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Modelling and probabilistic study of the residual stress of cold-formed hollow steel sections

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ABSTRACT

Cold-formed Hollow Steel Sections (HSS) are widely used in the construction industry. The distribution of residual stress in non-stress-relieved cold-formed HSS is complex due to the highly non-uniform variation around the cross-section and through the plate thickness. Modeling residual stress in frame analysis is therefore a difficult task. This paper presents a practical method for approximating the effects of different components of residual stress on the behavior of cold-formed HSS by modifying the steel stress-strain curve. The method proposes a convenient means of including residual stress in beam element-based nonlinear frame analysis. A probabilistic study is then carried out to study the effect of the uncertainty in residual stress on frame strength.

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1. Introduction

Cold-formed Hollow Steel Sections (HSS) are broadly used in the construction industry due to their superior mechanical properties and aesthetic appeal. A common method to produce HSS is by (1) uncoiling and levelling (flatten a sheet coil), (2) roll-forming (bend the sheet coil progressively along the width direction), (3) welding (seam-weld the flange tips of the bent strip to a closed circular hollow section (CHS)), and (4) sizing (finish the exact shape to form Rectangular Hollow Section (RHS) or Square Hollow Section (SHS)) [1]. Since there is a large permanent local deformation of the walls of HSS due to the longitudinal and transverse bending effects, residual stresses often exist in different parts of the section.

The strength and behaviour of cold-formed steel structural members may be greatly influenced by the presence of residual stress [2,3]. The residual stresses in a cold-formed steel sections have a substantial bending part and a comparatively small membrane part [2], different from the thermally induced residual stress in hot-rolled and fabricated sections [4]. The distribution of residual stresses in cold-formed structural steel members have been investigated experimentally and analytically. Davison and Birkemoe [5] presented the statistical data for the yield stress and residual stress of HSS. The data was based on experimental results obtained for stub and full-sized HSS to study the behaviour of cold-formed heat-treated and non-heat-treated HSS columns. Longitudinal bending residual stresses were measured by Rasmussen and Hancock [6,7] when investigating stainless steel sections subjected to compression and bending. The residual stress distributions in cold-bent thin steel plates were investigated experimentally and numerically by various researchers [8–10]. Key and Hancock [11] performed experiments on cold-formed Square Hollow Sections (SHS) and proposed a model for the longitudinal and transversal residual stress patterns. Li et al. [1,12] investigated the distribution and magnitude of the residual stress due to the cold-forming process for HSS members. Jandera et al. [13] explored the presence and influence of residual stress in cold-formed stainless steel box sections using experimental and numerical techniques and found that the effect of residual stress on the column buckling of SHS varies with the slenderness of the section. The effect of residual stresses on cold-formed HSS members has also been studied numerically using shell-element based finite element analysis [13,14].

Previous studies have used the Ramberg-Osgood material models to approximate the effects of residual stress on the behavior of cold-formed high strength steel sections [4,11,15–18]. The parameters of the Ramberg-Osgood model (e.g., the parameter controlling the transition from elastic to plastic state) needs to be determined from measured material properties typically obtained

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from coupon tests [17]. Moreover, this approach tends to overestimate the resistance of the member in the low slenderness range [17]. For hot-rolled I-section members, one practical way to include the effect of thermal residual stress on the behavior of highly compressed members is to use a tangent modulus approximation, i.e., to reduce the Young's modulus based on the member's axial force (e.g., using the AISC column curve). The Young's modulus may be further reduced based on major and minor axis bending moments (e.g., see [19]). However, such an approach cannot be used for cold-formed HSS, since the residual stress of cold-formed HSS is completely different from the thermal residual stress in hot-rolled sections.

This paper develops a practical method to approximate the effects of different components of residual stress on the behavior of cold-formed HSS by modifying the stress-strain curve, so that it can be conveniently used in beam element-based nonlinear analysis. The influence of different components of residual stress on frame ultimate strength is investigated numerically. A probabilistic study is then carried out to quantify the effect of the uncertainty in residual stress on frame strength.

2. Residual stress in cold-formed steel tubes

2.1. Residual stress around the cross-section

The residual stress pattern for cold-formed steel tubes has been reported in the literature. The residual stress involves two parts, including: (1) variation of the residual stress through cross-section wall thickness, and (2) magnitude and distribution of the residual stress around the cross-section. Three components of through-thickness residual stress in each direction exist, including: (1) membrane, (2) bending, and (3) layering residual stress. Descriptions of the different residual stress components around cross-section are presented in Table 1. Based on the experimental investigation of four cold-formed normal strength HSS, Key and Hancock [11] proposed the distribution patterns of the residual stress around cross-section in the longitudinal and transversal directions shown in Figs. 1 and 2, respectively.

Somodi & Kövesdi [15] and Ma et al. [21] examined the residual stress distribution of cold-formed *high strength* steel sections. Although the steel grades were different from those examined in [11], the residual stress patterns observed in these studies are comparable, and some common observations are:

1. The longitudinal bending residual stresses in the corner zone are significantly smaller than the values measured in the middle of the plates.
2. The longitudinal membrane residual stress is in compression at the corner and tension in the middle of the plate.
3. The average magnitude of transverse membrane residual stress is zero.

2.2. Residual stress through the section wall thickness

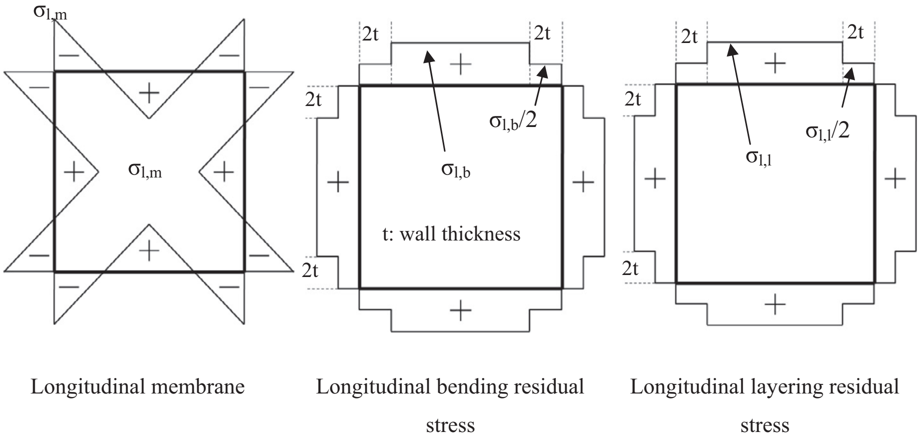
The model for the variation of residual stress through the section wall thickness is based on the experimental measurements in [11], which consists of three components in the longitudinal and transversal directions. The panel removal residual stress was modelled as the membrane and bending components of residual stress in the longitudinal and transversal directions, whereas the released residual stresses from layering was modelled as layering residual stress in the longitudinal and transversal directions. The analytical model satisfies the requirement of zero net axial force and moment [11]. The distributions of through-wall thickness residual stress in the longitudinal and transversal directions are shown in Figs. 3 and 4, respectively.

3. Simplified models of residual stress

The full residual stress pattern shown in Figs. 1–4 can only be incorporated into Shell Finite-Element or Finite-Strip models. To incorporate the effect of residual stress in beam element-based

Table 1
Descriptions of different residual stress components around cross-section.

Longitudinal membrane ($\sigma_{l,m}$)	Stresses varying from maximum tensile at the centre of each face to maximum compressive at the corner
Longitudinal bending ($\sigma_{l,b}$)	Uniform stress over each flat face of the section with half the face value at the corners
Longitudinal layering ($\sigma_{l,l}$)	Same distribution as longitudinal bending residual stress, as suggested in [5]
Transversal membrane ($\sigma_{t,m}$)	Magnitude of transversal membrane residual stress is assumed to be zero as suggested by Key and Hancock [11]
Transversal bending ($\sigma_{t,b}$)	Uniform distribution across each section face as proposed in [20]
Transversal layering ($\sigma_{t,l}$)	Same distribution as transversal bending residual stress, as suggested in [5]



Longitudinal membrane

Longitudinal bending residual stress

Longitudinal layering residual stress

Fig. 1. Residual stress distribution around cross-section in longitudinal direction [11].

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