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Stress-strain curves for hot-rolled steels

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ABSTRACT

The use of advanced analytical and numerical modelling in structural engineering has increased rapidly in recent years. A key feature of these models is an accurate description of the material stress-strain behaviour. Development of standardised constitutive equations for the full engineering stress-strain response of hot-rolled carbon steels is the subject of the present paper. The proposed models, which offer different options for the representation of the strain hardening region, feature an elastic response up to the yield point, followed by a yield plateau and strain hardening up to the ultimate tensile stress. The Young's modulus E, the yield stress f_y and the ultimate stress f_u are generally readily available to the engineer, but other key parameters, including the strains at the onset of strain hardening and at the ultimate stress, are not, and hence require predictive expressions. These expressions have been developed herein and calibrated against material stress-strain data collected from the literature. Unlike the widely used ECCS model, which has a constant strain hardening slope, the proposed models, reflecting the collected test data, have a yield plateau length and strain hardening characteristics which vary with the ratio of yield to ultimate stress (i.e. with material grade). The proposed models require three basic input parameters (E, f_y and f_u), are simple to implement in analytical or numerical models, and are shown herein to be more accurate than the widely employed ECCS model. The proposed models are based on and hence representative of modern hot-rolled steels from around the world.

1. Introduction

With the increasing use of advanced computational and analytical methods in structural engineering, there is a crucial need for accurate representations of the key input parameters. Development of accurate, yet simple models to describe the full stress-strain response of hot-rolled structural steels is the subject of the present paper. Representation of the full stress-strain curve is particularly important in analytical, numerical or design models for scenarios in which large plastic strains are encountered. Such scenarios include the simulation of section forming [1], the response of structures under extreme loads [2,3], the modelling and design of connections [4,5] and the design of structural elements incorporating inelastic behaviour and strain hardening [6,7].

Although a number of stress-strain models have been developed for hot-rolled carbon steels [8–10], they are either only applicable to a limited strain range or are too complex to be readily implemented in practice. Comprehensive reviews of existing stress-strain models for structural steel have been presented by Huang [9], Foster [11] and Bruneau et al. [12], while a brief overview is presented in the following section. In this paper, two material models for hot-rolled carbon steels are proposed – a quad-linear material model suitable for use in design calculations allowing for yielding and strain hardening and a bilinear plus non-linear hardening model suitable for incorporation into advanced numerical simulations. The proposed models are based upon and calibrated against data from over 500 experimental stress-strain curves collected from the global literature from 34 individual sources and featuring material produced around the world.

2. Overview of existing stress-strain models and previous work

2.1. General

A typical stress-strain curve of hot-rolled carbon steel subjected to quasi-static tensile load is illustrated in Fig. 1. In the elastic range, the slope is linear and is defined by the modulus of elasticity, or Young's modulus E, taken as 210,000 N/mm^2 for structural steel according to EN-1993-1-1 [13]. The linear path is limited by the yield stress f_y and the corresponding yield strain ε_y, and followed by a region of plastic flow at an approximately constant stress until the strain hardening strain ε_{sh} is reached. At this point, the plastic yield plateau ends and strain hardening initiates. Beyond this point, stress accumulation recommences at a reducing rate up to the ultimate tensile stress f_u and the corresponding ultimate tensile strain ε_u, as illustrated in Fig. 1.

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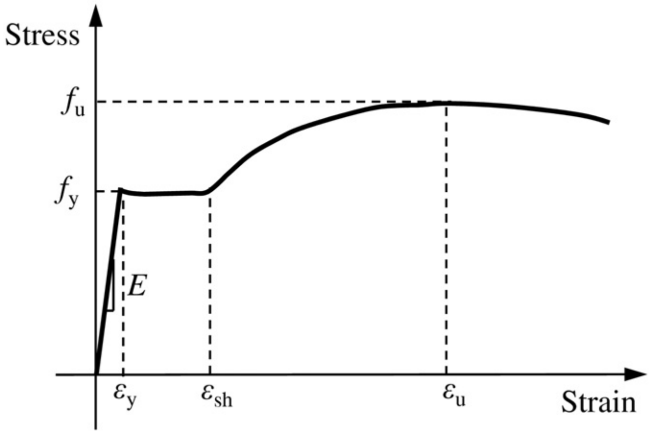

Fig. 1. Typical engineering stress-strain curve for hot-rolled carbon steel.

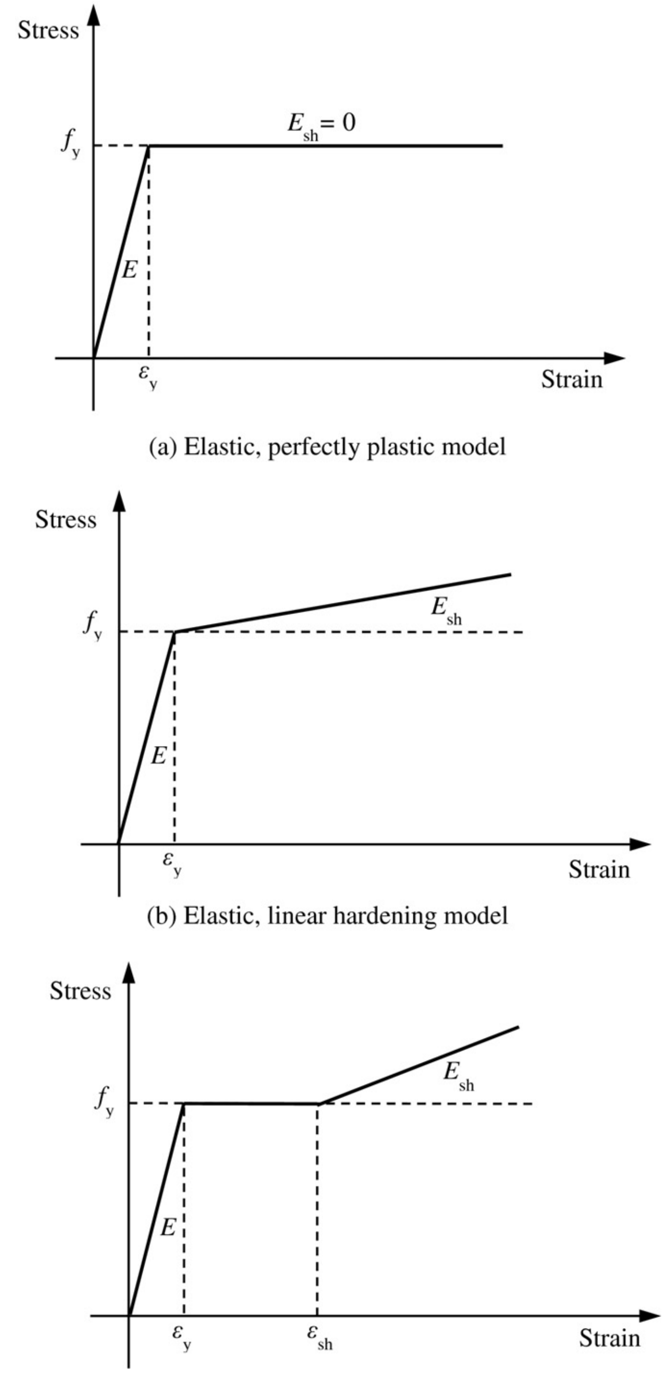

Fig. 2. Existing linear material models for hot-rolled carbon steels.

2.2. Existing stress-strain models

Various simplified models have been proposed to represent the material response of hot-rolled carbon steels, among which the linear models can be grouped as (1) elastic, perfectly-plastic, (2) elastic, linear hardening and (3) tri-linear. The elastic, perfectly-plastic model is illustrated in Fig. 2(a), and forms the basis of the current design methods in EN 1993-1-1 [13]. This model is a suitable simplification for scenarios in which strain hardening is not expected to feature (e.g. in the simulation or design of elements whose resistance is dominated by instability) or in which strain hardening is simply ignored. In this model, only two basic material parameters (E and f_y) are needed. The elastic, linear hardening model offers the simplest consideration of strain hardening, as illustrated in Fig. 2(b), where E_{sh} is the strain hardening modulus. This model considers strain hardening, is included in Annex C of EN 1993-1-5 [14], and has been used throughout the development of the strain-based continuous strength method (CSM), which allows for the beneficial influence of strain hardening on the design of structural metallic elements, including structural carbon steel [6,7,15], aluminium [16,17] and stainless steel [18,19]. However, due to the existence of a yield plateau, this elastic, linear hardening model is less suitable for hot-rolled carbon steels. The next level of complexity of material models after elastic, linear hardening is the tri-linear model which considers both a yield plateau and strain hardening, as shown in Fig. 2(c). Similar to the elastic, linear hardening model, the tri-linear model assumes a constant strain hardening modulus E_{sh} (after the yield plateau), but this does not accurately capture the observed strain hardening behaviour, which shows a progressive loss in stiffness up to the ultimate tensile stress f_u (see Fig. 1).

The Ramberg-Osgood model [20,21] is widely used to describe the rounded stress-strain response of metallic materials such as stainless steels, aluminium and cold-formed carbon steels that have undergone sufficient plastic deformation to eliminate the yield plateau. The Ramberg-Osgood expression is defined by Eq. (1) and features the Young's modulus E, the 0.2% proof stress $\sigma_{0.2}$, which is conventionally considered as an 'equivalent' yield stress, and the strain hardening exponent n. The Ramberg-Osgood model has been shown to be capable of accurately capturing the stress-strain curve up to $\sigma_{0.2}$, but can become inaccurate at higher strains, as demonstrated for stainless steels in [22]. This observation led to several studies aimed at improving the model at large strains [22–24]. Huang [9] proposed a three-stage stress-strain model based on the Ramberg-Osgood expression which includes both a yield plateau (assuming an inclined yield plateau) and strain hardening, as given by Eq. (2), where $\varepsilon_{0.2}$ is the total strain at the 0.2% proof stress, $E_{0.2}$ and E_{st} are the tangent moduli at the 0.2% proof stress ($\varepsilon_{0.2}$, $\sigma_{0.2}$) and the strain hardening point (ε_{sh}, σ_{sh}), respectively, and m_{sh} and m_u are exponents determining the shape of the second and third stages of the curve, respectively. The accuracy of the proposed model was assessed by comparing its predictions with experimental stress-strain curves as well as the predictions from two existing stress-strain models for metals with a yield plateau: Mander's model [25] and a modified power law model [26]. The proposed model could successfully predict the behaviour of hot-rolled carbon steels with a yield plateau over the full strain range up to ε_u. However, it is only