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Description of stress-strain curves for cold-formed steels

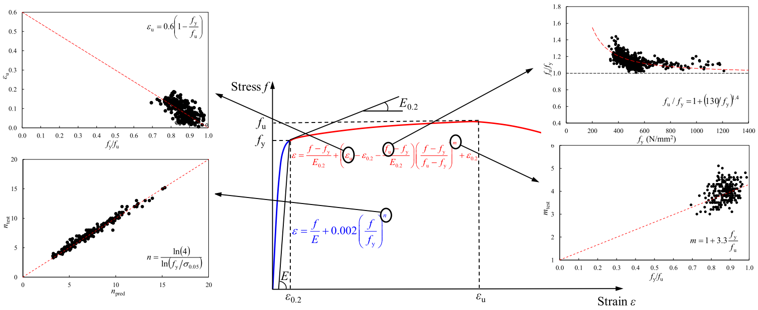
Leroy Gardner, Xiang Yun *

Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK

HIGHLIGHTS

- Review of existing stress-strain models and models for predicting the strength enhancements in cold-formed steel sections.
- Collection of data from over 700 experimental stress-strain curves on cold-formed steels from the global literature.
- Proposal of two-stage Ramberg-Osgood model to represent stress-strain curves of cold-formed steels.
- Development of predictive expressions and numerical values for the key material parameters for cold-formed steels.
- Evaluation of the accuracy of the proposed stress-strain curves through comparisons with experimental data.

GRAPHICAL ABSTRACT



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ABSTRACT

Cold-formed steels are generally characterized by a rounded stress-strain response with no sharply defined yield point. It is shown herein that this material behaviour can be accurately described by a two-stage Ramberg-Osgood model provided that the values of the key input parameters can be established. The focus of the present paper is to develop predictive expressions for these key parameters to enable the full engineering stress-strain response of cold-formed steels to be represented. The predictive expressions are based on the analysis of a comprehensive set of material stress-strain data collected from the literature. In total, more than 700 experimentally-derived stress-strain curves on cold-formed steel material have been collected from around the world, covering a range of steel grades, thicknesses and cross-section types. The strength enhancement in the corner regions of cold-formed sections has also been analysed and the applicability of existing predictive models has been evaluated. Finally, standardized values of strain-hardening exponents used in the Ramberg-Osgood model have been recommended for both flat and corner material in cold-formed steel sections. The proposed stress-strain curves are suitable for use in advanced numerical simulations and parametric studies on cold-formed steel elements.

1. Introduction

Cold-formed steel members are widely used in building construction due to their high strength and stiffness-to-weight ratios and ease of prefabrication and mass production. Press-braking and roll-forming are the two primary methods employed in the manufacture of cold-formed steel products. In both methods, steel sheet or strip, which would typically have been cold-rolled, serves as the feed material. In press-braking, sheet material is formed into the desired geometric shape by applying predetermined bends along its length, which are generally accomplished by punch and

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* Corresponding author.
E-mail address: x.yun14@imperial.ac.uk (X. Yun).

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die sets. The press-braking process is commonly used to produce cold-formed open sections, such as angles and channels. Roll-forming is a process by which steel sheet or strip is passed through a series of rollers that progressively shape the material into the final cross-section profile. Different levels of cold-work (plastic deformation) are generated during the manufacturing process, resulting in changes to the stress-strain characteristics of the material. Generally, cold-work results in a more rounded stress-strain response with an increased yield strength and, to a lesser extent, an increased ultimate strength, but reduced ductility. Non-uniformity of material properties is also commonly seen in cold-formed sections due to the varying level of cold-work experienced at different locations around the section shape. The corner regions of cold-formed cross-sections undergo large plastic deformation from cold bending due to their tight corner radii, hence resulting in a higher degree of strength enhancement but a corresponding loss in ductility.

Constitutive modelling is an essential part of structural engineering and a key component of analytical, numerical and design models. A number of material models have been developed to describe the nonlinear stress-strain response of metallic materials over the last few decades, as reviewed in the next section, the most widely used of which are based on the general expression proposed by Ramberg and Osgood [1] and later modified by Hill [2]. A number of studies have focused on the material modelling of stainless steels (Rasmussen [3], Quach et al. [4], Arrayago et al. [5] and Tao and Rasmussen [6]), but values and predictive expressions for the key parameters in these models require modification for applicability to the particular stress-strain characteristics of cold-formed steels. The aim of the present study is to develop an accurate stress-strain model for use in the advanced simulation of cold-formed steel members, based upon and validated against data from over 700 experimental stress-strain curves collected from the global literature, covering a wide range of steel grades, production routes and cross-section types. A rounded stress-strain response is associated with structural cross-sections that experience sufficient cold-work during sheet/section forming to erode the yield plateau, and is particularly common for cold-formed tubular sections. Cold-formed steels that exhibit this characteristic rounded stress-strain response with no yield plateau are the focus of the present paper.

2. Overview of existing models and previous work

2.1. Existing stress-strain models

The Ramberg-Osgood model (Ramberg and Osgood [1] and Hill [2]) is widely used to describe the rounded stress-strain response of aluminum alloys, stainless steels and cold-formed carbon steels. The Ramberg-Osgood model (see Eq. (1)) is generally defined using three basic parameters – the Young's modulus E, the material yield strength f_y (taken as the 0.2% proof stress) and the strain hardening exponent n. The strain hardening exponent n can be determined using an additional proof stress e.g. the 0.01% proof stress $\sigma_{0.01}$, as given by Eq. (2), or the 0.05% proof stress $\sigma_{0.05}$, as given by Eq. (3). The latter has been shown by Rasmussen and Hancock [7] and Arrayago et al. [5] to yield more consistent n values in comparison to curves fitted to stainless steel stress-strain data by regression analysis.

$$\varepsilon = \frac{f}{E} + 0.002\left(\frac{f}{f_y}\right)^n \tag{1}$$

$$n = \frac{\ln(20)}{\ln(f_y/\sigma_{0.01})} \tag{2}$$

$$n = \frac{\ln(4)}{\ln(f_y/\sigma_{0.05})} \tag{3}$$

Eq. (1) has been shown to be capable of accurately representing different regions of the stress-strain curve of stainless steel, depending on the choice of the n parameter, but found to be generally incapable of accurately representing the full stress-strain curve with a single value of n. This observation led to a number of developments and extensions to the Ramberg-Osgood model. Mirambell and Real [8] proposed a smooth two-stage stress-strain model, utilising the conventional Ramberg-Osgood relationship (Eq. (1)) up to the yield strength and introducing a second Ramberg-Osgood curve commencing at the yield strength f_y and continuing up to the ultimate tensile strength f_u, as given by Eq. (4). Continuity of position and slope is achieved at the transition point (i.e. the yield strength f_y) between the two stages (i.e., between Eqs. (1) and (4)). Fig. 1 shows a typical cold-formed steel stress-strain curve, together with the key material parameters used in the two-stage Ramberg-Osgood model.

$$\varepsilon = \frac{f - f_y}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{f_u - f_y}{E_{0.2}}\right)\left(\frac{f - f_y}{f_u - f_y}\right)^m + \varepsilon_{0.2}, \text{ for } f_y < f \leqslant f_u \tag{4}$$

In Eq. (4), ε_u is the strain at the ultimate strength f_u, $\varepsilon_{0.2}$ is the total strain at the yield strength f_y (0.2% proof stress), $E_{0.2}$ is the tangent modulus at the 0.2% proof stress, given by Eq. (5), and m is the strain hardening exponent for the second part of the two-stage model, which can be determined from the ultimate strength and an intermediate strength. Note that Eq. (1) remains applicable for strengths less than or equal to the yield strength f_y.

$$E_{0.2} = \frac{E}{1 + 0.002n\frac{E}{f_y}} \tag{5}$$

The two-stage Ramberg-Osgood model was simplified by Rasmussen [3] by approximating the plastic strain term $\varepsilon_u - \varepsilon_{0.2} - \frac{f_u - f_y}{E_{0.2}}$ in Eq. (4) to the ultimate strain ε_u, as expressed in Eq. (6). In addition, Rasmussen [3] also developed predictive expressions for the second strain hardening exponent m, the ultimate strain ε_u and ultimate strength f_u for stainless steel alloys, as given by Eqs. (7)–(9), respectively, using the three basic Ramberg-Osgood parameters (E, f_y and n). As a result, only the three basic parameters are required to describe full stress-strain curves for different stainless steel grades. Note that the simplified expression [Eq. (6)] predicts a stress-strain curve that does not pass exactly through the ultimate strength point (ε_u, f_u), though the discrepancies due to the approximation of ultimate strain in the Rasmussen model are small especially for the more ductile stainless

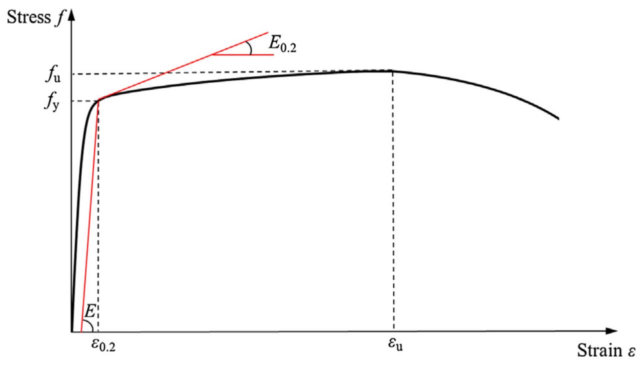

Fig. 1. Typical cold-formed steel stress-strain curve with definitions of key material parameters.