Journal of Constructional Steel Research 136 (2017) 65–74

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

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

Study on Ramberg-Osgood and Chaboche models for 42CrMo4 steel and some approximations

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ARTICLE INFO

Keywords:
Material parameters
Steel 42CrMo4
Ramberg-Osgood model
Chaboche model

ABSTRACT

Presented work is focused on experiment-based characterization and modelling of normalized and quenched and tempered low-alloy steel 42CrMo4 subjected to monotonic and cyclic loading and possibility to determine parameters of more complex models from simple ones. The main characteristics of the cyclic Ramberg-Osgood and rate-dependent as well as rate-independent Chaboche's material models, both of which are applicable for this material, have been presented. Similarities in the modelling and simulation of stabilized material behaviour confirmed possibility of such approximation for Ramberg-Osgood and rate-independent Chaboche model. However, due to inadequacy of Ramberg-Osgood for modelling of evolutionary material behaviour throughout loading cycles, separate study of the influence of saturation rate of isotropic hardening of rate-dependent Chaboche's model on modelling and simulation of material behaviour has been performed. The study showed that deviations of simulated material behaviour from the experimentally obtained behaviour are low, and in majority of the materials life negligible and recommendations on the range of values of saturation rate parameters differently heat treated 42CrMo4 steel are provided. In order to make possible further comparisons of analysed models and evaluate applicability of proposed approximations on other materials, further analyses on additional materials would need to be performed.

1. Introduction

Today, as always, engineers are facing the requirements to shorten the product development time but at the same time to deliver higher accuracy and more detailed knowledge of the behaviour and performance of the future products. A possibility to take into account additional conditions that mechanical components operate in, as well as to consider and correctly simulate different phenomena such as Bauschinger effect, kinematic and isotropic hardening (softening), viscoplasticity and temperature effects, among others, is one of the key drivers in making the transition from simple, conventional material models to the more advanced constitutive models of materials behaviour in engineering calculations. This is further supported by the rapid development of software tools and increase of computational power available so that consequently, application of advanced simulation methods and complex material models are becoming indispensable part of engineering practice and product development.

One of the main prerequisites for successful implementation of advanced materials models in simulation of product behaviour is knowledge of stress-strain response of the material i.e. in-depth information on related materials' parameters. This prerequisite is also one of the major obstacles preventing wider adoption of advanced materials models since experimental characterization of material behaviour and determination of parameters' values is long-lasting and complex and materials' data available in literature and other sources [1–5] are mainly limited to basic materials models only.

Finding ways to obtain advanced material information from simple material properties that are easy to determine in order to postpone experiments and/or to reduce their number has long been a practice and a matter of research. Example of this are well known and widely used methods for estimation of cyclic and fatigue parameters from monotonic tensile properties and hardness of steels as well as aluminium and titanium alloys [3,6,7]. Advanced constitutive models usually comprise large number of material parameters [8–11] so that estimation of their values from monotonic properties would be highly unpractical if not impossible. However, a possibility to use data or experimental results underlying certain simpler material models to estimate or determine parameters of more complex material models would offer significant advantages especially since this type of information is much easier to find in published results of materials research

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http://dx.doi.org/10.1016/j.jcsr.2017.05.010
Received 2 March 2017; Received in revised form 9 May 2017; Accepted 11 May 2017
0143-974X/

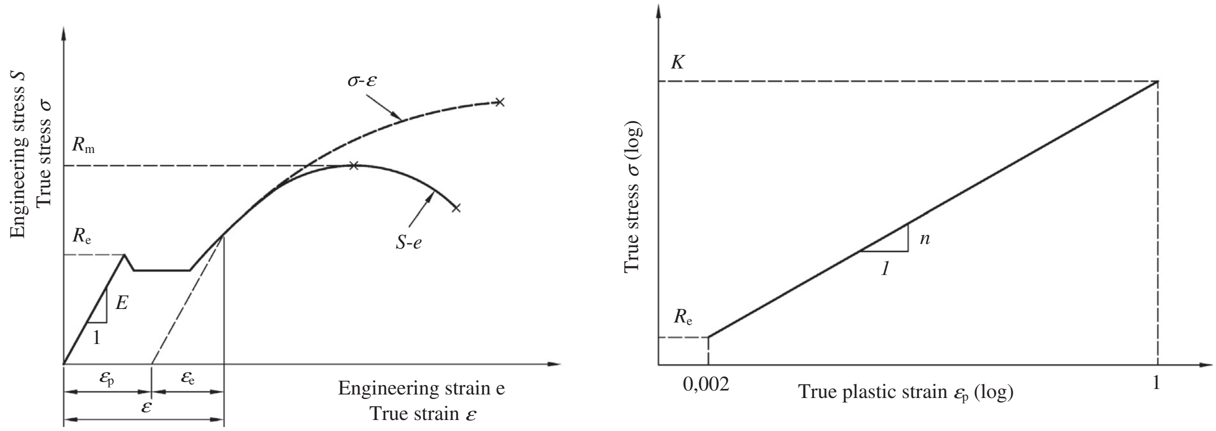

Fig. 1. Monotonic stress-strain curve with corresponding properties and monotonic Ramberg-Osgood parameters.

[3,5,12]. As an example, for modelling and simulation of cyclic elasto-plastic stress-strain behaviour of different metallic materials (particularly steels), material models of different complexity can be used such as simple and widely used Ramberg-Osgood material model (RO) [13], as well as more complex models, such as some variant of Chaboche's model (CH) [14]. Besides the number of phenomena they are able to capture and simulate, RO and CH models also significantly differ in the complexity and scope of experiments, procedures and data, which are needed for the identification of their corresponding material parameters.

The principal aim of the study presented in this paper is evaluation of usability of parameters of cyclic Ramberg-Osgood material model and underlying experimental cyclic stress-strain data for determination of parameters of Chaboche material model in its' saturation rate-independent (CHRI) and rate-dependent (CHRD) variant. Both are increasingly being used [15,16] and are part of number of numerical simulation software packages.

Additionally, since determination of cyclic saturation rate parameter in CHRD model requires detailed history of several cyclic tests and cannot be accurately determined otherwise, the analysis of its influence on modelling of evolutionary changes of maximum stresses until stabilization was performed in order to determine relevant boundary values which can be used in subsequent analyses. For this purpose, detailed results of experimental testing of differently heat treated low-alloy steel 42CrMo4 and corresponding parameters of RO, CHRI and CHRD material models were used.

Considering the differences among the material models mentioned above in their description and complexity of their calibration for the given material, as well as the similarities in their application in materials fatigue analysis, the objectives for the study that follows are appointed. It can be summarized through three points: principles, comparisons and prospects. The mechanical principles for the material characterization have to be given for the material models under consideration, supplemented with the calibration of material parameters procedures and parameter values. The comparison of the simulated material behaviour by using different material models with the experimental values can result with the recommendation for the possible wider use of complex material models, in this case CHRI model on the basis of known RO parameters for the investigated material. Since very scarce information on CHRI models parameters are widely available, the investigation of the similarities between these models is needed. Finally, the prospects for the application of even CHRD model for the material behaviour analysis on the basis of the simple RO model can be increased by isolation of the main characteristic which makes the difference in presented models. In this case, it refers to the rate of isotropic hardening and thus the extensive study on the material behaviour simulation with regards to this value is required.

2. Material models

2.1. Ramberg-Osgood model and parameters

Ramberg-Osgood equation [13] is applicable and widely used for simulation of stress-strain behaviour of majority of metallic materials (steels, aluminium alloys, titanium alloys, …) subjected to both monotonic and cyclic loading. While materials response in elastic region is described in linear form, exponential function that asymptotically saturates is used for region of plastic strain above yield.

For monotonic loading it can be written in following form:

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}} \tag{1}$$

where ε is true strain, ε_e true elastic strain, ε_p true plastic strain, σ true stress, E Young's modulus, K is strength coefficient and n is strain hardening exponent. For parameter determination, results of standard monotonic tensile test are used [17]. Additional definition and meaning of individual properties and indirect description of their determination are provided in Fig. 1.

For the case of cyclic loading, cyclic Ramberg-Osgood equation can be written as

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{2}$$

where $\Delta\varepsilon$ is true strain range, $\Delta\varepsilon_e$ true elastic strain range, $\Delta\varepsilon_p$ true plastic strain range, $\Delta\sigma$ true stress range, K' is cyclic strength coefficient and n' is cyclic strain hardening exponent. For the purpose of parameter determination, series of cyclic symmetric tensile-compressive strain-controlled tests at different strain amplitudes need to be performed and stabilized or half-life hysteresis loops need to be determined [18]. From sets of stress and strain values corresponding to tips of these stable hysteresis loops which define cyclic stress-strain curve, values of K' and n' are then determined by applying regression method (Fig. 2).

2.2. Chaboche model and parameters

One of the frequently used material models which takes into account cyclic plastic behaviour of the material on the microscopic level is well-known Chaboche material model. It is based on the assumption that isothermal conditions exist and that small strain framework is considered for the material behaviour modelling.

Since elastic–plastic behaviour of material is taken into account, total strain is given by the sum of its elastic and plastic part:

$$\varepsilon = \varepsilon^e + \varepsilon^p \tag{3}$$

which are described by separate constitutive relations. The linear stress strain relationship is described within the elasticity domain where