Journal of Constructional Steel Research 145 (2018) 414–424

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Modelling the strain rate dependent hardening of constructional steel using semi-empirical models

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ARTICLE INFO

Article history:
Received 17 July 2017
Received in revised form 29 January 2018
Accepted 16 February 2018
Available online 29 March 2018

Keywords:
Material modelling
Strain rate dependent
Constructional steel
Strain hardening
Yield plateau
Johnson-Cook
Cowper-Symonds

ABSTRACT

The importance of modelling the strain rate dependent material behaviour increases since structural components more and more have to be designed against extreme events. With growing usage of numerical programmes, good models become necessary. The goal of the ongoing research project is to find reasonable models for simulations concerning steel constructions. This paper discusses various models to describe the strain rate dependent hardening of mild steel. In this context, high speed tensile tests were performed and evaluated. Four commonly used material models and a new model were introduced and calibrated to the test results: The Johnson-Cook model, a modified Johnson-Cook model by Huh and Kang, the Cowper-Symonds model and a combined Johnson-Cook/Cowper-Symonds model. These four models do not describe the observed behaviour of constructional steels satisfactorily. Unlike these models, a newly introduced model is able to describe both a yield plateau and the slope of the strain hardening, both as a function of the strain rate. The quality of the approximations is discussed and further investigated by performing notched bar tensile tests and simulations. Finally, recommendations are given on the basis that the modelling of a yield plateau and the negative strain rate sensitivity of the strain hardening is necessary for modelling structural components under extreme events.

1. Introduction

In order to design structures against extreme events, such as explosions and impact, FE-simulation tools are used for the design of structural components and the evaluation of the robustness of building structures. Their use in areas of planning, development and production requires material laws describing the material-specific behaviour in various design situations with sufficient accuracy, considering different temperatures and extreme strain rates. Studies using modern techniques have been carried out mainly for special steels, e.g. in the field of automotive or aerospace engineering. The material behaviour of constructional steel differs from these steel types especially regarding the existence of a yield plateau but also with regard to strain hardening behaviour. Most of the existing material models do not consider a strain rate sensitive strain hardening behaviour. As the strain rate sensitivity of the yield strength is noticeably higher than the sensitivity of the tensile strength, this can lead to inaccurate results especially when a wide range of strain rates is investigated.

2. Material modelling

Modelling the strain rate dependent material behaviour of constructional steel is challenging because of the complex microstructural and physical processes during the elongation process at higher loading rates. As a consequence, the commonly used material models are semi-empirical. In the following, five models will be introduced and discussed in regard to the strain hardening behaviour of constructional steel. All models describe the Mises flow stress $\overline{\sigma}_F$ depending on the true plastic strain $\overline{\varepsilon}_{pl}$ and the true plastic strain-rate $\dot{\varepsilon}_{pl}$. Effects resulting from temperature changes are not considered in this work.

2.1. Johnson-Cook model (JC)

The Johnson-Cook model developed by G. R. Johnson and W. H. Cook [1] represents a constitutive equation to model the von Mises flow stress $\overline{\sigma}_F$ depending on the strain, the strain-rate $\dot{\varepsilon}$ and the temperature θ.

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https://doi.org/10.1016/j.jcsr.2018.02.013

The approach contains three factors representing these properties: The first term is equivalent to the Ludwik expression [2] and defines the stress-strain curve for $\dot{\varepsilon}^* = 1$. The second term takes into account the strain-rate dependent hardening and the last term the thermal softening.

$$\overline{\sigma}_F = \underbrace{\left[A + B(\overline{\varepsilon}_{pl})^n\right]}_{\substack{\text{strain}\\ \text{hardening}}} \underbrace{\left[1 + C\ \ln(\dot{\varepsilon}^*)\right]}_{\substack{\text{strain-rate dep.}\\ \text{hardening}}} \underbrace{\left[1 - \hat{\theta}^m\right]}_{\substack{\text{thermal}\\ \text{softening}}}$$

A, B, C,n and m are parameters which need to be fitted to the measured flow curves. $\dot{\varepsilon}^*$ is the dimensionless strain rate, $\hat{\theta}^m$ the homologous (dimensionless) temperature. The dimensionless strain rate is expressed as:

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}.$$

$\dot{\varepsilon}_0$ is the reference strain rate. Commonly $\dot{\varepsilon}_0$ is chosen to be 1s^{-1}.

2.2. Huh-Kang model (HK)

Based on the Johnson-Cook model, some models have been developed during the past years. One of those models is the modified Johnson-Cook model by Huh and Kang [3]. This model differs from the original model only in the expression of the strain rate dependent hardening, where a squared logarithmic term is added:

$$\overline{\sigma}_F = \left[A + B(\overline{\varepsilon}_{pl})^n\right]\left[1 + C_1\ \ln(\dot{\varepsilon}^*) + C_2\ \ln^2(\dot{\varepsilon}^*)\right]\left[1 - \hat{\theta}^m\right]$$

C_1 and C_2 are material constants. Especially in the case of constructional steel, this model improves the approximation of the strain rate dependent material behaviour.

2.3. Cowper-Symonds model (CS)

The Cowper-Symonds model is a combination of two equations [4]:

$$\sigma = \sigma_0 + \frac{E}{n}\varepsilon, \quad \dot{\varepsilon} = D(\sigma - \sigma_0)^p \quad \text{for} \quad (\sigma > \sigma_0).$$

The first equation defines the course of the strain hardening whereas the second equation defines the strain-rate effects. In this context, σ_0 describes the yield strength, E the Young's modulus and n the ratio of the slopes of the elastic and plastic portions of the stress-strain curve. D and p are material specific parameters adjusted to measured data.

Solving these equations for the von Mises flow stress $\overline{\sigma}_F$ yields

$$\overline{\sigma}_F = \overline{\sigma}_{F0} \cdot \left[1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{p}}\right],$$

where $\overline{\sigma}_{F0}$ represents the stress-strain curve in the case of $\dot{\varepsilon} = 0$. In this publication, idealized curves of the strain-stress curves gained in own quasi-static tensile tests are used.

2.4. Combined Johnson-Cook/Cowper-Symonds model (JC/CS)

Differing from the Cowper-Symonds expression, the combined Johnson-Cook/Cowper-Symonds expression defines the course of the reference stress-strain curve $\overline{\sigma}_{F0}$ as

$$\overline{\sigma}_{F0} = A + B(\overline{\varepsilon}_{pl})^n$$

in analogy to the first term of the Johnson-Cook model.

2.5. New mathematical model for constructional steels

In addition to the established models discussed above, a new model is introduced. This model describes the yield plateau of normalised constructional steel and the slope of the strain hardening, both

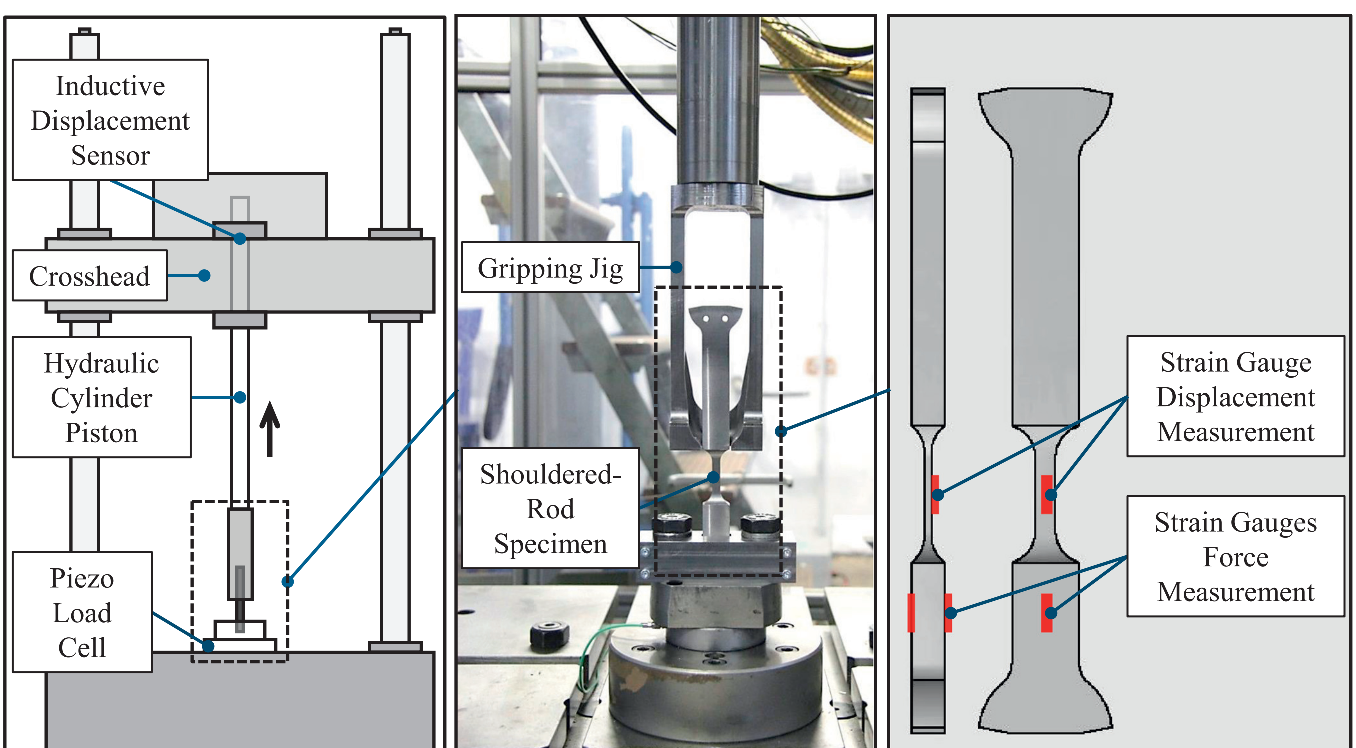

Fig. 1. Apparatus and test set-up [6].