Thin-Walled Structures 63 (2013) 63–69

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Generalized multistage mechanical model for nonlinear metallic materials

Petr Hradil [a,*], Asko Talja [a], Esther Real [b], Enrique Mirambell [b], Barbara Rossi [c]

[a] VTT, Technical Research Centre of Finland, PO Box 1000, FI-02044 VTT, Finland
[b] Department of Construction Engineering, Universitat Politècnica de Catalunya, UPC, C. Jordi Girona, 1-3. 08034 Barcelona, Spain
[c] Department ArGEnCo, University of Liège, 1,chemin des chevreuils, 4000 Liège, Belgium

ARTICLE INFO

Article history:
Received 11 November 2011
Received in revised form
15 October 2012
Accepted 17 October 2012
Available online 24 November 2012

Keywords:
Stainless steel
Nonlinear
Strain hardening
Material model
Generalization

ABSTRACT

Metallic alloys have a significant role in thin-walled engineering structures due to their unique properties such as corrosion resistance, low density or durability. Their mechanical behaviour is usually nonlinear, and this nonlinearity can be further increased during the work-hardening process. In such cases, designers have to take the proper stress–strain relationship into account to obtain reliable prediction of deformations or internal forces. In this paper, a theoretical model is proposed to match different kinds of measured data or already existing stress–strain models. It is flexible to accommodate any number of measured or recommended material parameters, and therefore makes design rules independent on testing standards. It is particularly suitable for computer code implementation. The approximate inversion of the multistage model is also included in the presented study. The general formula is applied on the set of parameters typically available for structural stainless steels in Europe (0.2% and 1.0% proof strength and ultimate strength) and compared to the existing models by curve-fitting of analytical equations to measured stresses and strains of austenitic, duplex and ferritic stainless steels. The comparisons clearly showed that this three-stage application of the generalized multistage model yields more accurate results compared to the existing material models both in its direct and inverse form.

1. Introduction

The use of metallic materials such as stainless steels and aluminium alloys in modern civil engineering structures brought up the difficulty of their mechanical behaviour implementation in design codes. Indeed, the nonlinear stress–strain relationship of such materials requires a proper analytical material model to be available. Several models have been developed during the last decades and some of them are already implemented in the European, Australian and American design standards for stainless-steels structures [1–3]. All those models have different level of complexity and limitations and generally rely on a set of material parameters obtained via experiments (coupon tests or stub column tests). Some of them show a good agreement with test results at very high strains while others focus on the range of strain expected in load-bearing structures.

The present study proposes a generalized multistage formula based on well-established material models. The formulation is able to intersect any number of measured points of the stress–strain curve, and the expression is therefore independent on particular testing methods or design standards. The proposed generalized model purpose is to unify most of the present modelling approaches in a single definition to enable a simpler and transparent cross-platform handling of the material data in order to offer a greater flexibility to designers and program developers.

The research leading to the presented results has received funding from a major European research project focused on the structural applications of ferritic stainless steels. A brief description of this project will be included herein.

2. Current research on ferritic stainless steels

Traditionally, although widely used in the automotive and domestic appliance sectors, ferritic stainless steels have been scarcely applied in engineering structures. However, the advantages offered in terms of low cost, price-stability and corrosion-resistance has led to an increase in attention from structural designers as well as researchers in recent years. Experimental and analytical works such as those presented in this paper have provided much of the current information that is known about these materials but currently, ferritic stainless steels are only partially covered by European structural standards and it has been recognised that further research investigations are necessary in order to provide more comprehensive design recommendations.

* Corresponding author. Tel.: +358 400209593; fax: +358 207227007.
E-mail address: petr.hradil@vtt.fi (P. Hradil).

0263-8231/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tws.2012.10.006

In this context, the European Community's Research Fund for Coal and Steel (RFCS) has provided sponsorship for a major three-year international research project into the structural applications of ferritic stainless steels. The primary objective of the project is to increase the use of load-bearing ferritic stainless steel in construction by providing practitioners with more reliable performance data and design guidance. The project is managed and co-ordinated by the Steel Construction Institute (SCI) in the UK and the other partners include AcerInox (Spain), Aperam (France), Arup (UK), Institute of Metals and Technology (IMT) (Slovenia), Outokumpu Stainless Oy (Finland), Universitat Politechnica de Catalunya (UPC) (Spain) and VTT Technical Research Centre of Finland (Finland), as well as subcontractors from University of Liege. Additional funding is also being provided by AcerInox, Aperam, Outokumpu Stainless Oy and the International Chromium Development Association (ICDA). The research project has been divided into the following studies: (i) Mechanical properties; (ii) Structural performance of light gauge members; (iii) Structural performance of steel decking in composite floor systems; (iv) Structural performance at high temperatures; (v) Structural performance of bolted and screwed connections; (vi) Structural performance of welded connections; (vii) Corrosion resistance; (viii) Design guidance and implementation into Eurocode 3. The work presented in this paper is developed in the framework of the structural performance of light gauge members and has as main objective to propose a constitutive model for ferritic stainless steel. Although the model has been developed for ferritic steels, it is able to describe the stress–strain behaviour of most of ferrous and non-ferrous metallic materials.

3. Existing material models

The need for a more accurate analytical description of the stress–strain relationship of materials, the behaviour of which does not show any clear yield point, appeared in 1939 when Holmquist and Nadai used a polynomial expression (see Eq. (1)) to describe the material behaviour beyond the proportional limit in order to predict the buckling resistance of tubes made of stainless steel, iron and brass [4].

$$\varepsilon = \frac{\sigma}{E_0} + \varepsilon_y \left(\frac{\sigma - \sigma_P}{\sigma_y - \sigma_P}\right)^n \text{ when } \sigma > \sigma_P, \text{ and } \varepsilon = \frac{\sigma}{E_0} \text{ otherwise} \quad (1)$$

where σ_y and ε_y are the yield stress and strain, respectively, E_0 stands for the initial modulus of elasticity and σ_P is the proportional limit. The parameter n determines the nonlinearity of the curve, resulting in perfect elastic–plastic behaviour when n is infinite. Ramberg and Osgood later developed a similar model for aluminium alloys [5],

$$\varepsilon = \frac{\sigma}{E_0} + K\left(\frac{\sigma}{E_0}\right)^n \quad (2)$$

which is, in fact, Holmquist and Nadai's model if we assume that the proportional limit is 0 and the Ramberg–Osgood constant K is

$$K = \varepsilon_y \left(\frac{E_0}{\sigma_y}\right)^n \quad (3)$$

The offset yield stress σ_y for stainless steel was agreed to be the conventional 0.2% proof stress $\sigma_{0.2}$ [6] and the basic equation turned to the well-known form presented in Eq. (4) which is widely used nowadays for example in AS/NZS 4373:2001 [2], Eurocode 3, Part 1–4 [1] and SEI/ASCE [3].

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \quad (4)$$

The nonlinear constant n is usually calculated using the 0.01% offset stress $\sigma_{0.01}$ as shown in Eq. (5).

$$n = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})} \quad (5)$$

Although the modified Ramberg–Osgood equation (Eq. (4)) is relatively simple, it does not fit well the observed behaviour of some materials at higher stress than the 0.2% proof strength. In case of stainless steels, several improvements of this model have been proposed recently. A smooth two-stage material model, established from Ramberg–Osgood's equation was proposed by Mirambell and Real [7]. It introduces a second Ramberg–Osgood curve originating from the 0.2% proof stress which continues with the same tangent modulus but using one additional parameter of nonlinearity, namely m (see Fig. 1),

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \text{ when } \sigma > \sigma_{0.2} \quad (6)$$

where σ_u and ε_u are the ultimate stress and strain, respectively, $\varepsilon_{0.2}$ stands for the total strain when the 0.2% proof stress is reached, $E_{0.2}$ represents the tangent modulus of elasticity at 0.2% proof stress and m is the nonlinear parameter of the second stage.

In the previous equation, the initial modulus of elasticity of the second stage has to be equal to the tangent modulus of elasticity at the last point of the previous stage defined by Eq. (4), and therefore ,it can be calculated using the following formula:

$$E_{0.2} = \frac{E_0}{1 + 0.002n(E_0/\sigma_{0.2})} \quad (7)$$

The model was revised for austenitic, ferritic and duplex stainless steels by Rasmussen [8] and its original six parameters reduced to three. This form is nowadays included in the Annex C of Eurocode 3, Part 1–4 [1]. The formula is based on the assumption that the ultimate plastic strain is approximately equal to the total ultimate strain and it is a function of the 0.2% proof strength to ultimate stress ratio (see Eq. (8)).

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(1 - \frac{\sigma_{0.2}}{\sigma_u}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \text{ when } \sigma > \sigma_{0.2} \quad (8)$$

The second nonlinear parameter m is calculated using the same ratio,

$$m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \quad (9)$$

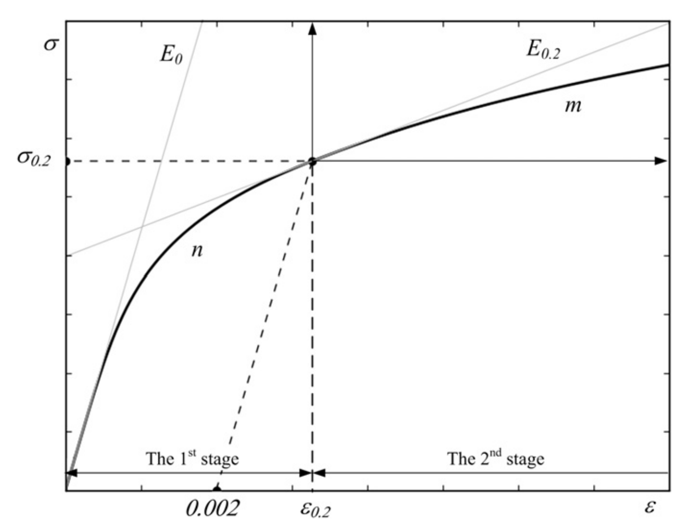

Fig. 1. Mirambell and Real's two stages model.