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Finite element model of the cyclic bending behavior of hollow structural sections

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ABSTRACT

Hollow structural sections (HSS) are desirable for utilization in structural applications due to their inherent flexural, compression, and torsional properties. These sections are highly efficient, but have been underutilized in cyclic bending applications due to a lack of understanding of their behavior under these loads. To address the limited experimental data and determine potential limiting parameters for the use of HSS in seismic bending applications, a finite element model (FEM) considering experimentally measured material properties, section geometry, and geometric imperfections has been calibrated and validated to experimental findings. A parametric study is conducted on 133 different standard HSS beam members of sizes ranging from HSS 152 × 50.8 × 4.8 to HSS 508 × 305 × 15.9. To provide insight into the parameters that limit stable hysteretic behavior, the decrease in the overall maximum moment capacity with cycling at a given rotation level, rotational capacity at a given degradation of the moment capacity, and decrease of the secant stiffness with cycling are considered. The findings provide information about the interdependence of the width–thickness and depth–thickness ratios on the cyclic bending behavior of HSS. Linear regression analyses provide a relationship between the width–thickness and depth–thickness ratios and member performance from which equations for predicting the degradation of moment capacity and rotational capacity can be defined.

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1. Introduction

Hollow structural sections (HSS) have proven to be an excellent structural member for applications in industrial buildings, towers, barriers, cranes, jibs, and mechanical/agricultural equipment [1]. Their desirable tension, compression, biaxial bending, and torsional properties provide inherent efficiencies to these systems. However, the more prevalent use of HSS in seismic flexural applications for building structures has been limited partially due to a lack of understanding of their behavior under large cyclic bending loads and possible lack of ductility and stable behavior over a number of cycles. Until now, structural applications have typically been limited to columns, truss elements, bracing members and cladding supports under static loading. Further applications in seismic low and mid-rise frames, such as beam and column members, can provide large benefits in terms of reduced seismic weight, decreased lateral bracing, applications in modular construction, and unique retrofit techniques. However, current seismic design requires strong-column weak-beam behavior with the majority of the inelasticity occurring in the beam member, which suggests that an understanding of the cyclic behavior of these members and an accurate means of modeling this behavior are necessary prior to the possible increased adoption of HSS for seismic flexural applications.

Until recently, most research on the flexural behavior of HSS focused on beam-column members. Dywer and Galambos [2] tested three different beam-column members to failure, noting the importance of the ratio of the length of the member to the member's radius of gyration (slenderness ratio, L/r) and the ratio of the applied axial load to the axial load causing yielding (axial load ratio, P/P_y). An experimental program by Nakashima and Liu [3] considered the effect of the slenderness ratio and axial load ratio on the hysteretic behavior to gain an understanding of the cyclic plastic hinging of HSS columns in seismic applications. Wang et al. [4] used hybrid testing to better understand the plastic hinge behavior of an HSS column base under varying axial load levels. Other studies considered the behavior of axially loaded truss-type connections and connections between HSS columns and wide flange beams for both hollow and concrete filled tube (CFT) sections [5–8].

With regard to HSS beam member bending behavior, a number of experimental studies considered a variety of monotonic loading conditions. These tests showed the importance of the width–thickness (b/t), depth–thickness (h/t), and aspect ratio (b/h) [9–12]. More recent large-scale experimental testing of HSS beam members considered flexural behavior under cyclic bending loads [13,14]. These experimental cyclic results reiterate the importance of b/t and h/t observed during monotonic testing and provide a further understanding of the expected

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cyclic local buckling behavior. Bending moment gradient, lateral restraint, and overall member slenderness were also shown to play an important role in the performance of HSS under cyclic bending loads [13]. However, experimental testing is still limited to a small subsection of available HSS members and continued study of their cyclic behavior is needed.

Analytical models also have been developed to both predict the behavior and understand the different failure modes associated with HSS members in structures. Sohal and Chen [15] considered the local buckling behavior of round HSS columns and developed a kinematic model that can be utilized to predict the cyclic behavior based on several assumptions including the critical strain, shape and propagation of the buckle, and stress in the HSS member. Key et al. [16] developed a theoretical plastic mechanism model to predict the post-peak load-deflection behavior of HSS columns. This yield line model based on the buckled shape is composed of three components: plate folding, corner yielding, and folding corner restraint mechanisms. However, the applicability of these models under cyclic bending loads is unknown.

Alternative numerical studies have successfully utilized finite element models (FEM) to capture the behavior of HSS columns and beam-columns. Nakashima and Liu [3] used FEM to study cyclically loaded HSS columns under different axial load ratios to failure. This study captured the local buckling behavior and noted the importance of the magnitude of the axial load and its effect on the hysteretic behavior. Goto et al. [17] modeled large HSS columns using a three-surface cyclic metal plasticity material model that can provide very accurate results when calibrated to experimental data. Kurata et al. [18] developed a phenomenological model that considers the effect of the axial load ratio and slenderness ratio on the hysteretic behavior, accounting for the negative hysteretic slope caused by degradation. Other models of HSS beam-column members consider their use as CFT beam-columns under cyclic loads. One recently developed model utilizes fiber elements that have constitutive relationships for both the concrete and steel and accounts for confinement of the concrete core and cyclic local buckling of the steel tube [19]. Also, it has been shown that finite element models can be used to consider the ductility and failure mode of wide-flange (W-shape) beam members with local and global instabilities leading to a robust method for predicting the ductility of a beam member based on cross-section geometry, unbraced length, yield strength, yield ratio, and strain hardening behavior [20]. Models of square and rectangular HSS beam sections are more limited and focus mainly on sections under monotonic bending loads [21]. This model utilized imperfections of the section geometry to produce buckling behavior and load-displacement results similar to those observed in experimental testing. The results from this model reiterate the importance of the b/t and h/t ratios on the local buckling behavior, but it has not been proven that such an approach is applicable for members under larger cyclic loads.

In order to further explore the behavior of HSS members under cyclic bending, a comprehensive finite element study is undertaken. This study adds to the minimal experimental data on the bending behavior of HSS members under large cyclic loads and provides a means of defining limiting parameters for their use in seismic bending applications. An experimental study is first undertaken to consider the variation in material properties with respect to location along the cross-section of an HSS member allowing for a more accurate definition of the material behavior in the model. The finite element model is then calibrated to experimental data to ensure that both global and local behaviors are accurately captured. With this model, a large parametric study of 133 different HSS sizes is conducted providing important information on the degradation of the moment capacity, rotational capacity, and stiffness with cycling.

2. Experimental bending study

2.1. Experimental specimens

A previously conducted experimental program considered the cyclic hysteretic behavior of eleven full-scale square and rectangular HSS cantilever beams under large cyclic bending loads [14]. The specimens were all stock U.S. cold formed members with ASTM A500 Gr. B steel material. These tests considered the ability of HSS beam members to develop stable plastic hinge behavior, ductility, and energy dissipation necessary for use as beam members in seismic moment frames. Table 1 provides the relevant geometric properties for the tested sections that include depths ranging from 203 mm to 305 mm; widths ranging from 102 mm to 203 mm; and wall thicknesses of either 6.4 mm or 9.5 mm. End displacements were applied to the HSS beams through a pin connection. The pin was attached to the load frame and fit through slotted holes perpendicular to the loading direction in the webs of the free end of the HSS member allowing the free end to rotate as the specified horizontal displacements were applied. The vertical slot also ensured that no axial load was applied during testing even as the member length decreased due to local buckling. The slotted hole was reinforced to prevent localized deformation. The fixed connection at the opposite end of the members was created by sandwiching the flanges of the HSS beam between two large stiffened angles. Stiffeners were welded across the web of the HSS member between the legs of the two opposing angles to prevent deformation in the connection region. The other legs of the angles were bolted to a stiffened base beam to fix the connection in place. Member rotations were calculated as the displacement at the pin divided by the span length of the beam (from the pin to the initiation point of the fixed connection that represented the column face of an actual connection). Testing was conducted in displacement control at a quasi-static loading rate with increasing displacement cycles (Fig. 1) to provide a means of evaluating the moment-rotation behavior of the HSS up to large rotations of 0.08 rad. Further details of the test setup and loading protocol can be found in Fadden and McCormick [14].

Table 1
Experimental section properties and geometry.

Section (mm × mm × mm)	Design wall thickness t (mm)	Area A (mm^2)	Width–thickness ratio b/t	Depth–thickness ratio h/t
HSS 203 × 102 × 6.4	5.66	3380	14.2	31.3
HSS 203 × 102 × 9.5	8.86	4890	8.46	19.9
HSS 203 × 152 × 6.4	5.66	3980	22.8	31.3
HSS 203 × 152 × 9.5	8.86	5790	14.2	19.9
HSS 203 × 203 × 6.4	5.66	4580	31.3	31.3
HSS 203 × 203 × 9.5	8.86	6710	19.9	19.9
HSS 254 × 102 × 6.4	5.66	3980	14.2	39.9
HSS 254 × 152 × 6.4	5.66	4580	22.8	39.9
HSS 254 × 203 × 6.4	5.66	5180	31.3	39.9
HSS 305 × 102 × 6.4	5.66	4580	14.2	48.5
HSS 305 × 152 × 6.4	5.66	5180	22.8	48.5

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