Investigations on the Seismic Performance of Hot-Finished Hollow Steel Sections

Paola Pannuzzo, Tak-Ming Chan

***Abstract*—**In seismic applications, hollow steel sections show, beyond undeniable esthetical appeal, promising structural advantages since, unlike open section counterparts, they are not susceptible to weak-axis and lateral-torsional buckling. In particular, hot-finished hollow steel sections have homogeneous material properties and favorable ductility but have been underutilized for cyclic bending. The main reason is that the parameters affecting their hysteretic behaviors are not yet well understood and, consequently, are not well exploited in existing codes of practice. Therefore, experimental investigations have been conducted on a wide range of hot-finished rectangular hollow section beams with the aim to providing basic knowledge for evaluating their seismic performance. The section geometry (width-to-thickness and depth-to-thickness ratios) and the type of loading (monotonic and cyclic) have been chosen as the key parameters to investigate the cyclic effect on the rotational capacity and to highlight the differences between monotonic and cyclic load conditions. The test results provide information on the parameters that affect the cyclic performance of hot-finished hollow steel beams and can be used to assess the design provisions stipulated in the current seismic codes of practice.

***Keywords*—**Hot-finished steel, hollow sections, cyclic tests, bending.

I. Introduction

In the context of earthquake-resistant applications, steel moment-resisting frames (MRFs) are still the most common systems used to resist seismic actions. In these systems, the formation of plastic hinges occurs in specific locations such as the ends of beams and at the column bases of the first floor. Therefore, members shall be chosen and designed in order to have enough stiffness, ductility and energy dissipation to undergo large deformations. For this reason, hollow sections might be an interesting choice. In particular, hot-finished steel sections have proved homogeneous material properties and good ductility [1]-[3]; however, so far, research on their bending behavior under seismic action has been limited. Moreover, the main codes do not provide any specific design rules for hot-finished hollow steel sections, especially for seismic design.

AISC 341-16 [4] defines cross-section slenderness limits for hollow sections in order to undergo sufficient plastic rotation under seismic action, namely, 0.02 rad or less for moderately ductile sections, l_{md}, more than 0.04 rad for highly ductile sections, $l_{hd,,}$ maintaining 80% of the maximum moment capacity. However, hollow steel sections (HSS) in North America are produced only as cold-formed members. Indeed, for seismic bending applications, the majority of studies have focused on cold-formed steel beam members [5]-[7]. These members displayed stable hysteretic behavior and high rotation capacity under large deformations, however, the limiting width-to-thickness and depth-to-thickness ratios even lower than those suggested by AISC.

As a result, cold-formed HSS seem not to be an economical choice for being used as members of frame systems in highly seismic regions, in fact, they are increasingly replaced by composite steel beams. Hence, the primary focus of this study is to experimentally investigate the behavior of square and rectangular hot-finished hollow steel beams, highlighting the differences between monotonic and cyclic load conditions. In particular, this study aims to better understand how local slenderness, flange-web interaction can play on the flexural performance of hot-finished hollow sections.

II. Experimental Program

A. Testing Matrix

In order to characterize the structural performance of hot-finished hollow steel beams subjected to large deformations, an experimental program is designed thoroughly. In total, this program was 12 specimens, with different width-to-thickness ratios (b/t), depth-to-thickness ratios (d/t) and similar member slenderness (L/r). Also, all specimens were tested under monotonic as well as cyclic loading. The section sizes were chosen so as to provide a sufficient scatter of b/t and d/t values with regard to the limits provided by AISC 341-16 [3] for highly, l_{hd} , and moderately, l_{md}, ductile members.

The sections were fabricated by European standard structural steel S355 in accordance with EN 10210-2 [8]. The members along with their associated parameters are listed in Table I.

TABLE I
TESTED SECTIONS AND PARAMETERS

Section	b/t	d/t	L/r	Ductile criteria (AISC 341-16)
100x100x6.3	13.6	13.6	23.1	Highly
120x120x6.3	16.2	16.2	21.3	Moderately
150x150x5	27.5	27.5	19.8	No ductile1
160x80x5	13.0	28.9	18.9	Highly
200x100x5	16.9	36.4	20.5	Moderately
250x150x6.3	21.4	37.5	28.2	Moderately

[1] Not used for seismic resistant systems

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B. Experimental Setup

Fig. 1 illustrates the reaction frame at the structural laboratory of The Hong Kong Polytechnic University that was designed and already proven for experimental testing of three-point simply-supported beams [9]; see also the schematic view with instrumentations in Fig. 2. The monotonic and the cyclic load was applied using a displacement control mechanism through a servo-controlled hydraulic actuator with a maximum stroke of ± 150 mm and capacities of 300 kN in compression and 150 kN in tension. Also, a rigid connector with vertical stiffeners was welded to the specimens at the mid-span where the load was applied. The effective length (L_{eff}) of bending was taken from the end of support to the vertical stiffeners at mid-span.

In order to measure the strains, to capture the first yielding and to verify the symmetry of test arrangement, eight strain gauges adhered to each specimen at different distances.

In addition, 10 linear variable displacement transducers (LVDTs) were installed to measure the corresponding vertical and horizontal displacements.

Fig. 1 Reaction frame at the structural laboratory of The Hong Kong Polytechnic University

Monotonic tests were carried out under displacement control whereas the SAC loading protocol [10] was adopted to apply the lateral cyclic load. The rate for the cyclic test was gradually increased with the increase of drift ratio, defined as the deflection at mid-span of the beam divided by the effective length, L_{eff}.

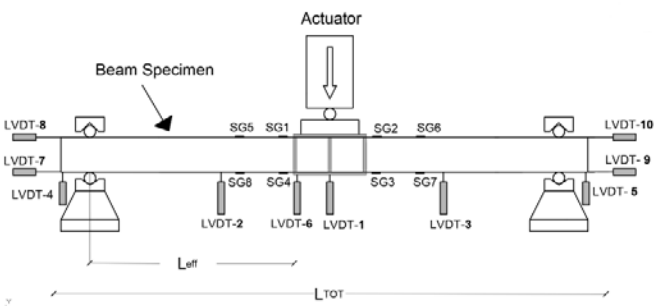
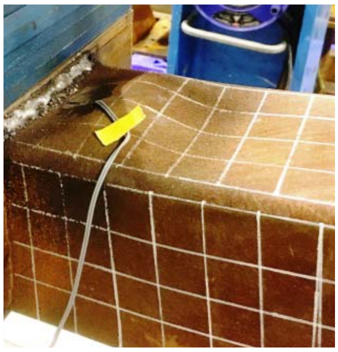
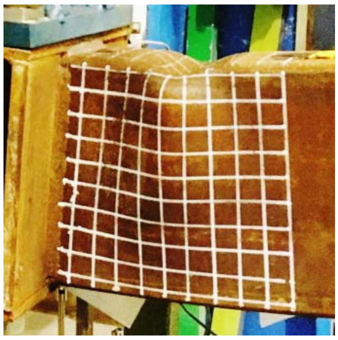


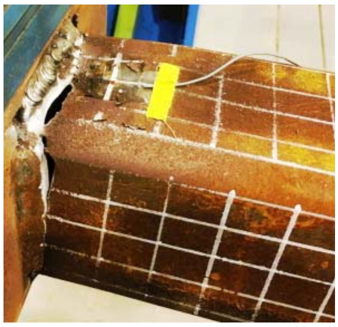
Fig. 2 Schematic three-points configuration with instrumentations



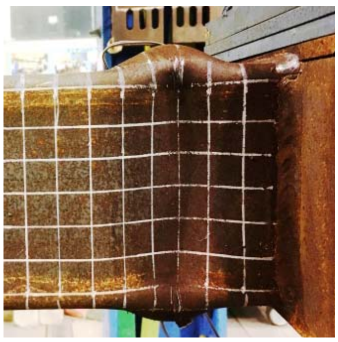
(a) Flange local buckling



(b) Web local buckling



(c) Fracture before local buckling



(d) Fracture after local buckling

Fig. 3 Example of failure modes

III. Test Results and Discussion

Fig. 3 illustrates the failure modes observed near the mid-span of the beams, just behind the vertical stiffeners.

In general, four kinds of failure modes can be recognized: flange local buckling (a), web local buckling after flange local buckling (b), fracture before (c) or after (d) local buckling.

Obviously, these phenomena are more significant for increasing values of lateral displacement. Through a first visual inspection, fracture with no evident early bulging was observed at the web-to-flange corners in the most compact sections, whereas in all other specimens, fracture occurred in the corner zone following the local buckling.

In order to evaluate the bending properties, the moment-rotation curve was constructed for each specimen.

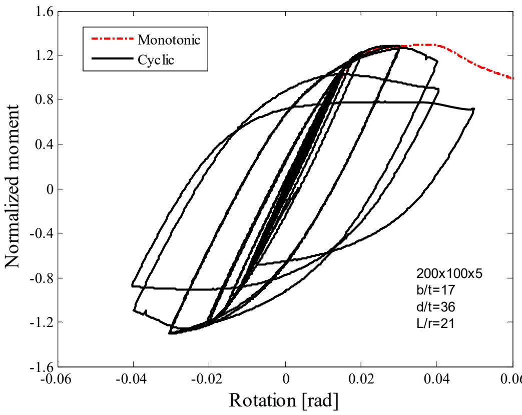


Fig. 4 Typical Normalized Moment-Rotation curves

Fig. 4 shows an example of normalized moment-rotation curves in which results obtained from monotonic and cyclic load conditions are compared. In general, it can be observed that all specimens displayed a lower rotation capacity under cyclic loading than monotonic loading, as obviously expected. However, each section exhibited full hysteretic loops indicating a good energy dissipation capacity. Moreover, normalized moment-rotation backbone curves were built to further compare the hysteretic behavior of all tested sections. The specimens were divided in three groups: (i) Square and Rectangular highly ductile sections, (ii) Square and Rectangular moderately ductile sections, l_{md}, (iii) Square out of moderately ductile limit and Rectangular moderately ductile section.

Looking at the first group of backbone curves in Fig. 5, despite all of them achieving high rotation levels with no moment degradation, rectangular sections attained lower over-strength as well lower rotation levels than square sections with similar b/t ratio.

Regarding the second group in Fig. 6, the moment degradation is more evident with increasing values of b/t and d/t ratios, especially for rectangular sections. This effect may be due to the interaction between flange and web local buckling. As a result, even if 120x120x6.3 section was classified as moderately ductile member could be classified as highly ductile members, 200x100x5 with similar b/t ratio did not behave as highly ductile members since higher d/t ratio affected the rotation capacity.

Finally, looking at the third group in Fig. 7, even if 150x150x5 is beyond of l_{md} limit performed better than 250x150x5 in terms of moment and rotation capacity, although, according to AISC classification, 150x150x5 cannot be used even for seismic applications.

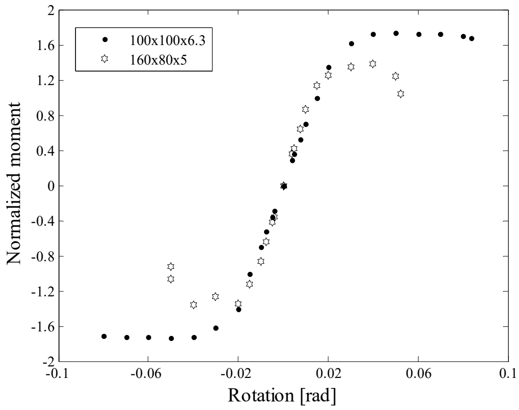


Fig. 5 Normalized moment versus rotation backbone curves for highly ductile members (i)

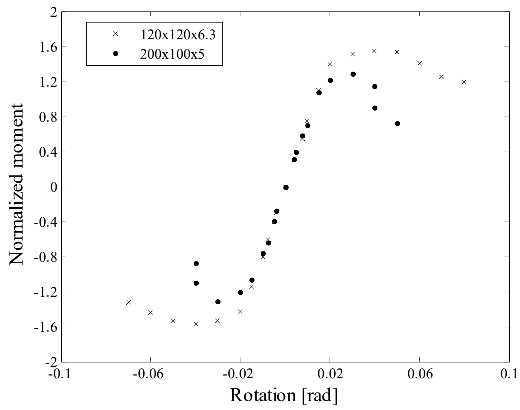


Fig. 6 Normalized moment versus rotation backbone curves for moderately ductile members (ii)

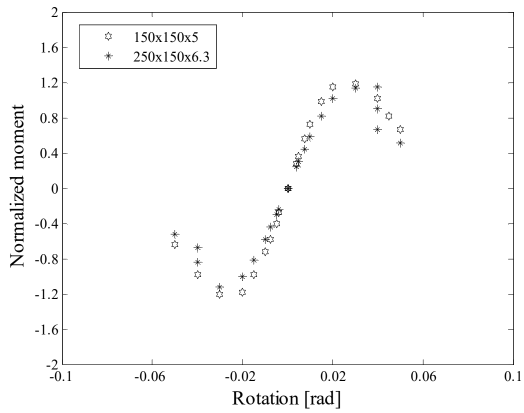


Fig. 7 Normalized moment versus rotation backbone curves for sections above and below the limit for Moderately ductile members (iii)

Overall, these first observations point to a review and an adjustment of cross-section classification limits, specifically for hot-finished hollow steel members, taking into account the improved material properties due to the manufacturing process and the web-flange interaction.

IV. Conclusion

This paper investigates the flexural behavior of hot-finished square and rectangular steel beams under monotonic as well as cyclic loadings. In total, the tests involved 12 three-point simply-supported beams. The key parameters were the width-to-thickness the depth-to-thickness ratios and loading conditions (monotonic as well as cyclic loading).

The test results provide information on local slenderness limits for hot-finished steel sections that can be used to assess the design provisions stipulated in the current seismic codes of practice and to encourage the use of hot-finished sections as members of MRFs keeping the structural and architectural advantages of empty hollow sections.

Acknowledgment

This study is based on work supported by the Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch) at The Hong Kong Polytechnic University. The authors would also like to thank the technical staff – Mr. Henry Cheung and Mr. Alfred Yiu of the Structural Engineering Research Laboratory at The Hong Kong Polytechnic University for their assistance on the experimental works.

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