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Cross-sectional behavior of cold-formed steel semi-oval hollow sections

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an investigation on the material properties, residual stress distributions and cross-sectional behavior of cold-formed steel semi-oval hollow sections. Four cross-section series were included in the test program. The test specimens were cold-formed from hot-extruded seamless steel circular sections. Tensile coupon tests were conducted on coupon specimens extracted from three critical locations, namely the flat, curved and corner portions, of each cross-section as well as half of the cross-section of a representative section. Membrane and bending residual stresses distributions on the representative section were measured in both longitudinal and transverse directions. In addition, initial geometric imperfections were measured for each cross-section series and stub column tests were conducted to determine the average stress–strain relationship over the complete cross-section in the cold-worked state and to examine the cross-sectional behavior of cold-formed steel semi-oval hollow sections. Furthermore, a finite element model was developed and validated against the test results. With the verified finite element model, an extensive parametric study over a wide range of cross-section geometries was performed. The load-carrying capacities of stub columns obtained from experimental and numerical investigation were compared with the design strengths predicted by the Direct Strength Method using the design equations originally developed for open sections and the Continuous Strength Method with the design curves originally developed for traditional tubular sections. The comparison results show that the existing design methods provide conservative design strength predictions. In this study, modification on the Continuous Strength Method is proposed, which is shown to improve the accuracy of the design strength predictions in a reliable manner.

1. Introduction

The rapid development of steel manufacturing industry in recent decades has allowed the rise of more stringent requirements on the design of steel structures with regards of both structural efficiency and architectural appearance. Nowadays, the major challenges that the structural engineers are facing are not only restricted to the structural performance, but also closely related to the architectural perspective. With these requirements, metallurgical industry has sought to respond to the needs of the market and developed new forms of tubular profiles.

Without jeopardizing the structural efficiency and in the meantime retaining the aesthetic appearance, an innovative cross-section profile, semi-oval hollow section (SOHS), is recently developed by cold-forming. The semi-oval hollow section investigated in this study is composed of one semi-circular flange, one flat flange, and two flat web plates, as shown in Fig. 1a. It integrates the architectural elegance of circular hollow section with the structural advantages of rectangular hollow section associated with different flexural rigidities about the two principal axes. Despite of the merits of SOHS, no investigation has been conducted on this section yet, which limits the structural application of this section.

In this study, the material properties, residual stress distributions and cross-sectional behavior of cold-formed steel SOHS were investigated. The material properties for each cross-section series and the distribution of material strengths along half of the cross-section profile were measured and examined through tensile coupon tests. The average stress-strain relationships over the complete cross-section in the cold-worked state were also obtained from stub column tests. The initial local geometric imperfections of each cross-section series were measured. The distributions of membrane and bending residual stresses along half-section profile of a representative section were obtained in both longitudinal and transverse directions. Non-linear finite element (FE) model was developed to simulate the cold-formed steel SOHS stub column tests. The model was validated against the experimental results and was further used in extensive parametric study to investigate the cross-sectional behavior of cold-formed steel SOHS with a wide range of cross-section geometries. The stub column strengths obtained from the experimental and numerical studies were compared with the design

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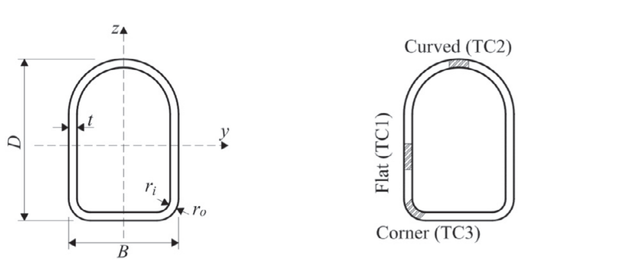
Nomenclature

B	overall width of the section
CHS	circular hollow section
COV	coefficient of variation
CSM	continuous strength method
D	overall depth of the section
DSM	direct strength method
E	Young's modulus
E_{SC}	Young's modulus obtained from stub column test
FE	finite element
L	specimen length
L_e	effective length
P_{CSM}*	nominal axial strength predicted by the modified continuous strength method
$P_{CSM,CHS}$	nominal axial strength predicted by the CHS approach in the Continuous Strength Method
$P_{CSM,RHS}$	nominal axial strength predicted by the RHS approach in the Continuous Strength Method
P_{DSM}	nominal axial strength predicted by the Direct Strength Method
P_{Exp}	experimental loading capacity
P_{FE}	finite element loading capacity
P_u	ultimate axial loading capacity
$P_y\hat{}$	squash load of cross-section considering the cold-forming enhancement
RHS	rectangular hollow section
r_i	inner corner radius of the section
r_o	outer corner radius of the section
SOHS	semi-oval hollow section
t	thickness of the section
TC	tensile coupon specimen
β	reliability index
δ_u	end shortening at ultimate load
ε_{csm}	limiting strain for the cross-section
ε_f	tensile strain at fracture
ε_i	residual strain on inner surface
ε_o	residual strain on outer surface
ε_u	ultimate strain
ε_y	yield strain
ϕ	resistance factor
λ_{CSM}	cross-section slenderness in the Continuous Strength Method
σ_b	bending residual stress
σ_m	membrane residual stress
σ_u	static ultimate tensile strength of material
$\sigma_{u\text{-}SC}$	static ultimate tensile strength of material obtained from stub column test
$\sigma_{u\text{-}TC}$	static ultimate tensile strength of material obtained from tensile coupon test
$\sigma_{0.2}$	static 0.2% tensile proof stress of material
$\sigma_{0.2\text{-}SC}$	static 0.2% tensile proof stress of material obtained from stub column test
$\sigma_{0.2\text{-}TC}$	static 0.2% tensile proof stress of material obtained from tensile coupon test
ω_l	initial local geometric imperfection

strengths predicted by the existing Direct Strength Method (DSM) [1] and Continuous Strength Method (CSM) [2–4]. Modification on the CSM is proposed in this study. The feasibility and reliability of the existing and modified design methods for SOHS were evaluated by means of reliability analysis.

2. Test specimens

Four series of SOHS were included in the experimental program with the cross-section geometry as defined using the nomenclature in Fig. 1a. The SOHS investigated in this study were fabricated by hot-extruded seamless steel circular hollow sections and then cold-formed into SOHS. Therefore, the SOHS are considered as cold-formed steel sections due to the involvement of the final cold-forming process. The nominal dimensions ($D \times B \times t$) of SOHS are $93 \times 62 \times 5.5$, $107 \times 68 \times 6.5$, $108 \times 79 \times 5.5$ and $125 \times 85 \times 6.5$, where D, B and t are the overall depth, overall width and thickness of the sections, respectively. The nominal cross-section aspect ratio (D/B) of the specimens varies slightly from 1.37 to 1.57.



(a) Cross-section geometry   (b) Locations of tensile coupon specimens

Fig. 1. Cross-section of SOHS.

3. Tensile coupon tests

3.1. General

Tensile coupon tests were conducted on coupon specimens extracted from three critical locations, namely the flat, curved and corner portions, of each cross-section as well as half of the cross-section of a representative section to determine the material properties of these sections and to investigate the distribution of material properties along cross-section profile. The material properties, including the Young's modulus (E), the 0.2% tensile proof stress ($\sigma_{0.2}$), ultimate tensile strength (σ_u) and tensile strain at fracture (ε_f), were measured.

3.2. Coupon specimens from critical locations

To characterize the material properties and examine the strength enhancement due to the cold-forming process for SOHS, twelve tensile coupon tests were conducted on four cross-section series of SOHS. For each cross-section series, tensile coupon specimens were machined from three critical locations, which are longitudinally along the flat web (TC1), the semi-circular flange (TC2) and the corner (TC3) of SOHS as shown in Fig. 1b. The flat coupon specimens were prepared in accordance with the American standard ASTM-E8M [5]. To examine the strength enhancement due to the cold-forming process of the specimens, curved coupon specimens extracted from the semi-circular flange and the corner region of the specimens were also prepared for testing. The nominal width of the curved coupon specimens for the gauge length of 25 mm was 4 mm. Two 7 mm diameter holes were drilled on both ends with the end clearance of 11.5 mm to avoid net section failure near the holes for the curved coupon specimens. The flat coupon specimens were 12.5 mm wide within 50 mm gauge length. Two strain gauges were adhered on both faces in the middle of the gauge length to determine the Young's modulus. The calibrated extensometer with 50 mm or 25 mm gauge length was mounted on the gauge length of the flat or curved coupon specimen, respectively, to capture the real-time