection material, angles, bent plates, base plates, outriggers, and braced frame gusset plates. This is a percentage of the Subtotal main member tonnage. Based on SteelFab's experience with similar projects this is taken as 18% for SCBF and 11% for BRBF. Gusset plates are significantly larger for SCBFs.
3. Same as for Table 3.
4. Same as for Table 3.
5. Same as for Table 3.

As indicated in Tables 3 and 4, there are three major components of the savings found in utilizing BFBFs:

1. Braced frame main members – This savings results from the significantly reduced base shear, which is lower due to the greater R value and the use of fundamental periods based on structural analysis.

2. Detailing/Misc – The gusset plates for SCBFs are significantly larger and the connections more complex with more labor required as compared to BRBFs.
3. Shop labor – The labor associated with the SCBF connection complexity is reflected in the increase in shop time required.

One will notice that even though field welding requirements are significantly less for BRBFs as compared to SCBFs, the cost of erection is not included in the charts above. SteelFab has found that erection costs in the southeast U.S. has been virtually the same for either system. This can be explained by a couple of factors: 1) erectors have not yet reached a level of familiarity with buckling restrained braces to understand the erection and welding requirements; and 2) current market volatility has caused significantly fluctuating pricing. Over time, as erectors become comfortable with BRBs and their use becomes more common, it is expected that the cost of erection will be an additional savings.

The size of foundations for braced frame buildings is often controlled by the need for uplift resistance. Individual column footings are often strapped together with grade beams or replaced by combined foundations. At the outset of this study, due to lower seismic base shears, it was expected that the foundations for the BRBF buildings would be less expensive than those for the SCBF buildings. The expectation was that with lower base shears, smaller uplift reactions would follow, and the stabilizing foundations under the braces would be smaller and less expensive. However, the analysis from the structural models revealed greater uplift forces using the BRBF systems. This counterintuitive outcome results from several factors:

a) The number of braces (SCBF braces had to be added due to the slenderness limitations discussed on page 5)
b) The number of lateral columns (more columns to resist uplift)
c) The configurations of the braces (distribution to more columns)
d) The distribution of seismic torsional forces (SCBFs has more symmetry, and therefore less building torsion)

Conclusions

Adaptability: As described in the Discussion section, BRBFs are allowed as a single diagonal in a framing line, whereas SCBFs are not. This allows the engineer more options in adapting to the architectural layout and function. Other bracing configurations that do not require the use of chevrons may show less cost savings than this study reveals, but this study shows the adaptability advantages of BRBFs.

Savings: The cost analysis shows the advantages of utilizing Buckling Restrained Braces can be quite significant. In our 5-Story example the savings is in excess of $5 per square foot. Building owners and developers will be interested in realizing this savings. Engineers can demonstrate their value as a member of the design team by utilizing a more cost-effective structural system. Steel fabricators can utilize this information in value engineering opportunities.

Performance: One of the goals to successful seismic performance is ductility, which efficiently dissipates seismic energy. Testing has demonstrated that BRBFs repeatedly perform in a manner consistent with this goal. The models codes have demonstrated confidence in this ductile behavior by endorsing and encouraging its use, assigning it the highest R value of any allowable system.

It is beyond the scope of this study, but further evaluation should be made for BRBFs in regions of moderate seismicity where traditional design has utilized R=3. The reduction in base shear due to the increased R value alone is 62.5%.

As the use of Buckling Restrained Braces increases, additional information will become available regarding the financial and engineering advantages it offers.

References

1. 2012 International Building Code; International Code Council, Inc.; Third Printing February 2013

2. Seismic Provisions for Structural Steel Buildings, AISC 341-10; American Institute of Steel Construction; June 22, 2010

3. Minimum Design Loads for Buildings and Other Structures, ASCE 7-10; American Society of Civil Engineers; 2010

4. "Buckling Restrained Braced Frame (BRBF) Structures: Analysis, Design and Approvals Issues"; by Hussain, Benschoten, Al Satari, & Lin

5. "Design of Buckling-Restrained Braced Frames"; by Sabelli & Lopez; Modern Steel Construction; March 2004

Acknowledgements

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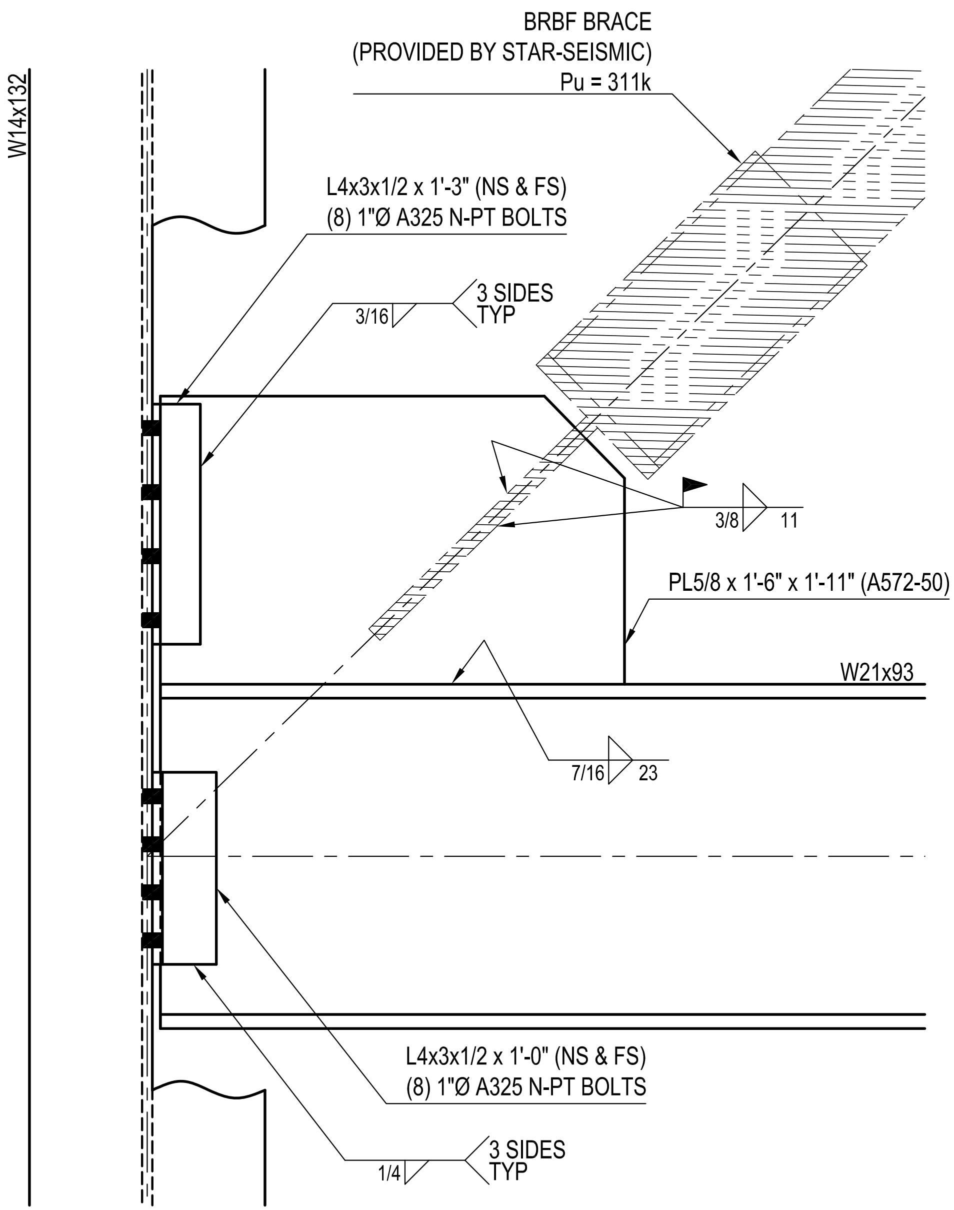
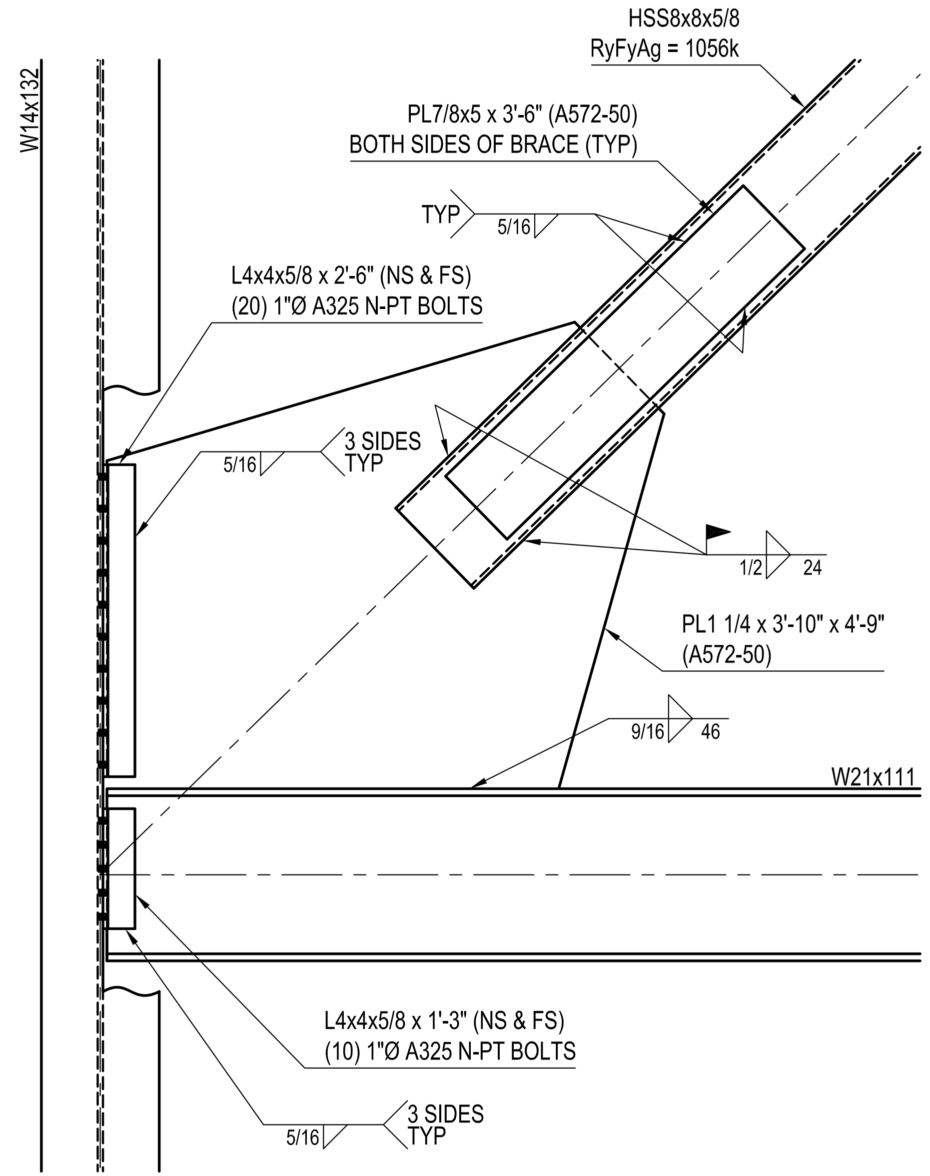
STEEL FAB, INC.
www.steelfab-inc.com

FABRICATION COSTS (CONNECTION MATERIAL & LABOR)	$ 140
ERECTION COSTS	$ XXX



BRBF CONNECTION

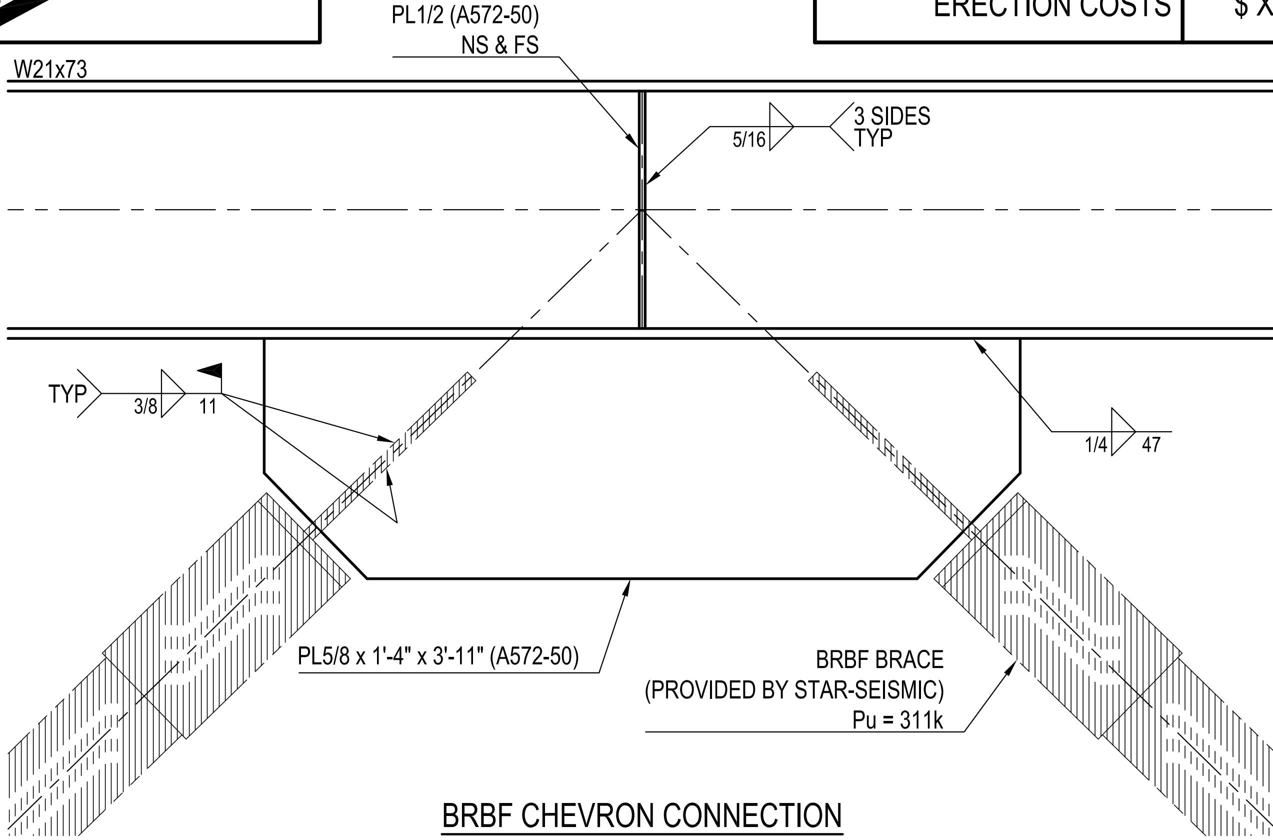
FABRICATION COSTS (CONNECTION MATERIAL & LABOR)	$ 784
ERECTION COSTS	$ XXX



EQUIVALENT SCBF CONNECTION

STEEL FAB, INC.
www.steelfab-inc.com

FABRICATION COSTS (CONNECTION MATERIAL & LABOR)	$ 229
ERECTION COSTS	$ XXX



BRBF CHEVRON CONNECTION

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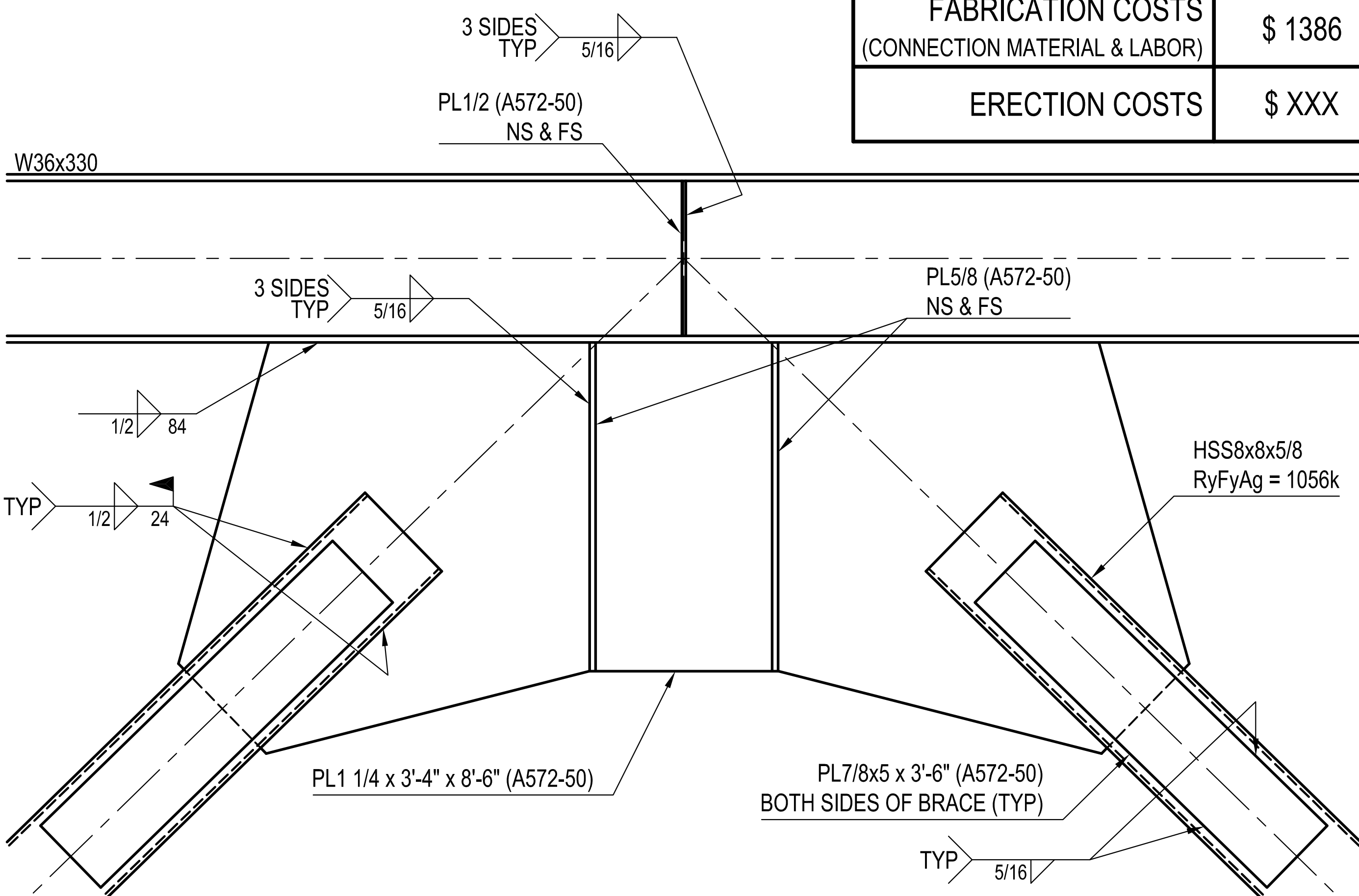
ERECTION COSTS	$ XXX



EQUIVALENT SCBF CHEVRON CONNECTION