

# Limiting slenderness ratio for hollow square braces in special concentrically braced frames

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ABSTRACT: Special concentrically braced frames (SCBFs) are commonly used to resist lateral forces in structures located in high-seismic regions. Steel braces undergo inelastic axial deformations and thus provides an adequate level of structural ductility and hysteretic energy dissipation capability to the frame under cyclic loading. Past studies have shown that the slenderness ratio and the width-to-thickness ratio of braces are primarily responsible for achieving enhanced seismic response in SCBFs. An increase in the brace slenderness ratio results in a reduction in its energy dissipation capacity along with a simultaneous increase in the ductility nearing its fracture. Since both energy dissipation capacity and ductility of braces are essential parameters in quantifying the seismic performance of SCBFs, there is a need of establishing the optimum range of brace slenderness ratio and width-to-thickness ratio. The main objective of this study is to find an optimum range as well as the lower limits of these parameters for braces of hollow square steel (HSS) sections. An extensive finite element (FE) parametric study has been conducted on a wide range of values of these parameters using a commercial software package ABAQUS. The FE models accounts for the inelastic hysteretic characteristics and the fracture behavior of braces. The results of simulation models matched very well with the past experimental results with respect to the performance points, namely, global buckling, local buckling, fracture initiation, complete fracture and ductility. Finally, the relationship between the lower limit of slenderness ratio and the width-to-thickness of square braces has been established based on the simulation results.

## 1 INTRODUCTION

Special concentrically braced frames (SCBFs) are one of the most economical lateral load resisting systems used in buildings worldwide. These frames provide adequate lateral strength, and stiffness to the structural systems so that they meet the serviceability and operability criteria for small frequent earthquakes and failure criteria for high infrequent type earthquakes. Conventional steel braces provide adequate energy dissipation and ductility to the structural system through their inelastic deformations to resist the earthquake forces effectively. The design of SCBFs is carried out in such a way that all the inelastic activities are concentrated only in the braces without any severe damages to the primary frame members of the structural systems. Thus, the primary frame members remain essentially elastic to resist the gravity loads. Over the years, many studies have been conducted to provide a framework for the selection of braced frame sections and their configurations (Bruneau et al., 2011), optimizing the gusset plate connections (Roeder et al. 2011), and design of support systems, such as, beams and columns, in order to achieve the desired seismic performance. The hysteretic response of braces depends on various parameters, such as, brace configuration, brace cross-section, loading history, loading rate, boundary conditions, and material property. However, optimum brace performance under seismic loading conditions largely relies on the slenderness ratio and width-to-thickness ratio (Tremblay, 2002).

Past studies focussed on understanding the influence of these parameters have yielded the following conclusions: (i) As the brace slenderness ratio increases, its energy dissipation capacity decreases. (ii) As the slenderness ratio increases, the ductility nearing the brace fracture increases. (iii) The width-to-thickness (B/t) ratio is responsible for the initiation of local buckling. The brace fracture is directly influenced by the amplified localized strain developed due to the combined action of global as well as local buckling during reversed cyclic loading. (iv) For a value of B/t ratio, which satisfies the compactness limits set by the codes, the braces with lower slenderness ratio may have premature fracture. Based on these observations, various international codes specify the limits of slenderness ratio and width-to-thickness ratio. These values have been revised many times following the increase in knowledge of brace response through experimental and analytical studies. Currently, ANSI/AISC 341-

10 (2010) sets the upper limit for brace slenderness ratio as 200. This value has been set considering the minimum amount of energy dissipated in the compression cycle so that the brace does not act as a tension-only member. On the other hand, some, brace configuration specific guidelines are available on the lower limit of the brace slenderness ratio. From the past studies, it has also been concluded that as the slenderness ratio is decreased, the force demand on the gusset plate and supporting members is increased. These observation have led way to the notion that a single limit on slenderness ratio or width-to-thickness ratio for sections may not provide an optimum performance of brace. Hence, there is a need for further investigation on the limits of these parameters of braces for enhanced seismic performance.

Square / Rectangular hollow steel (HSS) sections are the most widely used sections for braces. Ease in providing connection and easy availability with a wide range of geometrical properties makes these sections a default options for engineers worldwide. The number of experimental investigations on these braces surpass the numbers on other type of cross section like hollow circular and W section. It needs to be mentioned that the experimental work done so far have highlighted many aspects of the brace response but there are still many questions that remains to be answered to make SCBF an efficient lateral load resisting system. Results have shown that there is a higher tendency for square/ rectangular HSS braces to undergo fracture. Fracture in a brace as mentioned earlier is caused by the stress concentration due to the combined effect of global as well as local buckling and these two phenomenon are directly related to the slenderness ratio as well as width to thickness ratio of the brace. Hence, an extensive numerical simulation has been carried out for a wide range of slenderness ratios and width to thickness ratio of square HSS brace sections using a finite element (FE) software ABAQUS (2004) considering the global buckling, local buckling, fracture initiation, and complete fracture of braces into account. The analysis will further shed light on the relationship of slenderness ratio, width to thickness ratio for the optimum response of brace.

## 2 ANALYTICAL STUDY

Analytical models of hollow-square braces of varying slenderness ratios and width to thickness ratio have been developed in a commercial software package ABAQUS (2004) environment. All these models consider the effect of gusset plate connections in addition to the inelastic characteristics of brace material. The length of the braces has been kept a constant in the parametric study while varying the brace cross-section. The details of brace modelling, loading history, design approach and analysis results are discussed in the following sections.

## 2.1 Modelling of Braces

Four/eight-nodded doubly-curved shell (S4R or S8R) elements with 6-degrees of freedom at each node with reduced-integration and large-strain formulation was used to model the braces (ABAQUS, 2004). The shape metrics was checked for each model considering the face corner angle and aspect ratio. A damage plasticity model was used to model the behaviour of spatially concentrated steel braces subjected to cyclic loading conditions. The plasticity model included the nonlinear isotropic and kinematic hardening behavior, which was explicitly integrated with the damage model for modelling the low-cycle fatigue. A single set of parameters was required for the combined hardening law which would be able to simulate the behaviour of the specimen well. Since the validation of the ABAQUS model was to be done with a previous research data (Fell, 2008) the material model assumed in that study has been assumed here also. The values are as given in Table 1.

Table 1. Calibrated Kinematic and Isotropic hardening parameters

	$\sigma_y$ (MPa)	C (MPa)	γ	$Q_{\infty}(\mathrm{MPa})$	b
Brace Corner	504	5861	160	100	5.25
Brace Wall	469	2069	25	69	6
Gusset	345	3448	38	118	5

The welding connections between the brace and the gusset plate were not modelled explicitly in this study. Instead, a rigid connection between them was assumed in the analysis. The meshing pattern

consisted of a transition from the fine meshing at the mid-section of braces to a coarser meshing in the remaining regions. Further, the fine meshing was used in the plastic hinge regions of the gusset plates. Fig.1 shows the mesh pattern adopted for the modelling of braces. Rigid (fixed) boundary conditions are imposed on the ends of both gusset plates. Initially a buckling analysis was performed on the brace to obtain the mode shape that was applied as linear perturbation in the nonlinear analysis of braces. The magnitude of initial perturbation used to predict the buckling of braces was kept as L/1000 for all braces, where L is the length of braces. Later, brace models were subjected to a gradually-increased reversed-cyclic displacement as per a pre-defined loading history(discussed later).



Figure 1. Finite element mesh pattern used in the brace modelling.

### 2.2 Loading Protocol

Fell (2008) studied the influence of loading histories representing the far-field as well as near-field earthquakes on the performance of braces through large-scale component testing. This study concluded that the far-field ground motions proved more critical for the desired brace performance as compared to the near-field earthquakes. Hence, the standard cyclic loading protocol as per ATC-24 (1992) guidelines has been used in this parametric study. This chosen protocol is based on the non-linear time history investigation of the structural systems, which matches with the realistic demands in the system under the earthquakes. As shown in the Fig. 2, the loading protocol consists of three elastic steps comprising of six drift cycles each, followed by four cycles corresponding to the onset of inelasticity in the system. In this case, the onset of inelasticity was considered as the initiation of brace buckling under the compressive loading. In total 9 cyclic loading steps were applied with a maximum brace deformation in this study fixed corresponding to a story drift of 5% as recommended by Sabelli et al. (2013). However, there are several instances where the results have been presented beyond this drift value as well.



Figure 2.Standard cyclic loading protocol used in this study

#### 2.3 Design of Brace for Parametric Study

The objective of this parametric study warranted the selection of proper braces with varying slenderness and *B/t* ratio. The brace slenderness ratio was varied from 50 to 200. The lower limit of 50 was based on the brace sections observed from the earlier designs and the upper limit of 200 was based on the limiting values of slenderness ratio as specified in ANSI/AISC 341-10 (2010) provisions for SCBFs. Similarly, the value of *B/t* ratio was varied from 7.5 to 20. The width of the section, *B*, used in the above calculation was taken as B-3t, which is the overall width of the brace section minus three times the thickness of the brace. As per the code, for this study the upper limit of B/t ratio can be found to be 11.16. Since the section sizes required to satisfy the required values of slenderness ratio and B/t ratio of braces were not available in the AISC Shapes Database V14.1, imaginary sections were considered for this parametric study. The width and thickness of brace sections were altered to arrive at the desired sectional properties. This was done to be consistent with the realistic design procedure where the constant floor height of the building would result in same brace length. The gusset plate was also modeled along with the braces so as to consider the influence of gusset plate yielding on the overall cyclic performance of braces. The sizes of gusset plates were fixed using a balance design procedure proposed by Roeder et al. (2011) so as to prioritize the yield and failure mechanisms such that the undesirable behavior of the gusset plates would be avoided. Although this design procedure has not been adopted in the current AISC code provisions, past experimental studies have shown this method to yield better performance of SCBFs under seismic loading conditions.

#### 2.4 Validation of Analytical Model

The analytical model used for the parametric study was validated with the results of experimental study conducted by Fell (2008). Material properties, section dimensions, and loading cycles in the analytical models were kept exactly same as used in this past experimental study. Fig. 3 shows the comparison of analytical hysteretic response of braces with that obtained from the experiment. The predicted hysteretic loops matched very well with the test results at each drift cycle. In terms of the critical performance points in the brace hysteretic response, the global buckling of braces was the first phenomenon to be initiated, followed by the brace yielding in tension, local buckling, fracture initiation and complete fracture. The value at which the commencement of inelasticity in the brace, i.e. global buckling in compression, initiated matched for both the analytical as well as experimental result. The onset of local buckling in the brace was observed visually during the simulation and the drift corresponding to the same phenomenon in the experimental study matched accurately. Although a minor variation in the response of the brace was noticed in the final stages between the analytical and experimental results, the drift value at the occurrence of fracture initiation and the complete fracture matched perfectly. The minor variation in the results can be attributed to the meshing arrangement of the brace as well as the fracture evolution model incorporated in the simulation study. This validated simulation model was used in the subsequent parametric studies to understand the brace response for varying values of slenderness ratio as well as *B/t* ratio.



Figure 3. Comparison of predicted hysteretic response with the test results.

#### **3 RESULTS**

The hysteretic response of braces for slenderness ratio value of 70,120 and 180 for varying *B/t* ratio (7.5, 10, 15 and 20) has been shown in Fig. 4. Since the parametric study consists of more results only these three have been shown here. As per the current code provisions and the material property used for the parametric study the limiting B/t ratio for this study is calculated to be 11.16. As it can be seen that for varying slenderness ratio the brace with 7.5 as B/t ratio gives higher energy dissipation capacity. Also the concentration of stresses due to local buckling of brace did not deteriorate the performance of brace with smaller B/t ratio, whereas the brace with B/t ratio greater than 10 underwent fracture at quite an early stage. These results also show the increasing strain hardening effect in the brace for higher slenderness ratio, it was seen that the brace with lower slenderness ratio dissipates more energy than higher slenderness ratio. This matches with the previous findings but does not conclusively say the optimum range of slenderness ratio to be selected for designing a brace in a structural system.



Figure 4.Hysteresis Curve for (a) Slenderness Ratio 70, (b) Slenderness Ratio 120, c) Slenderness Ratio 180

The plot of cumulative hysteretic energy for each loading step with respect to the axial strain developed in the brace is as shown in Fig. 5. From this it is clear that by using a B/t ratio of 7.5 there is no degradation in the energy output for slenderness ratio more than 120. For a brace which failed for a lower slenderness ratio there seems to be an increase in its ductility once the slenderness ratio is increased, even though it needs to be mentioned that the quantity of the energy dissipated is less as the slenderness ratio is increased. Also looking at the current design code (ANSI/AISC 341-10) which provides the compactness limit for this study as 11.16 gives higher cumulative energy after sustaining 4% story drift only after a slenderness ratio of 160. The energy dissipation capacity of braces with B/t ratio 15 and 20 were very low and were subjected to premature fracture in almost all cases.



Figure 5. Cumulative Energy dissipated vs. Axial Strain for (a) Slenderness Ratio 70, (b) Slenderness Ratio 120, c) Slenderness Ratio 180

The next parameter to aid in finding the optimum range is the ductility of the brace. Displacement ductility of braces can be computed as the ratio of the maximum displacement prior to fracture to the corresponding yield displacement. Because of the unsymmetrical hysteretic response of HSS braces, displacement ductility is computed separately in both tension and compression sides of cyclic loading. Fig. 6 shows the variation of displacement ductility with B/t ratio and slenderness ratio of braces. As shown in Fig. 6(a), the compression displacement ductility of the braces increase nearly exponentially with the increase in the slenderness ratio. Further, the compression ductility of braces for a single slenderness ratio is found to be nearly a constant for a range of B/t ratio. For example, for a constant slenderness ratio of 50, braces having B/t ratio greater than 10 exhibited a compression ductility of 10 which increased to only a value of 15 for those having B/t ratio less than or equal to 10. For brace slenderness ratio greater than 140 and B/t ratio less than or equal to 10, no reduction in the compression ductility of the braces is noticed. However, as shown in Fig. 6(b), the tensile displacement ductility not only varies significantly with the slenderness ratio but also with the compactness ratio. It needs to be understood that maximum quantity of energy is dissipated by the tension brace and it needs to be ensured that these braces have adequate ductility to survive the high drift value imparted to it by the seismic activity. It is seen that appreciable ductility in the tension cycles is noticed for all the values of slenderness ratio if the compactness ratio value is smaller than 10. For compactness ratio above 15, there is a variation in the ductility level obtained, this is in accordance with the B/t ratio limit specified in the code. B/t ratio of 7.5, which is lower than the limit specified for the material assumed here gave maximum ductility for all slenderness ratio values. For B/t ratio 10, which is closer to the code specified limit, showed higher ductility after a slenderness ratio of 140. Even though the braces with lower B/t ratio showed higher ductility, all the braces showed different levels of brace fracture stages nearing the 5% story drift level. This re-affirms the findings from other experiments that the square /rectangular HSS braces has higher chances of undergoing fracture due to the stress concentration developed at the corners of the brace.



Figure 6. Variation of brace ductility with width-to-thickness ratio and slenderness ratio in (a) compression cycles and (b) tension cycles

#### **4 OPTIMUM RANGE OF SLENDERNESS RATIO**

Both energy dissipation potential and displacement ductility criteria have been considered in establishing the limiting values of brace slenderness ratio as well as compactness ratio. Fig. 7(a) shows the variation of energy dissipation potential of braces for varying B/t ratio as well as slenderness ratio. The cumulative energy dissipated for the entire load cycle of braces is reduced from 1700kNm for slenderness ratio of 50 to nearly zero value for the brace slenderness ratio of 200. Similar variation in the cumulative energy is noticed for varying B/t ratio in the smaller values of slenderness ratio. This shows that brace of slenderness ratio greater than 150 and of B/t ratio larger than 10 may not be preferred to be used in SCBFs and hence, these respective values can be considered as upper limits in SCBFs. This base line has been created from the analytical study with a brace length of 3m so the energy dissipation value will differ for different length. So to establish a range of slenderness ratio and B/t ratio

the energy dissipation as well as ductility has been considered together. From the previous Fig. 5, for a fixed value of B/t, the minimum slenderness ratio at which the brace gives positive energy dissipation till the end of 3% drift can been considered as the required response. From this, based on the cumulative energy dissipation criteria, a plot between the upper limit of B/t ratio for the slenderness ratio of braces is drawn as shown in Fig. 7(b). A curve-fitting procedure is adopted to establish the relationship between the minimum value of slenderness ratio ( $\lambda$  min) and B/t ratio. The exponential relationship in Equation (1) shows the best-fit curve with a  $R^2$ -value nearly equal to unity. This equation is valid for value of B/t ratio of square HSS braces varying between 7.5 and 20. If positive energy dissipation contribution is required till the end of 4% story drift then equation (1) changes to equation (2). So from Fig. 7(b), for a value of B/t closer to the code upper limit, i.e. 10, the value of minimum slenderness ratio for an optimum performance for a 3% story drift is 80 but by opting for a reduced B/t of 7.5 the usable slenderness ratio lower limit can be reduced to 50. From equation (2) for obtaining an optimum performance from the brace with B/t = 7.5, for a story drift of 4%, the minimum slenderness ratio required is 90. This value increases for higher B/t values. The equations mentioned (1 & 2) for positive energy dissipation potential for a particular drift value is specific for square hollow steel section. This equation will vary for other steel cross section (Kumar et al. 2015). The above discussed inclusion of ductility and energy dissipation into the brace design needs to looked very closely with respect to the design of the SCBF system as this procedure will definitely enhance the performance of the system.

$$\lambda_{min} = 24.865e^{0.1053(B/t)}$$

$$\lambda_{min} = 43.23e^{0.1036(B/t)} \tag{2}$$

(1)



Figure 7. (a) Variation of cumulative energy with B/t ratio and slenderness ratio, (b) Interaction between the maximum value of B/t ratio and the minimum value of slenderness ratio for optimum response at 3% story drift

#### 5 CONCLUSIONS

Based on the simulation results, the following conclusions can be drawn:

• Square HSS braces with B/t ratio of 7.5 showed maximum dissipation in energy but still underwent energy degradation post the 4% story drift level, for slenderness ratio less than 120.

• Considering the energy dissipation potential and ductility of braces, the maximum value of B/t currently adopted for square HSS section can be reduced further as the section with B/t 7.5 showed better ductility and energy dissipation capability than B/t 10 which is closer to the code specified limit. The comparison with the previous experimental results supports this fact.

• Based on the analytical results, a simple best-fit exponential equation has been proposed to establish

a relationship between the limiting values of slenderness ratio and B/t ratio for having positive energy dissipation and optimum ductility, e.g., minimum slenderness ratio of 50 for a maximum B/t ratio value of 7.5 for a peak response at 3% story drift level and likewise minimum brace slenderness of 90 for a maximum B/t ratio value of 7.5 for a peak response at 4% story drift level.

• Maximum slenderness ratio of 150 for all B/t ratio based on energy dissipation capability such that the brace does not act as a tension only member.

• Braces with B/t ratio of 15 and 20, which are higher than the code specified limits, exhibited low energy dissipation capacity because of pre-mature fracture during the inelastic loading cycles.

• The ductility of the brace with respect to the change in slenderness ratio and width to thickness ratio needs to be accounted for in design to obtain a high response SCBF system.

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