Cost advantages of Buckling Restrained Braced Frame buildings in accordance with Eurocode

This report compares Buckling Restrained Braced Frames to Concentrically Braced Frames as primary lateral load resisting systems from an economical perspective. It investigates the expected total costs of a 3-story and a 7-story steel frame structure for three different bracing options.

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INTRODUCTION

The presented study investigates anticipated cost advantages of Buckling Restrained Braced Frame (BRBF) systems compared to Concentrically Braced Frame (CBF, Frame with concentric bracings) systems. The former is a braced frame containing special diagonal members called Buckling Restrained Braces, characterized by balanced, highly ductile behavior. The latter is a conventional vertical truss system which is designed so that yielding of the braces in tension will take place before yielding or buckling of the non-ductile beams or columns or before failure of the connections. Two types of CBF systems are investigated: a low dissipative CBF with very limited ductility and a moderately ductile CBF with dissipative X bracing. Design seismic forces are affected by the level of ductility expected from each solution, thus buildings with BRBF systems have significantly lower design earthquake loads than their CBF equipped counterparts.

BRB IN EUROCODES

Unfortunately design regulations for BRBF systems are not yet included in the Eurocodes, therefore there is no corresponding behavior-factor defined for linear static analysis. However, as per Eurocode 8 Part 1, Section 4.3.3.4.2.1 seismic no-collapse requirement check by non-linear static (pushover) or non-linear dynamic (time history, response history) analysis is an alternative to linear static design. Thus the performance of BRBF equipped structures can and shall be verified using one of these non-linear techniques. Since the EN 15129 European Standard on Anti-seismic devices includes BRBF among displacement dependent devices, it is presumable that Eurocode 8 is going to contain details of BRBF design after its next revision in the near future.

AIM OF COST STUDY

The objective of this study is to show that in spite of being more expensive as a brace element, using BRBF in moderate or high earthquake prone regions leads to significant reduction in total structural cost by decreasing the required capacity of every non-dissipative structural member. The aforementioned three types of bracing solutions are compared in two structures with different heights in order to show how the savings scale as the number of stories increases.

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As earthquake awareness among engineers is enhanced by the European standards even in regions of moderate seismicity, the significance of economical solutions providing adequate resistance for structures is also increasing. Considering the European trends in the need of not only well-performing but also economical structural systems has led Star Seismic™ to focus its operations after North and South America to Europe as well. Star Seismic Europe™ has been set up to professionally serve the increasing European inquiries, providing a new, more cost-effective anti-seismic structural system in the European market. Star Seismic™ Buckling Restrained Braces can be applied both in new constructions and in seismic retrofit projects, and can be used in not only in steel, but also in reinforced concrete structures. Star Seismic Europe™ applies the proven technology of Star Seismic™ who has gained exhaustive experience over the fabrication of thousands of Buckling Restrained Braces.

ASSUMPTIONS AND DESIGN CRITERIA

The buildings modeled in this study are regular, steel frame structures with light weight decks. Their lateral force resisting bracings are located at the perimeter walls. Following are the key characteristics of the model:

Standard:	Eurocode (EC) 0, EC 1-1, EC 2-1, EC 3-1, EC 7-1, EC 8-1, EC 8-5
Peak ground acceleration:	0.25 g
Soil type:	C
Importance class and factor:	II, γ_I = 1.0
Analysis procedure:	Equivalent Lateral Force Method
Response spectrum:	type I elastic spectrum
Structural model:	3D
Dead load:	
floors:	4.15 kN/m^2
roof:	3.25 kN/m^2
Live load:	
floors:	3 kN/m^2
roof:	1 kN/m^2
Wind load:	negligible in current calculation
Snow load:	negligible in current calculation
Behavior factor:	
CBF:	*q*=1.5 (limited ductility) *q*=4.0 (moderate ductility)
Star Seismic™ BRBF:	*q*=7.0 (high ductility)
Foundation - piles:	100 cm and 120 cm in diameter 8 m to 18 m in length piles are designed for both tension and compression

BUCKLING RESTAINED BRACED FRAME SYSTEMS

Buckling Restrained Braces consist of an inner steel core and an outer casing (Figure 1). The axial forces acting on the brace are resisted by the core only, as the composite action is prevented by air gap inserted in between the casing and the core. The purpose of the casing is to prevent buckling of the core under compression.

Since the steel core is laterally supported by the casing, its performance under compression is not limited by buckling, thus smaller cross-sections can be used than in conventional braces. As a result of smaller cross-sections, structures with BRBF are generally not as stiff as their ordinary counterparts. The exclusion of buckling failure leads to similar element performance under compression and tension. Considerable plastic deformations can develop after yielding and before failure for both load directions, which leads to a highly ductile behavior. Laboratory test results have verified this behavior and shown no degradation in performance after several load cycles. Therefore BRB elements are able to dissipate a large amount of energy when subjected to cyclic loading. This attribute is recognized in the United States' standards by qualifying BRBF systems for the highest response modification factors (behavior factors - *q*) of 7 or 8 depending on design details. On top of the high ductility, the flexibility of the structure further decreases seismic loads by increasing the fundamental period of vibration.

Unlike BRBF, members of Concentrically Braced Frame systems are characterized by long unbraced lengths. The cross-sectional area of these members often has to be larger than necessitated by static demands in order to avoid premature buckling. Furthermore, tension diagonals are carrying the majority of lateral loading under seismic excitation, since members under compression are expected to buckle. This behavior leads to poor member utilization and unbalanced forces at certain joints.

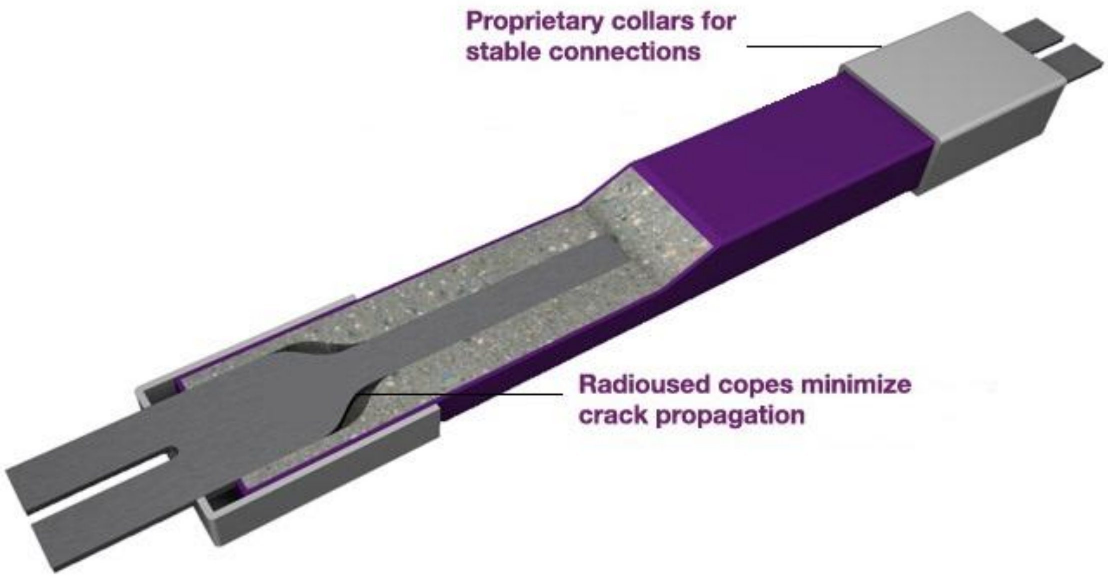


Figure 1: Star Seismic Europe™'s WildCat™ Buckling Restrained Brace

MODEL BUILDINGS

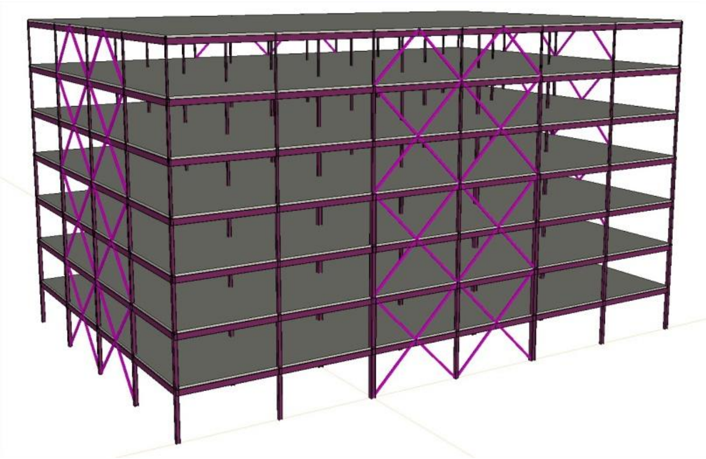


Figure 2: Isometric view of 7-story, 3D BRBF equipped model

Rectangular structures with four perimeter braced frames were designed to compare BRBF and CBF solutions. The three-story and seven-story buildings have a gross floor area of 5800 m^2 and 13600 m^2 respectively. Figure 3-10 show typical floor plans and frame elevations.

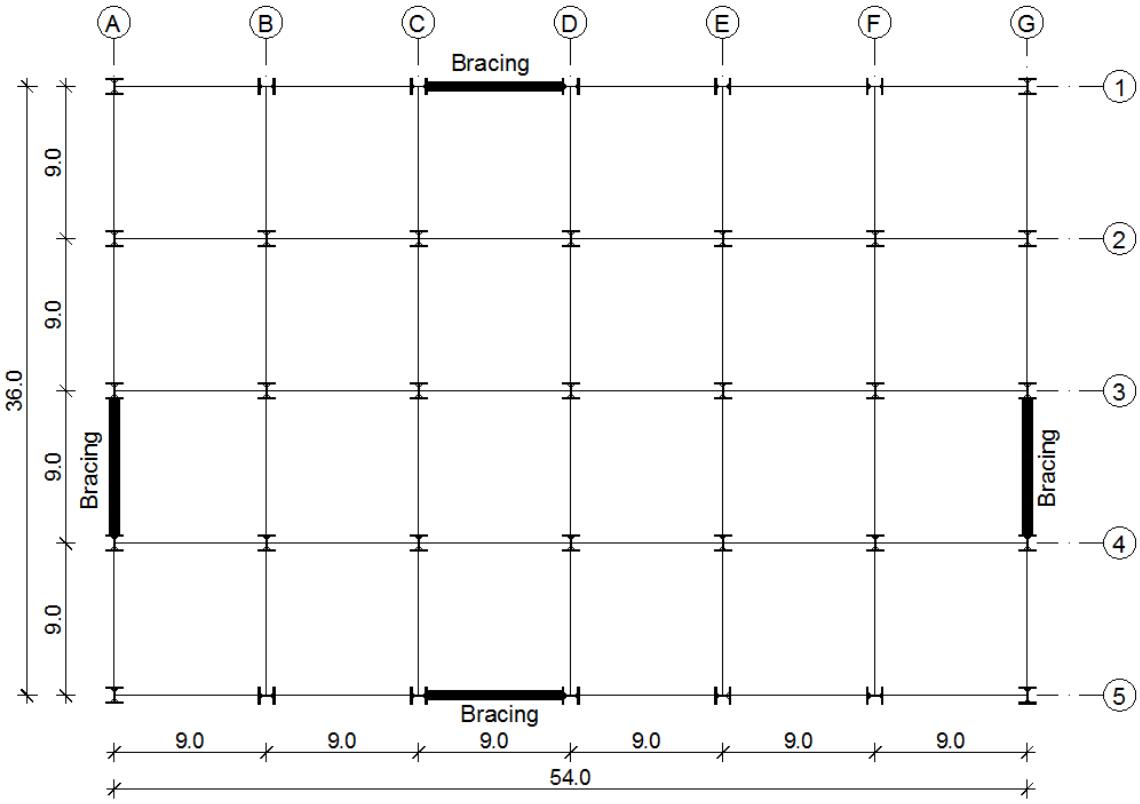


Figure 3: Model building floor plan - 3-story

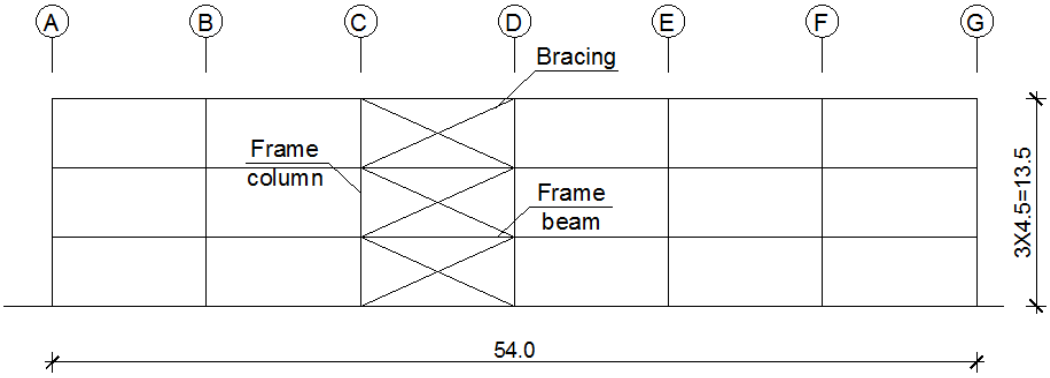


Figure 4: Model building elevation - 3-story CBF, q = 1.5

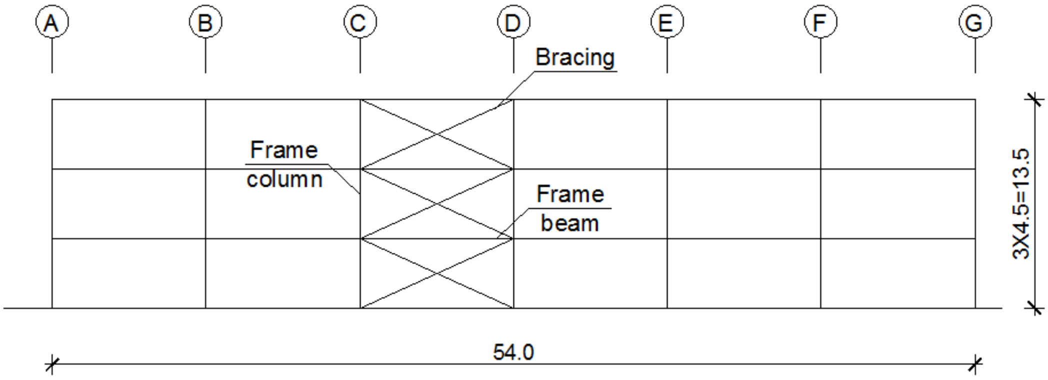


Figure 5: Model building elevation - 3-story CBF, q = 4

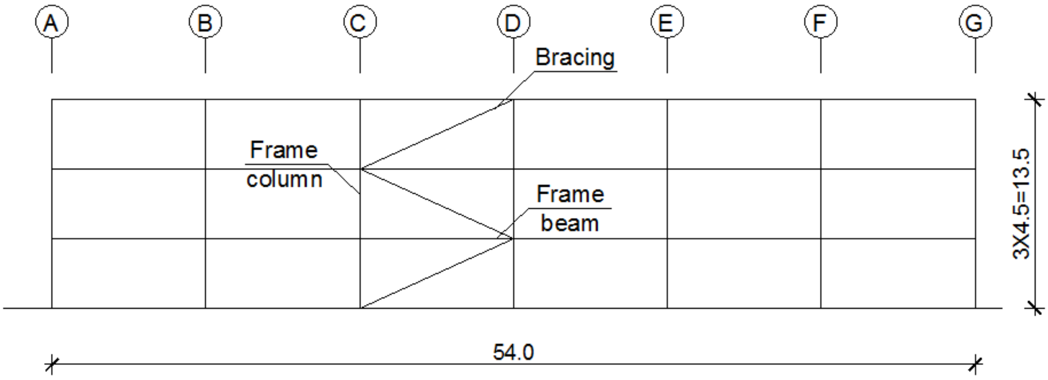


Figure 6: Model building elevation - 3-story Star Seismic™ BRBF, q = 7

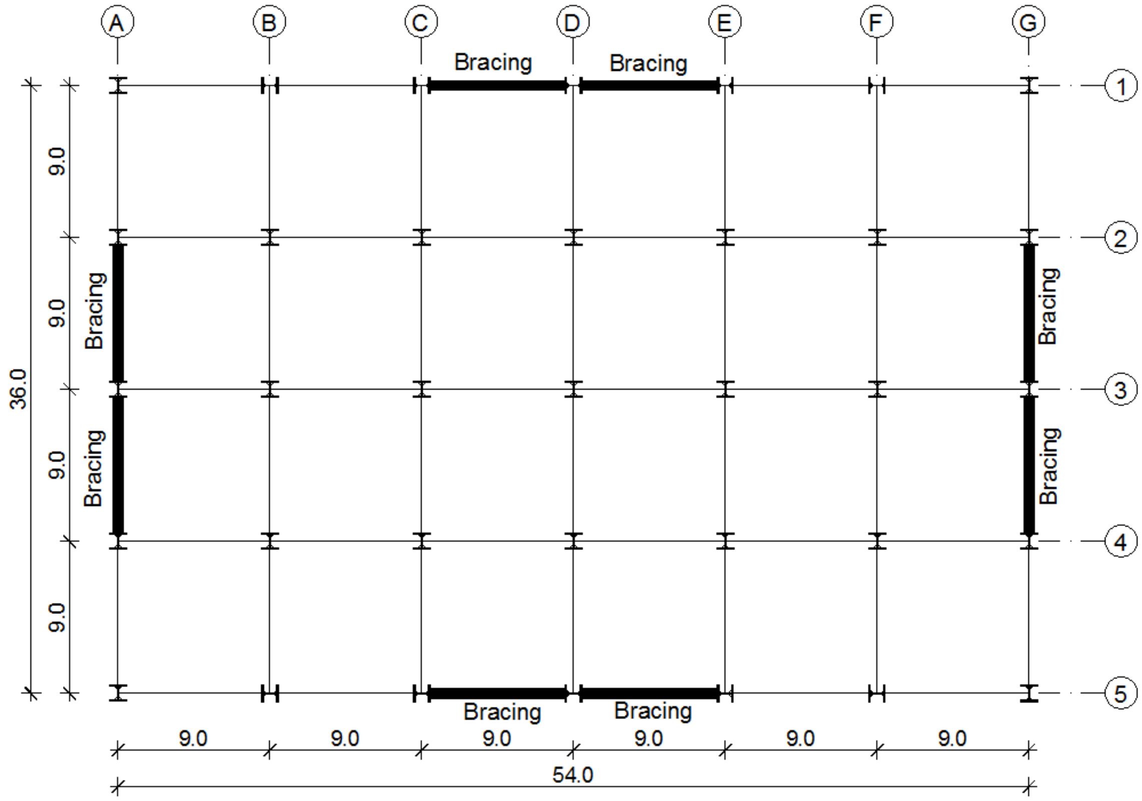


Figure 7: Model building floor plan - 7-story

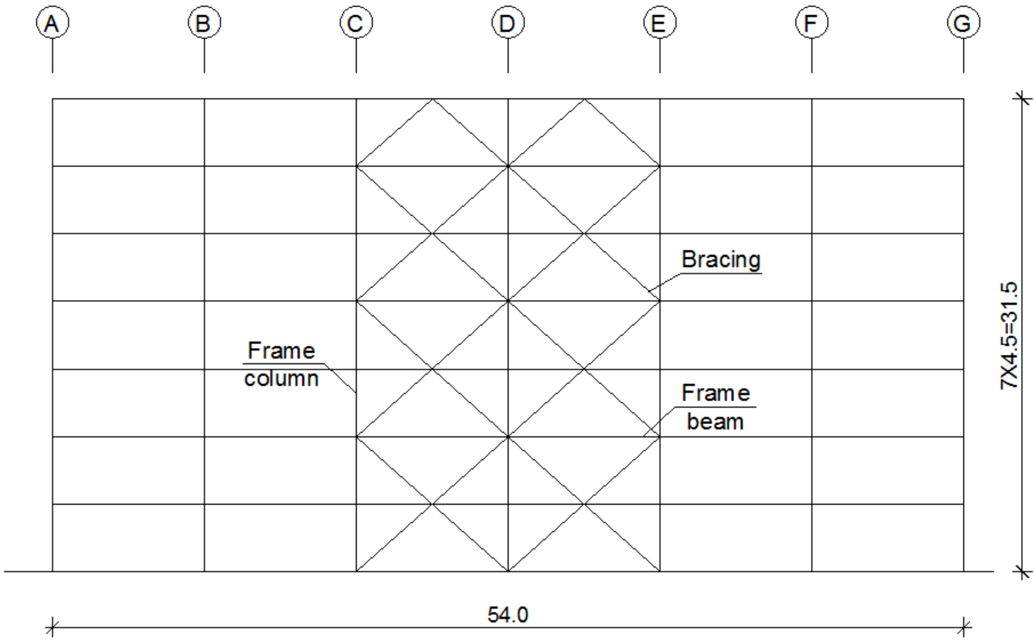


Figure 8: Model building elevation - 7-story CBF, q = 1.5

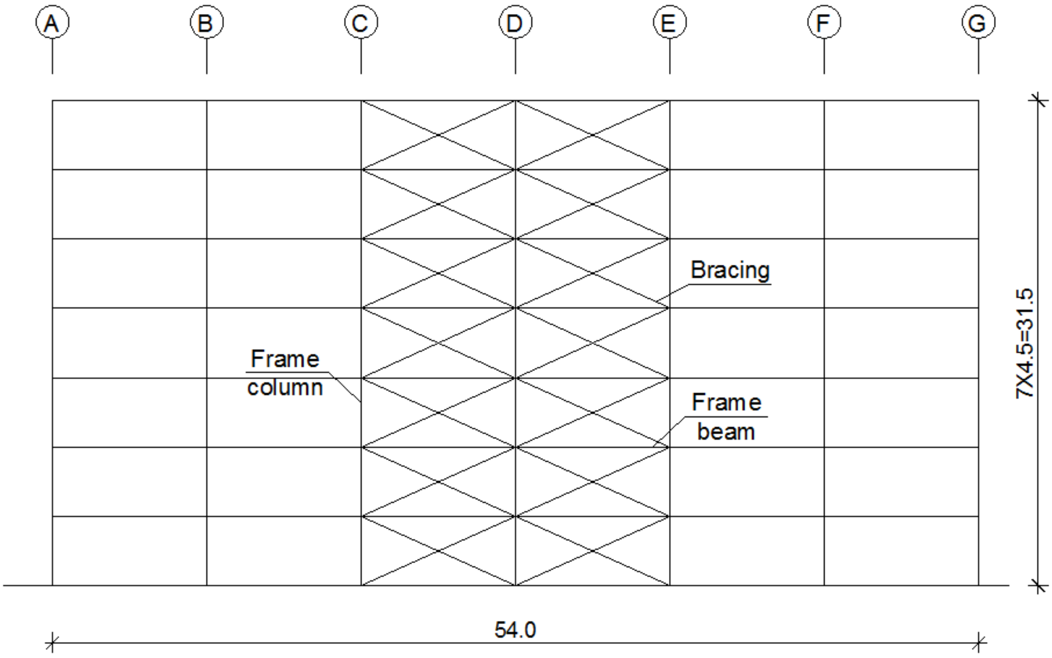


Figure 9: Model building elevation - 7-story CBF, q = 4

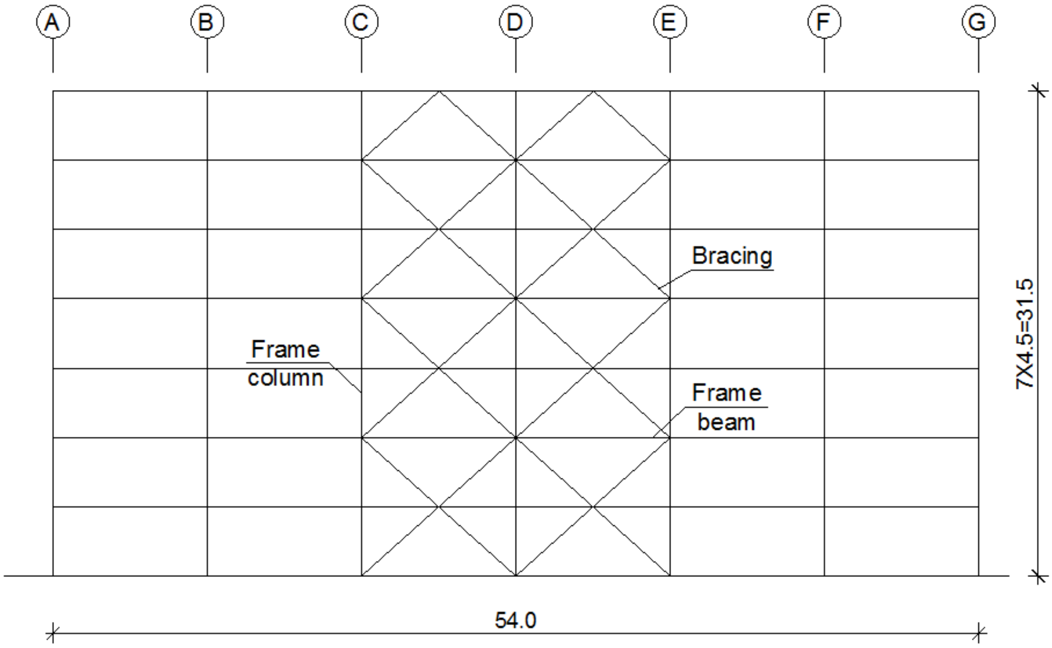


Figure 10: Model building elevation - 7-story Star Seismic™ BRBF, q = 7

All column elements are continuous and pinned at the foundation level in the structural model. Beams and braces connecting to the columns are also pinned, therefore earthquake loads are resisted by the braced fields only.

LATERAL ANALYSIS

Although the structural verification of the BRBF system requires non-linear analysis, for preliminary design stage, engineers are encouraged to use the *q*-factor method. In the current example with the consideration of pinned connections between columns and beams, *q*=7 behavior factor is to be applied. The higher behavior factor of structures with BRBF reduces the applicable design acceleration significantly as shown on Figures 11-12. The aforementioned flexibility of BRB elements also influences this value through the high fundamental building period (T), especially for taller buildings. At the investigated buildings the design is drift-controlled (i.e. the limited damage criteria governs), which is also reflected by the similar rigidity and thus fundamental periods of the two dissipative systems.

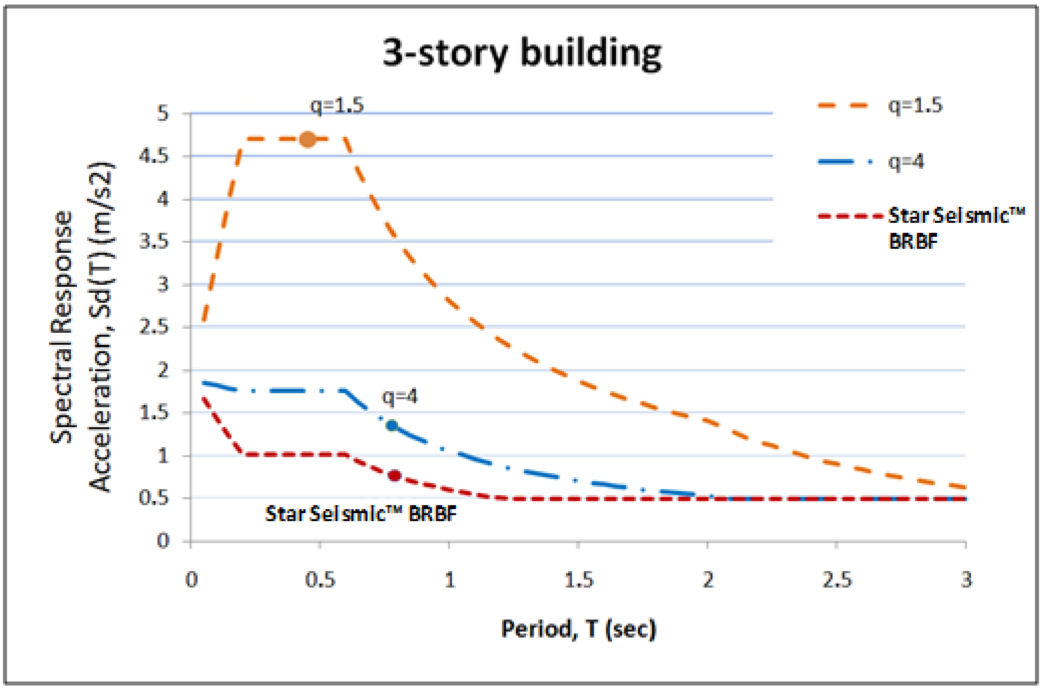


Figure 11: Response spectra for 3-story building

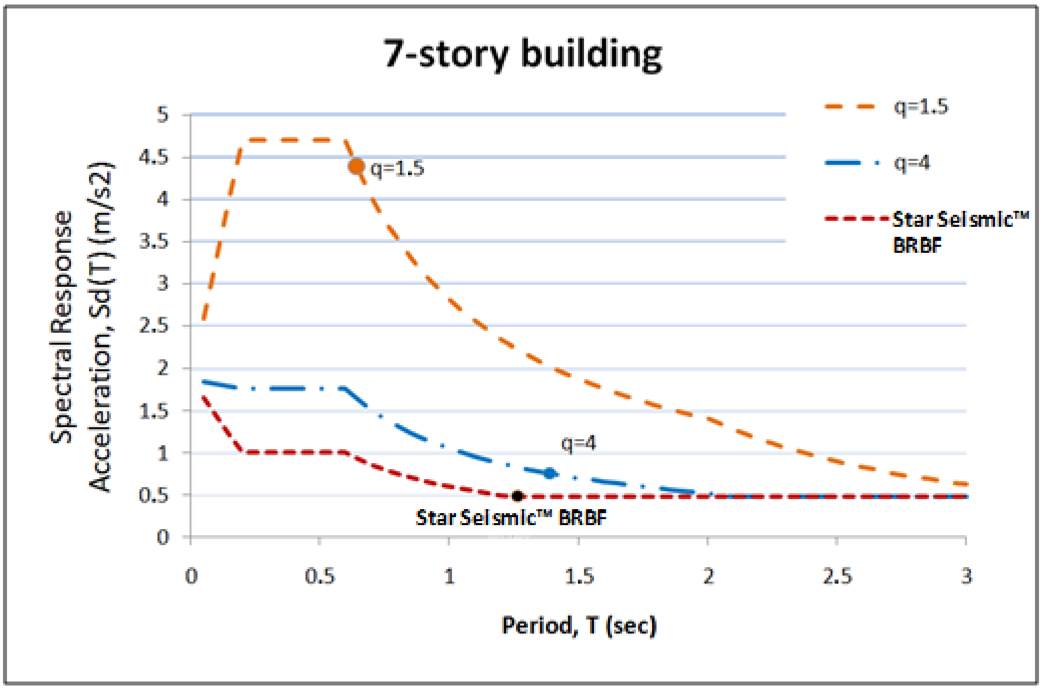


Figure 12: Response spectra for 7-story building

The following table summarizes the behavior factor, fundamental period and the resulting base shear force for each structure. Structures with BRBF have the smallest base shear forces in both cases.

	3-story			7-story		
	CBF *q* =1.5	CBF *q* =4	Star Seismic™ BRBF	CBF *q* =1.5	CBF *q* =4	Star Seismic™ BRBF
Behavior factor (*q*)	1.5	4	7	1.5	4	7
Fundamental period (s)	0.455	0.781	0.794	0.641	1.389	1.266
Spectral response acceleration (m/s^2)	4.700	1.356	0.765	4.400	0.761	0.491
Base shear force (kN)	11 847	3 308	1 861	27 386	5 279	3 401
Correction factor (λ)	0.85	0.85	0.85	0.85	1.00	1.00

Table 1: Different coefficients for 3-story and 7-story buildings

The base shear force is distributed vertically along the height of the structure and accidental torsional effects are taken into account according to provisions of Eurocode 8. Internal forces in decks and collectors are dominated by minimum requirements according to current standards, therefore the designs of these elements are identical for every building considered.

BUILDING DESIGNS

Due to reduced lateral loads, sections of BRBF members were generally smaller than their CBF counterparts. The non-ductile members of every structure were designed with the consideration of the overstrength factor. The capacity of certain members in BRB frames is not justified by the design loads, but by the applicable global displacement limits instead.

Sections used for the modeled buildings are summarized in Table 2-3.

Level	Braced columns			Braces			Braced beams		
	CBF q=1.5	CBF q=4	Star Seismic™ BRBF	CBF q=1.5	CBF q=4	Star Seismic™ BRBF	CBF q=1.5	CBF q=4	Star Seismic™ BRBF
	Section			Section			Section		
3	HD 400x287	HEB 700	HEB 450	SHS 250x16	SHS 160x8	3625 mm^2	IPE 550	IPE 550	IPE 550
2	HD 400x287	HEB 700	HEB 450	SHS 350x12.5	SHS 200x12.5	7000 mm^2	IPE 550	IPE 550	IPE 550
1	HD 400x287	HEB 700	HEB 450	SHS 400x16	SHS 200x16	7500 mm^2	IPE 550	IPE 550	IPE 550

Table 2: Member sizes, 3-story building

Level	Braced columns			Braces			Braced beams		
	CBF q=1.5	CBF q=4	Star Seismic™ BRBF	CBF q=1.5	CBF q=4	Star Seismic™ BRBF	CBF q=1.5	CBF q=4	Star Seismic™ BRBF
	Section			Section			Section		
7	HEA 400	HEB 220	HEB 140	SHS 200x10	SHS 140x3	800 mm^2	IPE 750x147	IPE 550	IPE 550
6	HEB 400	HD 400x287	HEB 260	SHS 300x12.5	SHS 150x6.3	2000 mm^2	IPE 750x147	IPE 550	IPE 550
5	HEB 400	HD 400x287	HEB 260	SHS 350x16	SHS 180x10	2800 mm^2	IPE 750x147	IPE 550	IPE 550
4	HD 400x347	HD 400x382	HD 400x262	SHS 400x20	SHS 200x12.5	3400 mm^2	IPE 750x147	IPE 550	IPE 550
3	HD 400x347	HD 400x382	HD 400x262	SHS 400x20	SHS 200x12.5	3800 mm^2	IPE 750x147	IPE 550	IPE 550
2	HD 400x634	HD 400x592	HD 400x509	SHS 450x20	SHS 200x12.5	4200 mm^2	IPE 750x147	IPE 550	IPE 550
1	HD 400x634	HD 400x592	HD 400x509	SHS 450x20	SHS 200x20	4400 mm^2	IPE 750x147	IPE 550	IPE 550

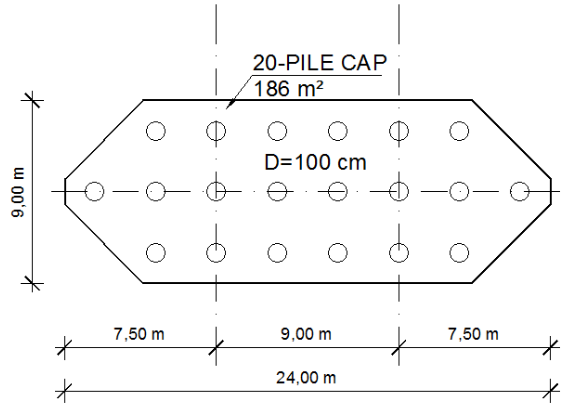
Table 3: Member sizes, 7-story building

Both shallow and deep foundations were considered for each model building. Structures with CBF require significantly stronger foundations due to higher lateral overturning forces. The intensity of tensile forces justifies the use of pile foundations for all buildings. However, if necessary it would be possible to use a BRBF system that reduces tensile forces enough to enable the use of mat foundations.

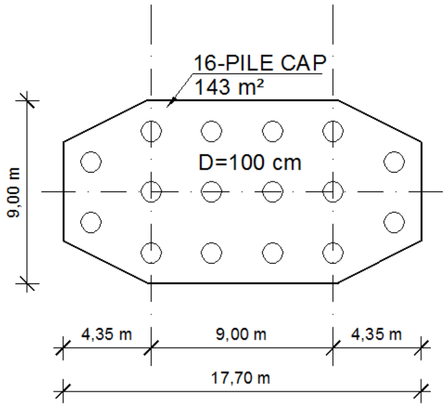
The following table and figures show the drastically decreased number of necessary piles and volume of pile caps. In order to fully utilize cost advantages of Buckling Restrained Braces, BRB design should be considered in early project phase.

		CBF *q* =1.5	CBF *q* =4	Star Seismic™ BRBF
3-story	**D [cm]**	100	100	100
	Number of piles	20	16	8
	Length [m]	12	8	8
7-story	**D [cm]**	120	100	100
	Number of piles	24	24	12
	Length [m]	18	14	12

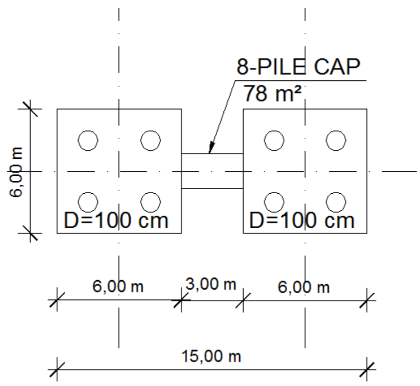
Table 4: Pile schedule



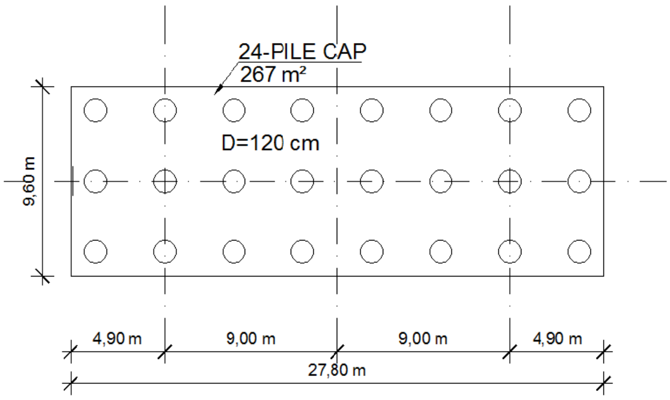
3-story CBF *q*=1.5, L=12 m



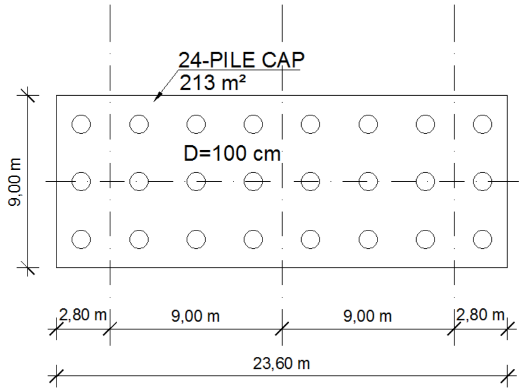
3-story CBF *q*=4, L=8 m



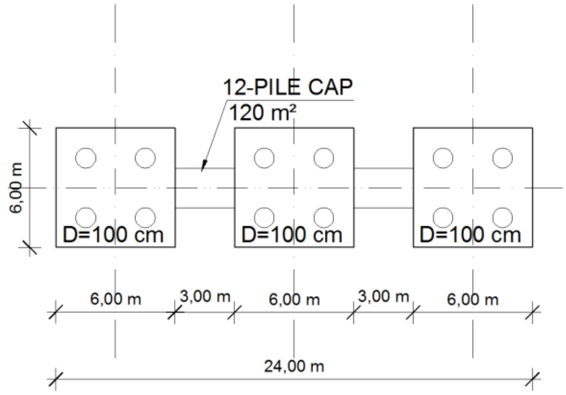
3-story Star Seismic™ BRBF *q*=7, L=8 m



7-story CBF *q*=1.5, L=18 m



7-story CBF *q*=4, L=14 m



7-story Star Seismic™ BRBF *q*=7, L= 12 m

Figure 13: Pile layout

Since connections are required to exceed the strength of connecting members, the smaller section of BRB elements compared to CBF members can lead to smaller connection demands. This results in smaller gusset plates and weld lengths as shown in Figure 14.

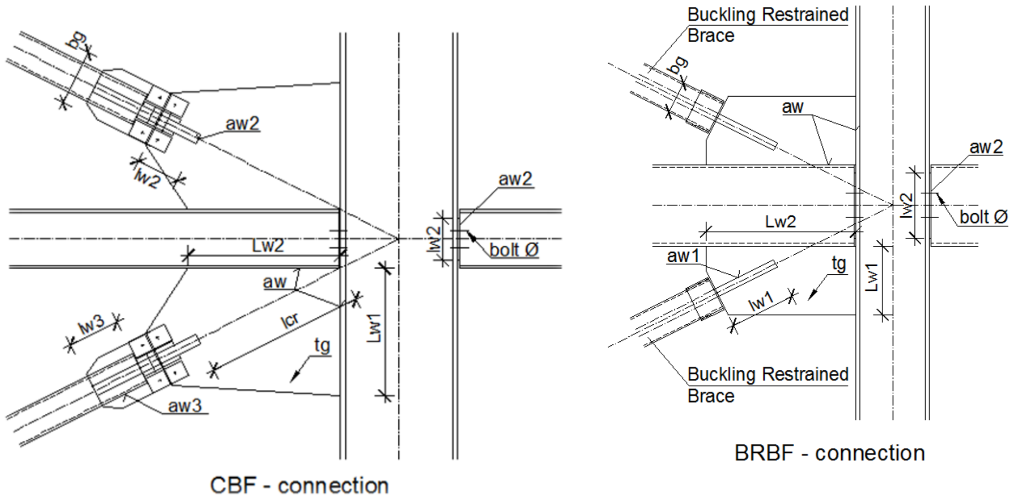


Figure 14: Connection details – CBF and Star Seismic™ BRBF

As an example, Table 5 shows the details of a connection at the first level in the 3-story building. Note the significant reduction in necessary gusset plate sizes in case of the BRBF system compared to CBF systems.

Connections		tg	bg	Lw1	Lw2	lw1	lw2	lcr
		mm	mm	mm	mm	mm	mm	mm
CBF $q = 1.5$	SHS 400x16	60	420	934	1399	-	350	1127
	Beam-column connection	-	-	-	-	-	4x250	-
CBF $q = 4$	SHS 200x16	60	335	759	907	-	300	947
	Beam-column connection	-	-	-	-	-	4x260	-
Star Seismic™ BRBF	7500 mm^2	30	300	422	918	400	-	-
	Beam-column connection	-	-	-	-	4x400	2x400	-

Connections		aw	aw1	aw2	lw3	aw3	Bolts		Gussets
		mm	mm	mm	mm	mm	Φ, mm	pieces	kg/pcs
CBF q=1.5	SHS 400x16	6	-	9	320	9	22	32	656
	Beam-column connection	-	-	3	-	-	20	8	
CBF q=4	SHS 200x16	9	-	9	260	10	30	16	361
	Beam-column connection	-	-	4	-	-	20	8	
Star Seismic™ BRBF	7500 mm^2	7	12	-	-	-	-	-	128
	Beam-column connection	-	3	3	-	-	20	8	

Table 5: Sample connection details

MATERIAL QUANTITIES AND COSTS

After considering the cost of all structural elements, structures with BRBF are found to be the least expensive among the three options examined. Even though there is a big difference in the cost of braces that favors conventional solutions, using BRBF saves such a large amount on other parts of the structure that makes it the recommended solution when it comes to cost efficiency. Tables 6-8 and Figures 15-18 show details of cost analysis and its results of the lateral force resisting system (LFRS) of the buildings. Please note that prices may differ depending on actual steel prices, geographical location, corrosion environment, etc.

	ITEM	CBF (*q* =1.5)		CBF (*q* =4)		Star Seismic™ BRBF	
		Quantities	EUR	Quantities	EUR	Quantities	EUR
3-story	Columns (kg, EUR)	31 055	57 762	25 943	48 253	18 482	34 377
	Braces (kg, EUR)	35 124	97 996	16 240	45 309	N/A	82 800
	Frame Beams (kg, EUR)	10 598	19 712	10 598	19 711	9 834	18 292
	Connections (kg, EUR)	15 355	171 366	7 917	73 628	2 832	21 067
	Piles (m, EUR)	960	240 000	512	128 000	256	64 000
	Pile Caps (m^3, EUR)	744	225 857	572	173 643	312	94 714
	Total LFRS costs (EUR):		**812 694**		**488 544**		**315 251**
7-story	Columns (kg, EUR)	86 335	160 583	93 473	173 860	63 478	118 069
	Braces (kg, EUR)	135 903	379 169	63 082	175 999	N/A	338 400
	Frame Beams (kg, EUR)	73 985	137 612	53 016	98 610	53 016	98 610
	Connections (kg, EUR)	59 245	661 170	31 436	292 352	11 649	86 672
	Piles (m, EUR)	1 728	493 714	1 344	336 000	576	144 000
	Pile Caps (m^3, EUR)	1 282	389 057	852	258 643	480	145 714
	Total LFRS costs (EUR):		**2 221 306**		**1 335 463**		**931 465**

Table 6: Lateral force resisting system costs and material quantities

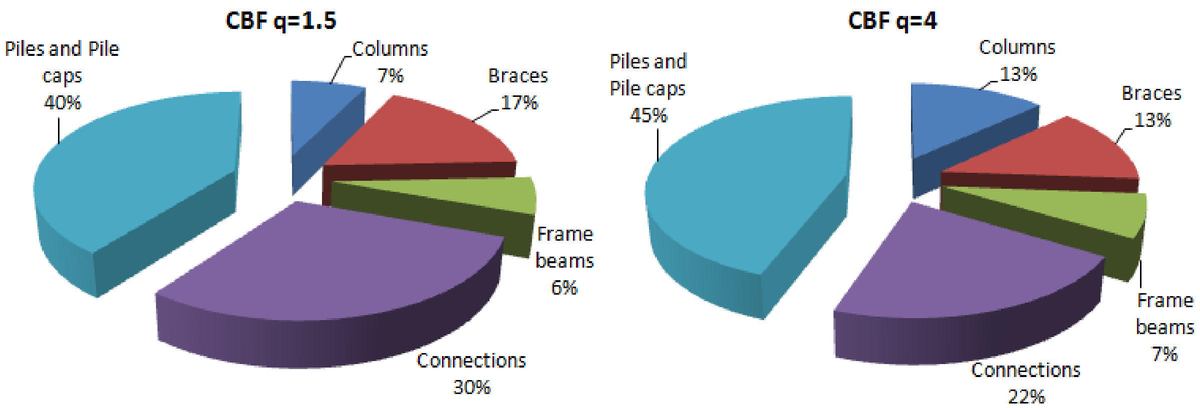
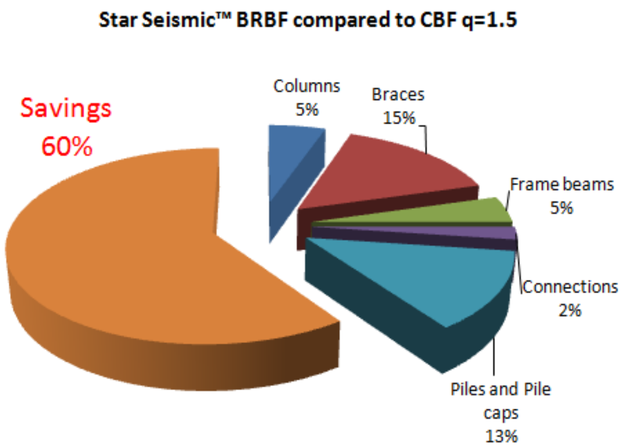


Figure 15: Cost of lateral force resisting system elements, CBF *q*=1.5 and *q*=4

According to Table 7 and Figure 16, significant savings can be realized against both CBF equipped structures by the use of BRBF. Not only lighter columns and beams can be used with the BRBF system due to lower seismic forces, but also significant economic advantage lies in the cost of connections. Since the stable and highly ductile behavior of the braces does not require stiffeners installed in gusset plates, light and easy-to-fabricate gussets can be used saving a considerable amount of material. Most importantly, loads on foundations are notably smaller with BRBF system, therefore the number and length of piles, volume of pile caps are drastically reduced.

	ITEM	Star Seismic™ BRBF savings			
		to CBF (q =1.5)		to CBF (q =4)	
		Quantities	EUR	Quantities	EUR
3-story	Columns (kg, EUR)	12 573	23 386	7 461	13 877
	Braces (EUR)	N/A	15 196	N/A	-37 491
	Frame Beams (kg, EUR)	764	1 420	763	1 419
	Connections (kg, EUR)	12 524	150 299	5 085	52 560
	Piles (m, EUR)	704	176 000	256	64 000
	Pile Caps (m^3, EUR)	432	131 143	260	78 929
	Total LFRS savings:		**497 443**		**173 294**
7-story	Columns (kg, EUR)	22 857	42 514	29 995	55 791
	Braces (EUR)	N/A	40 769	N/A	-162 401
	Frame Beams (kg, EUR)	20 969	39 002	0	0
	Connections (kg, EUR)	47 595	574 498	19 786	205 680
	Piles (m, EUR)	1 152	349 714	768	192 000
	Pile Caps (m^3, EUR)	802	243 343	372	112 929
	Total LFRS savings:		**1 289 841**		**403 998**

Table 7: Material and cost savings of the lateral force resisting system



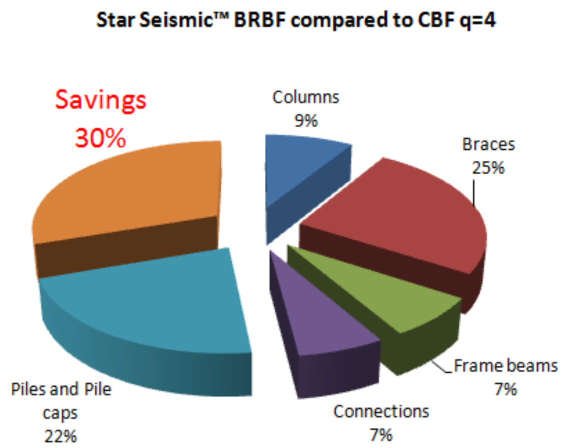


Figure 16: Cost of elements, Star Seismic™ BRBF compared to CBF q=1.5 and q=4

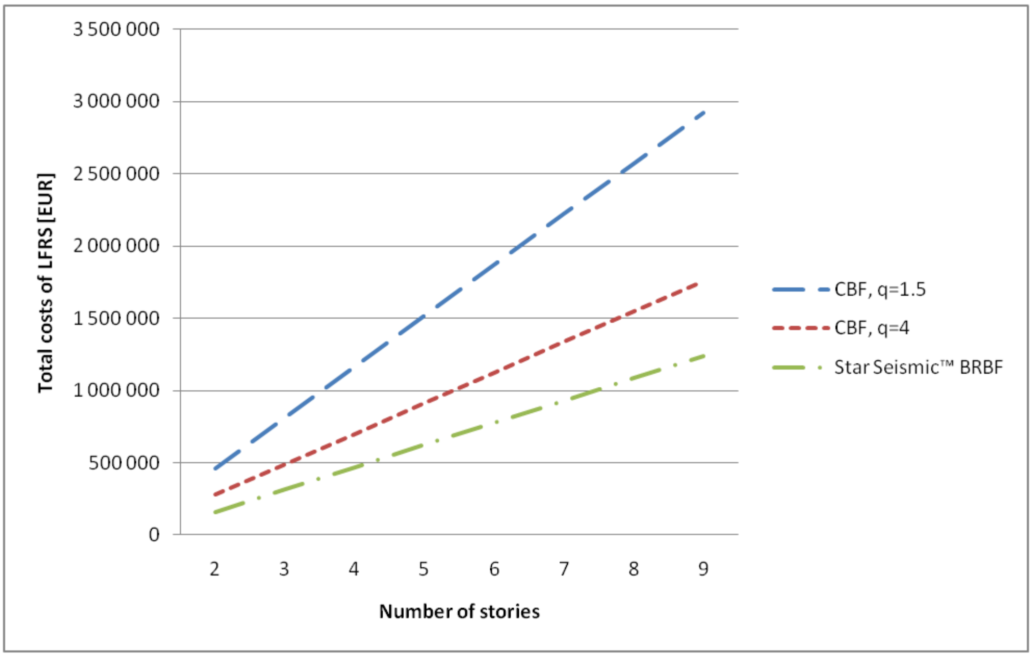


Figure 17: Cost of lateral force resisting system relative to building height

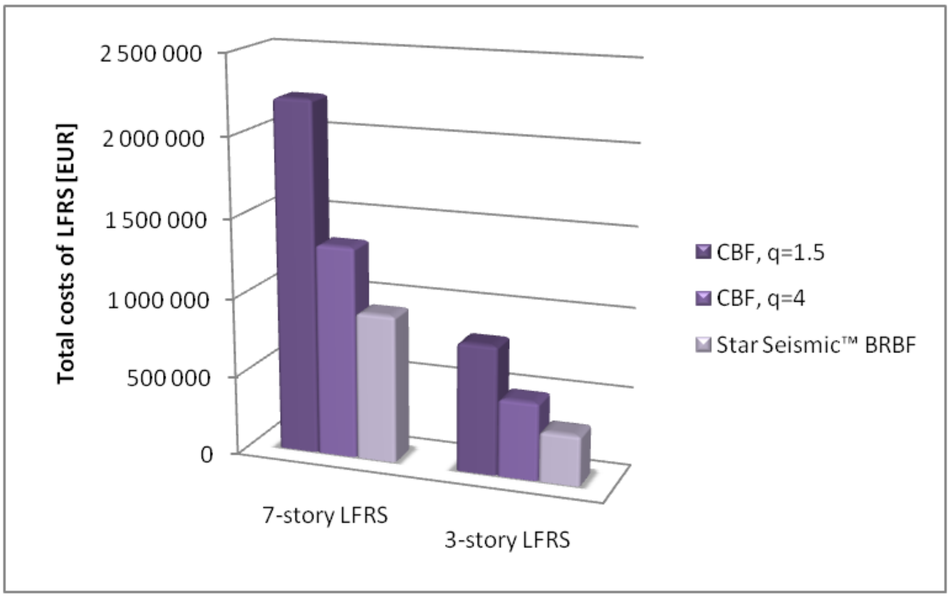


Figure 18: Cost of lateral force resisting system of CBF and Star Seismic™ BRBF buildings

As Figures 17-18 confirm, the amount of savings is proportional to the height of the building. BRBF is a lateral force resisting system with the lowest system cost and the lowest total structural cost (including each and every column, beam, brace, connection and foundation of the building) among the considered solutions. Savings are only realized in the lateral force resisting system as seismic forces are not the governing actions in the rest of the building. Needless to say, in case of structures with relatively high ratio of braced bays, such as technological and industrial structures, total structural cost savings can be almost identical to savings on the lateral force resisting system.

	ITEM	CBF (q =1.5)		CBF (q =4)		Star Seismic™ BRBF	
		EUR	EUR/m^2	EUR	EUR/m^2	EUR	EUR/m^2
3-story	Total structural cost	3 944 694	680	3 620 544	624	3 447 251	594
3-story	LFRS cost	812 694	140	488 544	84	315 251	54
7-story	Total structural cost	9 565 306	703	8 679 463	638	8 275 465	608
7-story	LFRS cost	2 221 306	163	1 335 463	98	931 465	68

	Total structural cost savings with Star Seismic™ BRBF system	
	compared to CBF (q =1.5)	compared to CBF (q =4)
3-story	**86 EUR/m^2**	**30 EUR/m^2**
7-story	**95 EUR/m^2**	**30 EUR/m^2**

Table 8: Unit costs and savings

Table 8 indicates that significant, 30 EUR/m^2 saving can be achieved in comparison to a moderate dissipative, q=4 CBF system. Compared to low dissipative, q=1.5 CBF systems, even higher, 86 EUR/m^2 and 95 EUR/m^2 can be saved in case of the 3-story and 7-story buildings respectively, meaning so significant cost advantages in building construction that may extremely improve design firms' competitive advantage.

Direct material savings are not the only sources of the cost advantages of the system. The erection of smaller structural members means faster and cheaper on-site construction. Further than that, project owner can occupy the building earlier, providing the potential of generating revenue ahead of schedule. Beams, columns and connections are not designed to go through inelastic behavior in case of the design earthquake; seismic energy is dissipated only in the braces. Therefore, if it is needed, only BRB elements should be replaced after a design seismic event, which is much simpler, than the replacement of beams, columns or shear links.

CONCLUSION

This study confirms the cost benefits of using BRBF as a primary lateral force resisting system in comparison to two CBF solutions. Even though the braces are more expensive, a significant amount of money can be saved by using less steel, simpler joints and smaller foundations. Cost differences are especially extreme when comparing BRBF to CBF with limited ductility (q=1.5), but they are also significant when the moderately ductile CBF (q=4) is used for comparison. The results also show that the amount of savings, within the range of investigated structures, is proportional to the height of the building. The investigation of direct investment costs was the main priority of this study, but there are various sources of indirect savings in the construction phase and after greater seismic events as well.

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