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Comparative study of analytical expressions for the modelling of stainless steel behaviour

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ABSTRACT

During the last decades, various material models have been proposed describing stainless steel nonlinear behaviour through different parameters. The differences among these models are analysed herein using experimental data of different stainless steel types. An interactive computer programme, usable for any series of experimental data, is developed and presented: the procedure for the determination of Young's modulus (E_0) is pointed out and the least-square adjustment to optimize the strain-hardening exponents of different material models is described. Different expressions for the calculation of the parameters, proposed by several authors and used in a variety of codes, are analysed and new ones are proposed.

1. Introduction

Stainless steel is a relatively recent material that combines excellent corrosion resistance and suitable mechanical properties for structural applications, but its nonlinear stress–strain behaviour makes it different from carbon steel. Current modelling techniques require the definition of an analytical expression describing this nonlinear stress–strain relationship through a material model. Different analytical expressions reproducing this behaviour can be found in the literature [1–8], all of them based on the expression originally proposed by Ramberg–Osgood [9] and modified by Hill [10].

Those material models use parameters that can be determined by fitting the analytical curve to stainless steel experimental data. These parameters show great variability between different stainless steel grades. Additionally, values for these parameters can be obtained both from tables in AS/NZS 4673 [11], SEI/ASCE-8 [12] and EN 1993-1-4 [13] and from analytical expressions (previously calibrated for certain stainless steel grades). Results obtained from both methods are usually very different, and also when compared to experimental results. Hence, it is necessary to carry out an extensive study on material parameters by developing a tool that automatically determines these parameters from experimental data for the most relevant material models.

This paper presents a computer programme which estimates, using experimental data, values of mechanical properties and optimum strain-hardening parameters corresponding to different material models. The differences between these models are analysed in order to determine the most appropriate approach, and some expressions for the estimation of material parameters that fit the stress–strain behaviour of different stainless steel grades are analysed and proposed.

Even though many authors have highlighted that cold-working processes result in enhancement of the yield stress and ultimate strength and causes important residual stresses [14–17], this preliminary study covers coiled materials only.

2. Material models and standards

2.1. Existing material models

During the last decades, various material models that reproduce stainless steel behaviour have been developed, and some of them are included in EN 1993-1-4 [13]. All these models are based on the general expression proposed by Ramberg–Osgood [9], later modified by Hill [10]. This basic equation is presented in the following equation, where E_0 is the elastic modulus or Young's modulus, $\sigma_{0.2}$, conventionally considered as the yield stress, is the proof stress corresponding to a 0.2% plastic strain and n is the strain-hardening exponent, usually calculated from Eq. (2), where $\sigma_{0.01}$ is the proof stress corresponding to a 0.1% plastic strain:

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \tag{1}$$

$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \tag{2}$$

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The Ramberg–Osgood expression provides accurate results for stresses up to the yield stress, but when stresses increase, experimental and predicted stress–strain curves diverge. In order to analytically describe stainless steel behaviour for higher stresses, Mirambell–Real [1] proposed a two-stage model. In this model Ramberg–Osgood's expression Eq. (1) is used for a first stage that covers stresses up to 0.2% proof stress, and a second curve is defined for stresses $\sigma > \sigma_{0.2}$. The curve corresponding to this second stage has a new reference system and a different strain-hardening exponent m

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \quad \text{for } \sigma > \sigma_{0.2} \tag{3}$$

$$E_{0.2} = \frac{E_0}{1 + 0.002 n \frac{E_0}{\sigma_{0.2}}} \tag{4}$$

where $E_{0.2}$ is the tangent modulus at 0.2% proof stress defined by Eq. (4), σ_u and ε_u are the ultimate strength and strain, respectively, $\varepsilon_{0.2}$ is the total strain at 0.2% proof stress, and m is the strain-hardening coefficient of the second stage.

Rasmussen [2] revised this model for austenitic, ferritic and duplex stainless steels and proposed some simplifications in order to reduce the number of parameters needed to define the material model. The second stage is, in this new version, defined by the modified equation Eq. (5), which assumes that the ultimate plastic strain is equal to total ultimate strain. In addition, the author proposed expressions for the second strain-hardening exponent m Eq. (6) and for the ultimate strain ε_u and strength σ_u Eq. (7) and Eq. (8), using the three basic Ramberg–Osgood parameters only. This proposal has been included in Annex C of EN 1993-1-4 [13] for modelling stainless steel behaviour

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u \left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \quad \text{for } \sigma > \sigma_{0.2} \tag{5}$$

$$m = 1 + 3.5 \frac{\sigma_{0.2}}{\sigma_u} \tag{6}$$

$$\varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u} \tag{7}$$

$$\frac{\sigma_{0.2}}{\sigma_u} = \begin{cases} 0.2 + 185\frac{\sigma_{0.2}}{E_0} & \text{for austenitic and duplex} \\ \frac{0.2 + 185\frac{\sigma_{0.2}}{E_0}}{1 - 0.0375\cdot(n-5)} & \text{for all stainless steel alloys} \end{cases} \tag{8a, b}$$

In order to obtain a more consistent model for compression, Gardner and Nethercot [3] proposed additional modifications of the two-stage model. By shifting the limit between stages and placing it at the 1% proof stress, this model presents excellent agreement with experimentally measured stress–strain curves in both tension and compression. Moreover, it provides accurate predictions of stress–strain behaviour in the structural-purpose strain range, where strains are not very high

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_{1.0} - \varepsilon_{0.2} - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n0.2-1.0} + \varepsilon_{0.2} \quad \text{for } \sigma > \sigma_{0.2} \tag{9}$$

where $\sigma_{1.0}$ is the proof stress corresponding to a 1% plastic strain, $\varepsilon_{1.0}$ is the total strain at the 1% proof stress, and $n_{0.2-1.0}$ is the strain-hardening coefficient of the second stage for Gardner's model.

However, advanced numerical modelling requires deep knowledge of stainless steel behaviour and an accurate prediction of experimental stress–strain curves over a wide strain range, especially for modelling cold-forming processes. Quach et al. [5] proposed a full-range three-stage material model calibrated from virgin material and flat portions of cold formed sections. This model, which uses the three basic Ramberg–Osgood parameters, models both tensile and compressive behaviour. For the first stage, which covers stresses up to the yield stress, this model uses the Ramberg–Osgood equation and the expression used for the second stage (stresses up to 2% of the proof stress) is a modified Gardner proposal. Lastly, for the third stage (stresses up to the ultimate strength) the author proposes a new expression based on the assumption that, when true stress-nominal strain variables are considered, stress–strain behaviour at high strains can be modelled as a straight line passing though the point of 2% proof stress and the ultimate strength.

Hradil et al. [8] developed a new three-stage model which uses the Ramberg–Osgood equation for every stage, but with different reference systems. This model was developed to fit experimental curves up to ultimate strains. Other authors [18–20] have proposed two-stage models describing stress–strain behaviour of stainless steels at high temperatures.

The main differences among these models lie in the election of the stress–strain curve ending point and in the number of necessary parameters for their definition. The Ramberg–Osgood model is used for stresses up to the 0.2% proof stress and needs only the strain-hardening exponent n; Mirambell–Real and Rasmussen models are defined for strains up to the ultimate strength σ_u and use two strain-hardening parameters, n up to 0.2% proof stress and m for the second stage. The main difference between these two models is the number of material parameters needed for their definition; Mirambell–Real model needs six parameters while Rasmussen model needs only three.

As it has been explained before, Gardner's model is defined for stresses up to the 1% proof stress and needs also two strain-hardening coefficients. In both three-stage material models presented in this section, the first stage corresponds to stresses up to the 0.2% proof stress. However, the limit between the second and the third stages is slightly different: while model [5] locates this limit at the 2% proof stress, model [8] uses the 1% proof stress as frontier between stages. Ultimate strength σ_u is the upper limit for both three-stage models.

2.2. EN 1993-1-4

Expressions for the analytical description of the stainless steels behaviour proposed in EN 1993-1-4, Annex C [13] are derived from Rasmussen material model Eqs. (5)–(7)), but instead of obtaining the ultimate strength σ_u using an expression, EN 1993-1-4 proposes different σ_u values depending on stainless steel grades. Values for $\sigma_{0.2}$ and E_0 are also proposed. The value of the first strain-hardening exponent n can be obtained from Eq. (2) or from Table 2.1 in EN 1993-1-4.

3. Test data

In order to obtain the main parameters for each material model, experimental data from previous experimental tests carried out at UPC and Outokumpu have been analysed. Of the 42 experimental stress–strain curves studied (see Table 1), 24 have already been published in literature [21–23]. The remaining 18 data where provided by Outokumpu. All the studied coupons were coiled and cut from plate elements in the rolling direction.

4. Developed software: highlights

The obtention of material properties and optimum values of the strain-hardening exponents from experimental stress–strain