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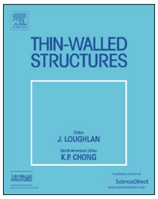

Full length article

# Fracture ductility of hollow circular and square steel braces under cyclic loading

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ABSTRACT

Steel braces of a concentrically braced frame (CBF) undergo inelastic cyclic axial deformations under earthquake loading to result in the hysteretic energy dissipation in a structure. However, the occurrence of low-cycle fatigue fracture of these braces significantly reduces the effectiveness of CBFs in dissipating the input seismic energy. Additionally, inaccurate quantification of fatigue fracture may lead to erroneous result interpretation of the collapse performance assessment of braced frames using numerical analysis tools. Hence, in this study both experimental and numerical studies have been carried out to accurately quantify the fracture ductility of braces of hollow circular (HCS) and square (HSS) sections under cyclic loading conditions. Experimental studies have been conducted for varying values of slenderness and width (or diameter)-to-thickness ratio of braces. Parametric study results from the validated simulation models have been used to verify the efficacy of the available empirical relations for the prediction of fracture ductility of HSS brace sections. Additionally, an expression for fracture ductility relating the slenderness ratio and diameter-to-thickness ratio has been proposed for HCS braces using the numerical model results. These expressions and numerical results have been compared with the past and present experimental results to highlight the efficiency of the available as well as the proposed empirical methods.

## 1. Introduction

Concentrically braced frames (CBFs) are considered as one of the most cost-effective lateral force-resisting systems in structures located in the seismic regions due to high lateral strength-to-weight and stiffness-to-weight ratios. Conventional steel braces in CBFs provide the desired lateral strength, stiffness, and ductility under lateral loading. However, low-cyclic fatigue fracture of these braces and concentration of damage in frame members at a particular story level (i.e., soft-story mechanism) have raised apprehensions on the efficiency and adequacy of these systems in the event of earthquakes [1–9]. Steel braces are the primary energy dissipating elements in a CBF and hence, they should have adequate ductility prior to their fracture under seismic loading. In order to ensure the ductile behavior, current design codes of practice specify the limiting values of width-to-thickness ratio of brace cross-sections [10]. Several past studies [11–14] have concluded that these braces may suffer from the low-cycle fatigue fracture even when the brace cross-sections satisfied the width-to-thickness ratio requirements of design codes. The occurrence of brace fracture has been understood to be not only dependent on the width-to-thickness ratio of cross-sections, but also on slenderness ratio of braces [1,2]. Stress concentration at a particular location due to the combined effects of global and local buckling results in the fracture of braces; however, it is very difficult to incorporate the effects of local buckling and subsequent interaction of stresses and strains into a fracture prediction model.

The methods of predicting brace fracture have evolved over the years with the early studies mostly focused on establishing the empirical and semi-empirical relations based on the limited test results [11,12,15–17]. In these studies ductility was expressed as a sum of cumulative normalized axial deformation in compression and tension until the brace failure. Tang and Goel [18] deviated from this approach and expressed the fracture ductility in terms of standardized number of cycles until fracture. With the advent of better computational tools, attempts have been made to predict the brace fracture more precisely. Analytical studies relying on rule-based brace models [19–21] and concentrated hinge brace models [22,23] are found to be inept at simulating the localized behavior of braces and the spread of inelasticity across the length and brace cross-section. Even though improvements have been made in such models [24], both fiber-based [13,25] and continuum-based [14,26–29] modelling of braces have shown to be

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effective in predicting the local buckling and other inelastic behavior of braces more reasonably. Notably, Karamanci and Lignos [25] used the fiber-based brace simulation model in which the brace fracture was modelled using the fatigue material model developed by Uriz [13]. This fatigue failure model is based on the linear accumulation of strain as per the Coffin-Manson relationship [30]. Even though, the findings are promising for a range of geometrical parameters of brace sections, the core of this approach lies in the empirical calibration of fracture parameter using previous experimental results. The phenomenon of ductile fracture of braces can be related to the void growth and coalescence [31]. Kanvinde and Deierlein [26] proposed a cyclic void growth model based on the micro-mechanics of void growth [32] under cyclic loading. Although this model does not employ the empirical relationships, it is laborious to be adopted in the real practice. However, this model can be effectively used for different geometrical configurations of braces, loading histories and steel types.

Current design codes recommend the limiting values of width-to-thickness ratios for braces to achieve a desired level of ductility and yield mechanism. However, no specific guidelines are available to predict their low-cycle fatigue fracture capacity under seismic loading. Further, in many cases, steel braces satisfying the requirements of slenderness ratios and width-to-thickness ratios have fractured prematurely under the cyclic loading. Hence, it is necessary to quantify the low-cyclic fatigue capacity of braces in order to carry out accurate collapse-performance assessment of braced frames. In this paper, the term “fracture life” as used in previous studies has been replaced by “fracture ductility” to highlight the brace fracture as a function of steady deformation capacity rather than number of cycles.

## 2. Objectives and scope of this study

The main objective of the present study is to develop a simplified expression to predict the fracture ductility of hollow circular steel (HCS) and assess the available methods for hollow square steel (HSS) braces. The disparity between the objectives of HCS and HSS section is due to the reason that there are many empirical methods developed for HSS sections, whereas very few have been developed for HCS sections. Further, the fracture ductility evaluated here is not considered at the complete fracture of the brace but at a lower value. This lower value represents a more reliable quantity that is devoid of the uncertainty observed from the point of initiation of fracture to the complete fracture of the brace. Both experimental and numerical studies are utilized to investigate the low-cyclic fatigue fracture behavior of steel braces. Initially, a slow-cyclic testing has been carried out on selected steel braces to investigate their overall hysteretic response and fracture ductility. The prediction of fracture ductility is carried out based on the uncoupled phenomenological fracture initiation numerical model [5,33–35], which has been validated with a past experimental study [14]. In the present study, the analysis results of the extensive parametric study [5,33] based on the validated simulation model is used to verify the efficacy of the available empirical relations for prediction of ductility for HSS brace sections. In addition, an expression for fracture ductility relating the slenderness ratio and diameter-to-thickness ratio has been proposed for HCS braces. Finally, the empirical relations for predicting the fracture ductility have been compared with the past and present experimental results to highlight the efficiency of the available as well as proposed methods.

## 3. Experimental study

Nine steel brace specimens were selected for the experimental investigation in this study. These specimens were subjected to gradually increasing reversed-cyclic displacements until their fracture. The main objective of this experimental study was to investigate the inelastic cyclic response of braces, to enhance the global database of experimental results on HCS sections and, more importantly, to assess the accuracy of the fracture prediction model described later in this paper. The main parameters investigated in the experimental study were the hysteretic response, cumulative energy dissipation potential, displacement ductility, and failure mechanism of test specimens. The details of test specimens, material properties, test setup, instrumentation, and loading history are provided in the following sections:

### 3.1. Test specimens

Six HCS brace specimens of material properties conforming to the Indian Standard [36] specifications were selected for the experimental study. The values of slenderness ratio (λ) and diameter-to-thickness (*D/t*) ratio of the selected HCS sections were varied in the range of 76–213 and 11–28, respectively. Since extensive test results are already available in the literature for HSS braces, only three HSS sections conforming to the Indian Standard [37] specifications were selected in this study for the comparison purpose. The values of slenderness ratio and width-to-thickness (*B/t*) ratio of HSS specimens were varied in the range of 94–169 and 8–18, respectively. The effective length of all test specimens was taken as 2300 mm. Section properties of specimens were altered to get the desired range of slenderness ratio and width (or diameter)-to-thickness ratios of test specimens. Table 1 summarizes the nominal geometric properties of all brace specimens used in this experimental study. These sections were judiciously chosen to encompass (i) the early fracture behavior of braces having the smaller slenderness ratio and the higher width (or diameter)-to-thickness ratio and (ii) the ductile performance for braces having the higher slenderness ratio. Though the selected brace sections were relatively small as compared to those used in the practice, scale-effect should not have any significant influence on the fracture ductility of braces [33]. Hence, the findings of this study can also be applied to the braces used in the construction practice.

**Table 1**
Geometric properties of brace specimens used in the experimental investigation.

| Specimen | Section | *D* (or *B*) (mm) | *t* (mm) | *A* (mm$^2$) | *r* (mm) | *L* (mm) | λ | [a]*B/t* (or *D/t*) ratio |
|---|---|---|---|---|---|---|---|---|
| C1 | HCS 33.7 × 3.2 | 33.7 | 3.2 | 306 | 10.8 | 2300 | 213 | 11 |
| C2 | HCS 42.4 × 2.6 | 42.4 | 2.6 | 325 | 14.1 | 2300 | 163 | 16 |
| C3 | HCS 42.4 × 4.0 | 42.4 | 4.0 | 482 | 13.6 | 2300 | 169 | 11 |
| C4 | HCS 48.3 × 3.2 | 48.3 | 3.2 | 453 | 15.9 | 2300 | 145 | 15 |
| C5 | HCS 60.3 × 2.9 | 60.3 | 2.9 | 523 | 20.3 | 2300 | 113 | 21 |
| C6 | HCS 88.9 × 3.2 | 88.9 | 3.2 | 861 | 30.3 | 2300 | 76 | 28 |
| S1 | HSS 38.0 × 38.0 × 4.0 | 38.0 | 4.0 | 503 | 13.6 | 2300 | 169 | 8 |
| S2 | HSS 49.5 × 49.5 × 2.9 | 49.5 | 2.9 | 519 | 18.8 | 2300 | 122 | 15 |
| S3 | HSS 63.5 × 63.5 × 3.2 | 63.5 | 3.2 | 745 | 24.4 | 2300 | 94 | 18 |

*Note*: *D* = External diameter; *B* = External width; *t* = Thickness; *A* = Gross cross-sectional area; *r* = Radius of gyration; *L* = Effective length; **λ** = Slenderness ratio.
[a] The value of *B* used in computation of *B/t* ratio is taken as (*B-3t*).