NUMERICAL ASSESSMENT OF THE FLEXURAL BEHAVIOR OF HOT-FINISHED STEEL BEAMS UNDER MONOTONIC AND CYCLIC LOADING

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Abstract

Hollow steel sections are an interesting choice for bending applications since, unlike the open sections, they are not susceptible to weak-axis and lateral-torsional buckling. However, the use of hollow steel sections earthquake-resistant applications is limited due to stringent ductility requirements to develop adequate plastic rotation capacity and stable behavior under reversed cyclic loading. As a result, hollow sections are increasingly replaced by composite steel beams, losing the main benefit of empty hollow steel sections in terms of reduced seismic weight. However, hollow sections can be produced by different manufacturing processes varying significantly the structural behavior. In particular, hot-finished steel sections show homogeneous material properties and good ductility, but their cyclic bending behavior is not yet well investigated. Consequently, the parameters affecting their hysteretic behavior are not well understood and, thus, their use in seismic applications is not common.

In this study, a parametric study has been conducted on a wide range of square and rectangular hot-finished hollow sections, in order to investigate the flexural performance in terms of rotational capacity under monotonic and cyclic loading. The investigation is carried out through detailed finite element models that are first validated with experimental results of initial three-point bending tests conducted in parallel in this research program.

Width-to-thickness and depth-to-thickness ratios have been chosen as the key parameters to assess the plastic rotation level achieved under monotonic and cyclic loading and to compare the finding limits with the requirements specified in the current seismic codes. In particular, the rotation capacity R has been chosen as index to define ductility in the static case, following the same approach of Eurocode 3 and AISC 360-16. Whereas, for the seismic case, plastic rotation Qp has been chosen as AISC 341-16.

The findings suggest reviewing the cross-section classification limits under non-seismic and seismic conditions, taking into account the web-flange interaction and the improved material properties of hot-finished hollow steel members.

Keywords: Cyclic effects, Finite Element modelling, Hot-Finished Hollow Sections, Rotation capacity,

1. Introduction

Structural hollow sections are widely used in engineering applications because of their high structural efficiency, especially for their torsional properties and biaxial bending. However, there are some concerns in their use in seismic bending applications due to not well understanding of their hysteretic behavior and ductility level under large deformations.

It is worth pointing that, the most common hollow steel profiles used for seismic flexural applications are manufactured as cold-formed sections that may experience enhanced strength but less ductility. A valid alternative might be provided by hot-finished hollow steel sections with homogenous material properties and good ductility. Until now, sufficient research works have been conducted on static behavior and comparison between cold-formed and hot-finished steel beams and, also, on their hysteretic performance under axial cyclic proving that the static and axial cyclic performance of hot-finished hollow sections is highly satisfying [1-3].

Nonetheless, until recently, research studies on the bending behavior of hot-finished hollow steel members under seismic action have been limited and, consequentially, they have been underutilized for cyclic bending since the parameters affecting their hysteretic behavior are not well exploited in the existing codes.

Indeed, in the current seismic provisions, there are no specific design rules for hot-finished hollow steel members, Eurocode 8 [4] adopts the same section classification proposed in EC3[5] for static design; limits of width–thickness and depth–thickness ratios are provided for general case of hollow sections to ensure sufficient rotation capacity for plastic analysis but with no distinction between monotonic and cyclic loading conditions. Whereas, the current seismic code in the US, AISC 341-16 **[6],** defines lower cross-section slenderness limits for seismic applications to ensure 0.02 rad of plastic rotation for moderately ductile sections, λ_{md}, more than 0.04 rad for highly ductile sections, λ_{hd}, maintaining 80% of the maximum moment capacity. In addition, hollow steel sections (HSS) in North America are produced mainly as cold-formed members. Indeed, the recent research studies have focused on cold-formed steel beam members [7-9] experimental and detailed finite element (FE) studies limit the width-to-thickness and depth-to-thickness ratios even lower than those suggested by AISC, for this reason, they are progressively supplanted by composite steel beams.

Hence, this paper aims to provide an initial assessment of the flexural performance of hot-finished steel beams through detailed FE analysis, focusing on the parameters that limit the cyclic performance of beam members and compare the finding limits with the requirements specified in the current seismic codes, highlighting the improved performance of empty hot-finished steel hollow sections compared with the most common cold-formed steel hollow sections.

Due to the scarcity of experimental data, firstly, hot-finished steel sections were tested under monotonic as well cyclic loading in a three-point bending test arrangement at the structural laboratory of The Hong Kong Polytechnic University, as shown in Fig.1. A more in-depth discussion on a similar test setup can be found in Chen [10].

Finite element model (FEM) is calibrated to experimental data and, then, a parametric study of square hollow sections (SHS) and rectangular hollow sections (RHS) is conducted to provide information on how width-to-thickness and depth-to-thickness ratios can affect the rotational capacity of hot-finished hollow steel beams under large deformation, highlighting the difference between monotonic (Static case) and cyclic behavior (Seismic case).

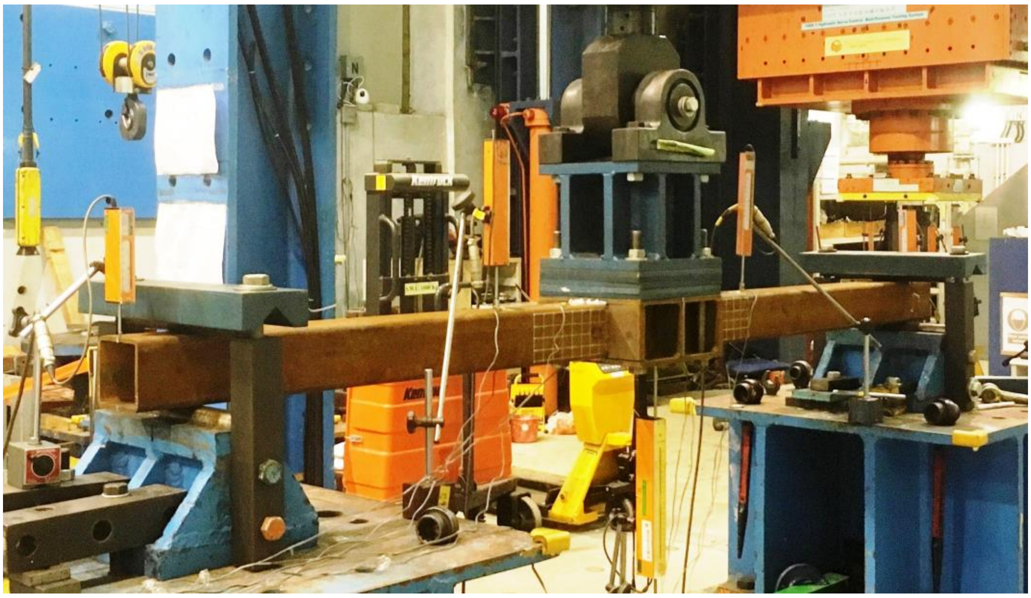

Fig 1. Testing frame at the structural laboratory of The Hong Kong Polytechnic University

2. Development of the Finite Element Model and Validation

Finite Element (FE) models capable of simulating the monotonic and cyclic response of hot-finished steel beams were developed and calibrated on the basis of the results obtained from the initial test specimens conducted in parallel in this research program. FE models were generated in ABAQUS (Version 6.13-4) [11] by symmetric half models to improve computational efficiency (Fig.2). A comparison of results obtained from the half model and the model of complete beam member was carried to confirm the validity of the modeling approach, it is not reported for brevity.

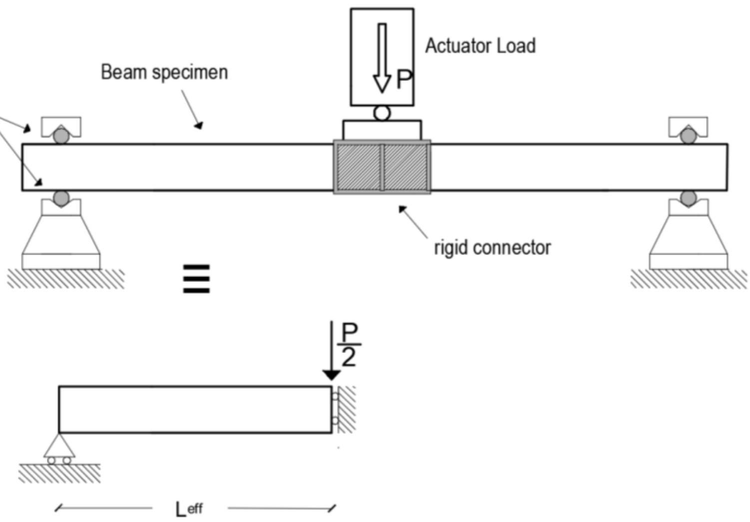

Fig. 2- Schematic view of beam setup

The measured dimensions of the cross-section are 119.3×119.6×6.29 and the effective length, $L_{eff,}$ is equal to 1025mm. Rollers are fixed at the end of the beam while fixed boundary conditions with free vertical displacement are applied in correspondence of the load. The rollers were modeled as rigid parts and the interaction between rollers and beam is modeled as surface-to-surface contact including penalty contact interaction with a static friction coefficient of 0.2 to provide a good representation of greased steel rollers. S4R shell elements are used to model the HSS member with a mesh size of 6.30mm×6.30mm equal to the thickness of cross-section.

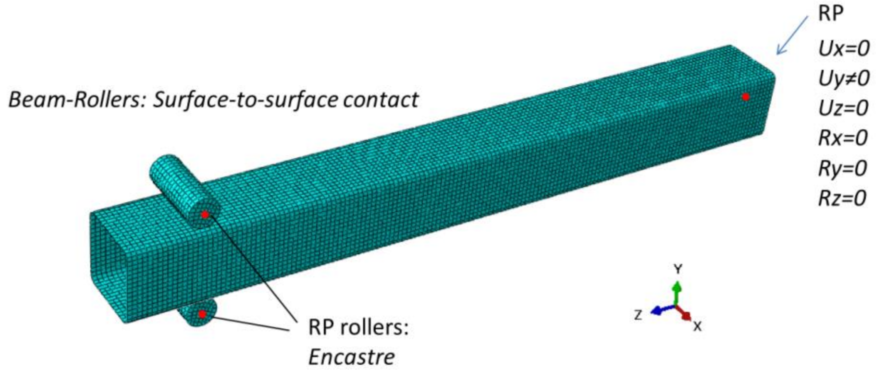

Fig. - Boundary conditions and mesh discretization

Local imperfections were considered in the FE models. The buckling analysis was carried out to capture the shape of initial local imperfection by using the appropriate buckling mode. The magnitude of the local imperfection is chosen as half of the tolerance prescribed by EN 10210-2-1997 [12], which is 1% of the side. This amplitude was chosen after a sensitive study providing good agreement in the maximum moment between the experimental and FEM results. Residual stresses are neglected in this study because although they can be present, they have no impact on the plastic moment of a cross-section.
Two different material models were assumed to reproduce the monotonic and cyclic behavior of the tested beams. Material properties were obtained from flat coupon test Fy=452MPa, Fu= 530MPa, and E=202000MPa. The values of the stress-strain curve were converted into true stress-strain and introduced directly in the FE model. The monotonic load was simulated as imposed vertical displacement equal to 15% of effective length, L_{eff}.
Whereas the cyclic behavior was simulated using a nonlinear combined kinematic and isotropic hardening model, where kinematic and isotropic parameters are determined were calibrated so as to provide a good agreement between the numerical and experimental cyclic responses.
The SAC loading protocol [14] 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}.

A comparison of the moment-rotation response of the finite element model to the experimental data is shown in Fig.4. From this figure, it can be noted that the FE model captures very accurately both monotonic and cyclic curves.

Looking at monotonic curves, as stated above, residual stresses were neglected, this might explain the early yielding in the experimental curve. However, the plasticity moment has been unchanged. Moreover, no degradation can be seen with increasing lateral deformation, as expected in the static case, being within class 1 or Compact Section, according to Eurocode 3[5] and AISC 360-16 [15] classification, respectively.

As regards the cyclic case, the models also exhibit similar cumulative energy dissipation throughout the loading protocol, confirming also that the loading condition has a significant influence on rotation capacity and moment degradation. In this specific case, even though the tested specimen would be classified as a moderately ductile member according to AISC, it can be observed that it can achieve a 6% drift maintaining

80% of the maximum moment capacity, performing as a highly ductile member. For this reason, a parametric study is needed to better explore the resources of hot-finished hollow steel sections under seismic action.

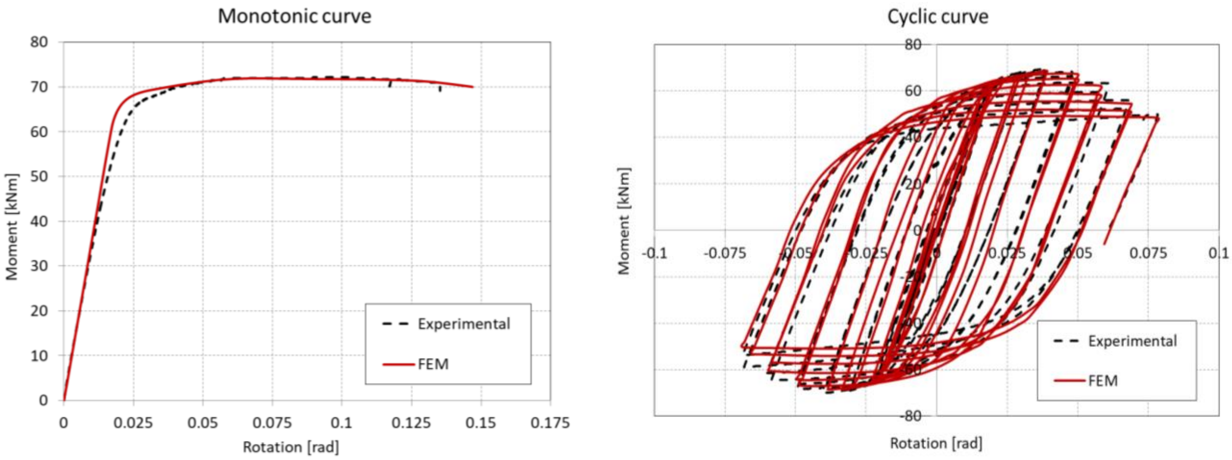

Fig. 4- Comparison of experimental and analytical end moment versus chord rotation

3. Parametric Study

A parametric study is conducted involving 10 pairs (under monotonic and cyclic loading) of hot-finished hollow steel beams with width-thickness and depth-thickness ratios that range between 13 to 29.
Cross-section sizes of hot-finished square and rectangular hollow steel beams are chosen in order to represent a comprehensive range of slenderness values above and below the limits provided by AISC 341-16 for highly, λ_{hd}, and moderately, λ_{md}, ductile members. These limits are calculated according to the equation provided by the AISC and the limits are 14 and 25 for the highly and moderately ductile criteria, respectively.
Table 1 summarizes the selected sections used for simulation. The key parameters are their width–thickness ratios (b/t) and depth–thickness ratios (d/t). Rectangular sections are chosen to keep the aspect ratio (D/B) equal to 1.5 and, also, the lengths of beams are chosen to keep similar member slenderness to the tested specimens.

4. Result and Discussion

4.1 Static case

Both Eurocode 3 and AISC 360-16 use the same ductility index, namely, the rotation capacity that can be defined as $R = \Theta u/\Theta y - 1$, where Θu is the ultimate rotation corresponding to the 80% of the maximum moment capacity, Θy is the rotation corresponding to the flexural yielding.
Both codes are consistent to state that “sections capable of developing a fully plastic stress distribution and possessing a rotation capacity of approximately three before the onset of local buckling”, as reported in AISC 360-16, can be used for plastic design.
Looking at Fig. 5, in general, it can be confirmed the satisfying static flexural performance in terms of rotation capacity R. In particular, the degradation of rotation capacity is more evident in rectangular sections (RHS). This effect may be due to the interaction between flange and web local buckling. As a result, even though 200×200×6.3 and 200×300×6.3 sections are both classified as Non-Compact/ Class 2 sections, the square section, achieving rotation capacity higher than 3, could be used for plastic design. These first

observations lead to study better the web and flange slenderness interaction in order to re-assess the limits provided by existing codes for plastic design.

Table 1- List of sections included in the computational parametric study.

	Section	b/t	d/t	Ductile criteria Static (AISC 360-16/ Eurocode3)	Cyclic (AISC341-16)
1	SHS_100×100×6.3	13	13	Compact/Class 1	Highly
2	SHS_120×120×6.3	16	16	Compact/Class 1	Moderately
3	SHS_140×140×6.3	19	19	Compact/Class 1	Moderately
4	SHS_160×160×6.3	22	22	Compact/Class 1	Moderately
5	SHS_200×200×6.3	29	29	Non compact/Class 2	No ductile[1]
6	RHS_100×150×6.3	13	21	Compact/Class 1	Highly
7	RHS_120×180×6.3	16	26	Compact/Class 1	Moderately
8	RHS_140×210×6.3	19	30	Compact/Class 1	Moderately
9	RHS_160×240×6.3	22	35	Compact/Class 1	Moderately
10	RHS_200×300×6.3	29	45	Non compact/Class 2	No ductile[1]

[1] Not used for seismic resistant systems

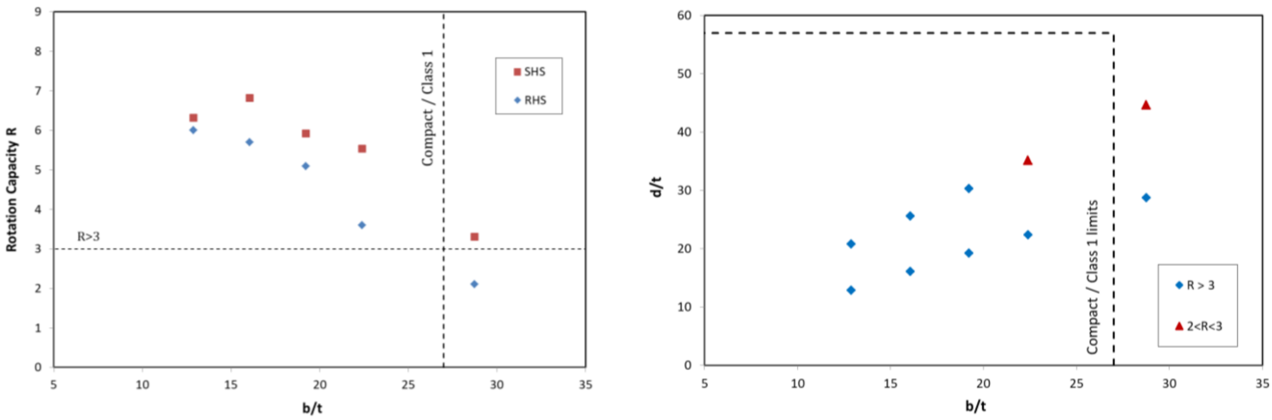

Fig. 5- Effect of b/t and d/t on Rotation Capacity of hot-finished steel hollow sections for the static case

4.2 Seismic case

Eurocode 8 maintains the same classification for plastic design, whereas AISC 341-16 uses the plastic rotation as ductility index. Specifically, a member expected to undergo more than 0.04 rad of plastic rotation is defined as Highly Ductile Member, whereas less 0.02 rad as Moderately ductile member.

From Fig. 6 it can be observed that square hollow sections (SHS) classified as moderately ductile member can achieve values of plastic rotation higher than 0.04 rad. However, rectangular hollow section with the same b/t ratios is not able to achieve the same rotation level. Fadden [9] already proposed new limits for b/t and d/t for cold-formed steel hollow sections but, comparing the performance of hot-finished hollow steel sections to the proposed limits, they are conservative to be adopted for hot-finished steel sections. It means that both b/t and d/t need to be re-assessed.

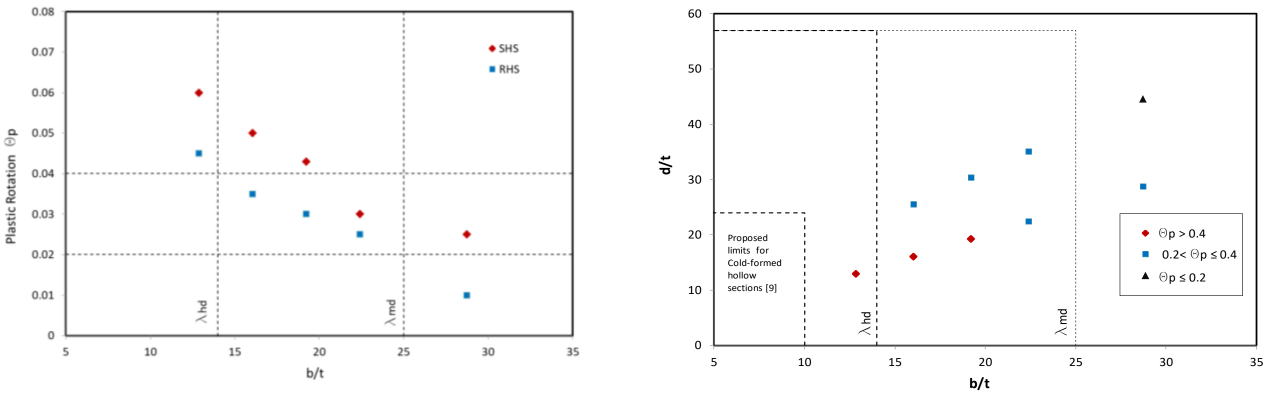

Fig. 6- Effect of b/t and d/t on Plastic Rotation of hot-finished steel hollow sections for seismic case

5. Conclusions

This paper discusses the flexural performance of hot-finished hollow steel sections through finite element investigation under monotonic (static case) as well cyclic (seismic case) loading. The finite element models were first validated with experimental results obtained from the initial test specimens conducted in parallel in this research program. Both finite element models successfully reproduced the experimental data in terms of Moment- Rotation curves. Using the validated FE modeling approach a parametric study was conducted to investigate the effect of key parameters, width-to-thickness (b/t) and depth-to-thickness (d/t) ratios on rotation capacity, highlighting the difference between monotonic and cyclic case. Results from the parametric study show that under cyclic loading conditions the rotation capacity drastically decreases when compared with monotonic loading conditions and, especially for rectangular sections. These observations lead to explore further the interaction between flange and web buckling of hot-finished hollow sections especially under cyclic loading.
In general, the performance improvements of hot-finished hollow steel sections result being able to meet the ductility requirement of Eurocode and AISC for both static and seismic cases. And also, the results suggest the possibility to relax the current local slenderness.
These findings encourage the use of hot-finished steel hollow members for seismic bending applications.

6. Acknowledgments

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