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Limiting values of slenderness ratio for circular braces of concentrically braced frames

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ABSTRACT

Special concentrically braced frames (SCBFs) are commonly used to resist lateral forces in the structures located in high-seismic regions. Steel braces of SCBFs are expected to undergo large inelastic axial deformations in order to provide an adequate level of structural ductility and hysteretic energy dissipation under cyclic loading. The energy dissipation capacity and ductility of SCBFs largely depend on the slenderness ratio and width-to-thickness ratio of braces. The main objective of this study is to find an optimum range of these parameters for braces of hollow circular steel (HCS) sections in order to achieve the enhanced seismic performance of SCBFs. A finite element (FE) study has been conducted on a wide range of values of these parameters using a software package ABAQUS. The FE models account for the inelastic hysteretic characteristics and the fracture behaviour 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, and complete fracture. Finally, a relationship has been established between the slenderness ratio and the width-to-thickness of HCS braces based on the simulation results.

1. Introduction

Concentrically braced frames (CBFs) are one of the most economical lateral force-resisting systems (LFRS) used in the buildings worldwide. These frames provide adequate lateral strength and stiffness to the structural systems to meet the serviceability and operability criteria under the frequent minor earthquakes and the failure (collapse) criteria under the infrequent major earthquakes. Conventional steel braces provide adequate hysteretic energy dissipation and displacement ductility through their inelastic axial deformations, which help the CBFs to resist the seismic actions effectively. The structures located in high-seismic regions are subjected to high ductility and energy dissipation demand. Hence, the design of special concentrically braced frames (SCBFs) is carried out in such a way that the large inelastic activities are mostly concentrated only in the braces without any severe damages to the primary frame members (i.e., beams and columns) of the structural systems. Over the years, many studies have been conducted to provide a framework for the selection of braced frame sections and their configurations [1–3], the optimization of gusset plate connections [4–9], and the design of beams and columns [10–13] in order to achieve the desired seismic performance of SCBFs. The hysteretic response of braces depends on various parameters, such as, brace configuration, loading history, rate of loading, brace infill, boundary conditions and material property. However, the optimum performance of braces under cyclic loading conditions largely relies on their slenderness ratio, width-to-thickness ratio, and cross sectional shapes [14–23]. The results of these studies have shown that the increase in brace slenderness ratio results in the reduction of energy dissipation capacity of braces, whereas it increases the ductility nearing their fracture. The past studies have also shown that the width (or diameter)-to-thickness (b/t or D/t) ratio is mainly responsible for the initiation of local buckling of braces and brace fracture is directly influenced by the amplified localized strain developed due to the combined action of global and local buckling under the reversed cyclic loading. For a given value of D/t ratio, braces with lower slenderness ratio may undergo premature fracture due to local buckling effects.

Various international codes specify the limits of slenderness ratio and width-to-thickness ratio of braces in order to achieve an appreciable level of energy dissipation and ductility. The American code ANSI/AISC 341-10 [24] specifies an upper limit of brace slenderness ratio as 200 for SCBFs. The lower and upper limits of non-dimensional slenderness ratio specified by the Eurocode EC8 [25] are 1.3 (for diagonal X-braces only) and 2.0, respectively. While the upper limits of brace slenderness ratio are provided to ensure that these braces do not act as tension-only members and a minimum amount of energy dissipation is achieved in the compression regions of cyclic loading in the event of earthquakes [26,27], the lower limit of brace slenderness ratio has been put in place to protect the columns from being overloaded during the pre-buckled stage of brace loading. Similarly, the limiting values of diameter-to-thickness (compactness) ratio specified in various codes [e.g., 24,25,28] are intended to provide a minimum level of brace

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ductility prior to their fracture under the design level of seismic performance of SCBFs. Though these provisions include the effects of global buckling, local buckling and low-cycle fatigue life of braces, a unique range of parameters may not be applicable for all types of braces considering the fact that the optimum range of brace slenderness ratio depends on the compactness criteria and configuration of braces. Further, very limited test data is available on the cyclic response of braces of hollow circular steel (HCS) sections [17,18,33–35]. Hence, there is still a need of further research to investigate the optimum range of slenderness ratio and diameter-to-thickness ratio for HCS braces.

2. Research significance

Hollow square steel (HSS) sections, HCS sections and wide-flange sections are commonly used as braces in SCBFs. HSS sections are more prone to the premature fracture as compared to both wide-flange and HCS sections under cyclic loading conditions [14,15,18,23,29–31]. This is primarily due to the high concentration of strains at the corners of tubular brace sections during the fabrication process [3]. Though the wide-flange brace sections are relatively more ductile as compared to the HCS sections, the HCS sections are preferred to wide-flange sections in SCBFs because of the simpler connection details and the availability of wide range of sections satisfying the strength and compactness criteria requirements of SCBFs [18,23,32]. Further, the gradually changing radii of the HCS sections allow for the gradual and minor reduction in their fracture toughness as compared to the HSS sections. Therefore, there is a need for further research on the cyclic response of HCS brace sections of varying slenderness ratios and diameter-to-thickness (D/t) ratios. Hence, an extensive analytical investigation has been carried out in this study for a wide range of slenderness ratio and D/t ratio of HCS brace sections using a finite element (FE) software ABAQUS v.6.10 [36]. The analytical models consider the effects of global buckling, local buckling, fracture initiation, and complete fracture of braces in order to capture their more-realistic cyclic performance.

3. Analytical study

Three-dimensional continuum FE models of HCS braces are modelled in the ABAQUS v.6.10 [36] environment. All these models consider the effect of gusset plate connections in addition to the inelastic characteristics of brace material. A wide range of slenderness ratio and D/t ratio of HCS braces are considered in the analytical study by varying the cross-sections for a constant length of braces. The details of brace modelling, material property, loading history, design approach and analysis results are discussed in the following sections.

3.1. Modelling of braces

The constitutive relationship, continuum elements, large displacement formulations, and the occurrence of local as well as global buckling are incorporated in the simulation models of HCS braces. Doubly-curved shell elements with six degrees-of-freedoms (DOFs) at each node with the reduced-integration and large-strain formulation are used to model the braces and gusset plates. Four nodded shell (S4R) elements are used in the analytical model in order to capture the local buckling and fracture behaviour of braces. The welding connections between the brace and the gusset plates are not modelled explicitly in this study. Thus, a rigid connection between the brace and the gusset plates is assumed in the simulation models. As shown in Fig. 1, the meshing pattern consists of a transition from the fine meshing at the mid-length of braces to a coarser meshing in the remaining regions. In addition, the fine meshing has been used in the end regions of gusset plates where the inelastic deformation is expected because of the out-of-plane deformations of braces under the cyclic loading. Rigid (fixed) boundary conditions are imposed at the ends of gusset plates. The shape metrics for the FE meshes are checked for each model considering the face corner angle varying between 30°–160° and aspect ratio value being less than twenty.

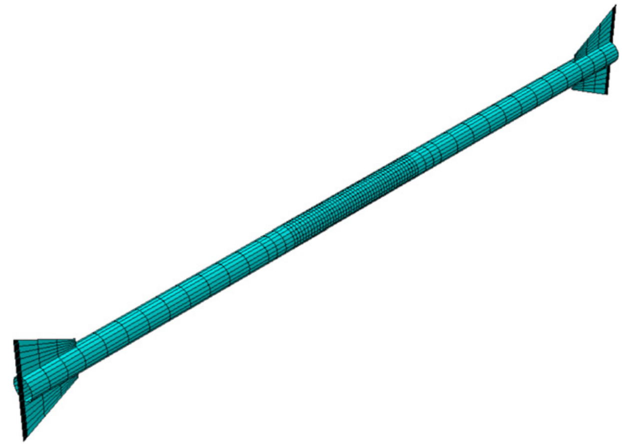

Fig. 1. Finite element mesh pattern used for the brace modelling in this study.

Brace dimensions are varied in order to satisfy the desired range of slenderness ratio and D/t ratio considered in this parametric study. The size of gusset plates and the detailing of connections play an important role in the cyclic performance of braces [5]. In order to evaluate the effect of slenderness ratio on the cyclic behaviour of braces, it is important to include the effect of gusset plate connections. The design of gusset plates for each brace section in the parametric study has been carried out using the recently developed "Balanced design" procedure proposed by Roeder et al. [5]. This design procedure ensures that a desired ductility level is achieved by the braces by allowing the inelastic deformation of gusset plate and by prioritizing the sequence of yielding in braces and gusset plates. In order to verify this progressive yield mechanism, a component testing was conducted on HSS brace sections in the present study. Table 1 shows the cross-sectional dimensions of the HSS brace used in this experimental investigation. The design of braces and gusset plates was carried out assuming a material yield strength of 300 MPa. The loading protocol applied to the specimen is the same as that applied to the simulation model and is discussed in the later section. A gradually-increasing cyclic loading was applied to the brace till a brace strain of 1.1%, corresponding to a storey drift of 1.7%, assuming an angle of inclination of brace as 45°. However, the tensile coupon test results showed that the material yield strength of the brace was 500 MPa. As a result, the axial resistance of the brace exceeded the rated capacity of the servo-hydraulic actuator used to apply the cyclic displacements. Thus, the testing beyond this drift level was not carried out. Fig. 2(a) shows the hysteretic response of the test specimen. Brace buckling was noticed at the mid-span regions as shown in Fig. 2(b). In addition, the yielding of gusset plate during the cyclic response of braces was noticed in the clearance zone as shown in Fig. 2(c). Even though the design and detailing of gusset plate was carried out for a nominal yield stress of 300 MPa, the expected yielding mechanism was noticed in the experimental investigation even for the braces made of high-strength steel. The test results showed that the

Table 1
Geometric details of brace used for cyclic study.

Sl. no.	Brace size	Brace length	b/t	Slenderness ratio[a]	Gusset plate size
SS-01	HSS38 × 38 × 4.0	2300	7.5	169 (0.85)	138 × 98 × 6

b = width; t = thickness; all dimensions are in millimetres.
[a] Value in parenthesis represent the ratio of the specimen's slenderness ratio to the limit specified in AISC 341-10 [24].