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Strength enhancements in cold-formed structural sections — Part II: Predictive models

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ABSTRACT

Cold-formed structural sections are manufactured at ambient temperature and hence undergo plastic deformations, which result in an increase in yield stress and a reduction in ductility. This paper begins with a comparative study of existing models to predict this strength increase. Modifications to the existing models are then made, and an improved model is presented and statistically verified. Tensile coupon data from existing testing programmes have been gathered to supplement those generated in the companion paper [1] and used to assess the predictive models. A series of structural section types, both cold-rolled and press-braked, and a range of structural materials, including various grades of stainless steel and carbon steel, have been considered. The proposed model is shown to offer improved mean predictions of measured strength enhancements over existing approaches, is simple to use in structural calculations and is applicable to any metallic structural sections. It is envisaged that the proposed model will be incorporated in future revisions of Eurocode 3 [2,3].

1. Introduction

Cold-formed structural sections are widely used in construction, offering high strength and stiffness-to-weight ratios. Structural elements in a range of section shapes — tubular sections, including the familiar square, rectangular and circular hollow sections and the recently added elliptical hollow sections, and open sections such as angles, channels and lipped channels — are commonly used in building design. Cold-formed structural sections are manufactured at ambient temperature and hence undergo plastic deformations, which occur during both the sheet rolling and cross-section forming processes, causing strain hardening of the material. Upon application of stress, the strain hardened or cold-worked material follows a new loading path with an increased yield stress and ultimate stress, but reduced ductility. In metallic materials with a distinctly defined yield point, such as carbon steels, the stress–strain behaviour becomes rounded following the cold-forming process. Non-uniformity in the material properties around cold-formed sections also exist, due to the varying level of plastic strain experienced, with the corner regions being the most influenced. Materials, such as stainless steel, with rounded stress–strain behaviour and significant strain hardening show a more pronounced response to cold-working.

With increasing emphasis being put on the sustainable use of resources, fully exploiting material properties in structural design is paramount. The performance of finite element (FE) models is also often highly sensitive to the prescribed material parameters, making an accurate representation of the material characteristics essential. Therefore, developing suitable predictive models for harnessing the increases in material strength caused by plastic deformations, experienced during the cold-forming production routes, is required.

In this paper, predictive models from the literature for determining the strength enhancements observed in cold-formed metallic sections are reviewed. Two recently proposed predictive models, developed by Cruise and Gardner [4] and Rossi [5], have been assessed extensively. Improvements to the existing models have been made and a new predictive model is presented. In the companion paper [1], a laboratory testing programme was conducted to measure the level of strength enhancement induced in cold-formed structural sections. Material tests on a total of 51 flat coupons and 28 corner coupons, extracted from the flat faces and corner regions of square hollow sections (SHS) and rectangular hollow sections (RHS) tubes, were performed. The generated tensile coupon test results, combined with those from existing experimental programmes, have been used to validate the predictions from the models and make comparisons between the presented predictive equations. In total, the collated database covers a range of structural section types — SHS and RHS, circular hollow sections (CHS), angles, lipped channels and hollow flange channel sections from both cold-rolling and press-braking fabrication processes — and structural materials, namely carbon steel and stainless steel (EN 1.4301, 1.4306, 1.4307, 1.4318, 1.4404, 1.4571, 1.4401, 1.4016, 1.4003, 1.4509, 1.4512, 1.4462 and 1.4162).

2. Production routes

Cold-rolling and press-braking are the two methods commonly employed in the manufacture of light gauge cold-formed structural

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sections. In press-braking the sheet material is formed into the required shape by creating individual bends along its length. It is a semi-automated process used to produce open sections, such as angles and channels, in limited quantities. Air press-braking, where elastic spring back is allowed by over-bending the material, is more commonly adopted than coin press-braking, where the die and the tool fit into one another. Cold-rolling is an automated continuous bending process in which the gradual deformation of the uncoiled metal sheet through a series of successive rollers produces the final cross-section profile.

In case of tubular box sections, the flat metal sheet is first rolled into a circular tube and is welded closed. It is subsequently deformed into a square or rectangle by means of dies as depicted in Fig. 1. The tube's cross-section is initially circular whereas the cross-section at the end of the process is a square or rectangle with round corners.

3. Predictive models

3.1. Introduction

Finite element simulations of processes involving complex contact and springback problems, such as stamping processes, can be achieved with good accuracy. But, simulating the continuous cold-rolling process using FE methods requires complicated three-dimensional models which becomes computationally expensive due to the relatively high mesh density that must be employed to result in accurate solutions. As examined by Rossi et al. [6], many recent studies have focused on comparisons between different types of finite element formulations and integration schemes for modelling the plastic deformations occurring in the highly bent corner regions of the sections, the change in thickness or springback as well as accurate modelling of the material stress–strain response. But, FE modelling of this continuous process of fabrication is usually not used for determining the strength enhancement occurring in cold-formed sections. Alternatively, closed-form analytical solutions, such as that of Quach et al. [7], of the residual stress distribution and plastic strains induced during press braking exist for elastic–plastic plane strain pure bending with materials assumed to obey the von Mises yield criterion. The analytical models developed to date are restricted to coiling followed by uncoiling and press braking. In the current study, predictive models for the strength increases in the corner regions and flat faces of cold-formed cross-sections are examined.

3.2. Literature review

Early studies of the strength enhancement in the corner regions of cold-formed carbon steel sections were carried out by Karren [8]. A power model to predict the strength increases in the corner regions

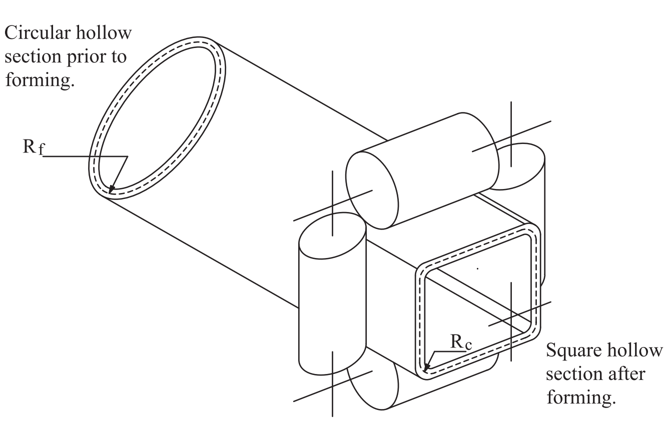

Fig. 1. Cold-rolling fabrication of tubular box sections.

of cold-formed sections, in terms of the yield stress of the unformed sheet material and the internal corner radius to thickness ratio was proposed. The model was developed based on available test data, including specimens formed by both cold-rolling and press-braking processes. The author suggested that since the corner regions typically represent 5% to 30% of the total cross-sectional area, the influence of the enhanced corner strength should be incorporated in structural calculations. Coetzee et al. [9] performed an experimental study into strength enhancements in cold-formed stainless steel sections. Material tests on press-braked lipped channel sections of three stainless steel grades (EN 1.4301, 1.4401 and 1.4003) were conducted. Karren's expression was later modified by van den Berg and van der Merwe [10] on the basis of Coetzee et al.'s [9] test data and further test data on stainless steel single press-braked corner specimens in grades EN 1.4301, 1.4016, 1.4512 and 1.4003. Gardner and Nethercot [11] studied test data from cold-rolled box sections and observed a linear relationship between the 0.2% proof strength of the corner regions and the ultimate strength of the flat faces.

Ashraf et al. [12] analysed all stainless steel test results, from a variety of fabrication processes, to investigate the application of the predictive equations proposed by van den Berg and van der Merwe [10]. Comparisons of the predicted strength and the test results showed that modifications to the models were required. Three empirical predictive models for the evaluation of the corner yield strength were proposed. Two power models based on the properties (0.2% proof strength and the ultimate tensile strength) of the unformed sheet material were developed to predict the corner 0.2% proof strength of both cold-rolled and press-braked sections. The linear expression proposed by Gardner and Nethercot [11], to predict the 0.2% proof strength of the corners in cold-rolled box sections was also recalibrated. Furthermore, in order to obtain full insight into the influence of cold-work on the corner material properties, an equation to predict the ultimate tensile strength of the corner material was developed.

Cruise and Gardner [4] later recalibrated the Ashraf et al. [12] expressions in light of further stainless steel experimental data and proposed two revised expressions to predict the enhanced corner strength of press-braked and cold-rolled sections. In addition, expressions for evaluating the 0.2% proof stress and the ultimate tensile stress of the flat faces of cold-rolled box sections were developed. Similarly, based on corner material test results on structural carbon steel box sections, Gardner et al. [13] modified the predictive model given in the AISI Specification for the Design of Cold-formed Steel Structural Members [14]. Values of the coefficients in the predictive equation were proposed that enabled the model to be applied to the assessment of the enhanced corner strength of cold-rolled square and rectangular hollow sections.

An alternative formula to evaluate the enhanced 0.2% proof strength in the flat faces and corner regions of cold-formed sections, using the properties of the unformed sheet material and the final cross-section geometry, was proposed by Rossi [5]. The proposed equation is established using the inverted Ramberg–Osgood material model without introducing empirical parameters, allowing its application to a range of non-linear metallic materials.

3.3. Cruise and Gardner [4] predictive model

Cruise and Gardner [4] carried out an extensive experimental study of cold-formed stainless steel structural sections made of grade EN 1.4301 material, produced from both cold-rolling and press-braking production routes. Based on the experimental results, including tensile coupon tests and hardness tests, the distributions of the 0.2% proof strength and ultimate tensile strength around a series of cold-rolled box sections and press-braked angle sections were identified. The generated test data were combined with all other available published experimental data and used to develop models for predicting the strength enhancements around stainless steel sections due to cold-forming. The