EAN 2014
52nd conference on experimental stress analysis

Testing and Modeling of Uniaxial and Multiaxial Stress-Strain Behaviour of R7T Wheel Steel

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Keywords: Cyclic plasticity, nonproportional loading, ratcheting, FEM.

Abstract. This conference paper is a contribution to the category of experimental works as a tool for the verification of stress-strain behavior characterization. An experimental study on the R7T wheel steel specimens including uniaxial as well as multiaxial tests has been conducted. The main attention was paid to such effects as ratcheting and nonproportional hardening of the material. A cyclically stable behavior of the steel under higher amplitude loading was found. The MAKOC model, which is based on AbdelKarim-Ohno kinematic hardening rule and Calloch isotropic hardening rule, has been applied in subsequent finite element simulations. The numerical results show very good prediction of stress-strain behaviour of the wheel steel.

Introduction

There is still a big gap in the sense of FE prediction quality between cyclic plasticity models implemented in current commercial FEM based software and state of the art constitutive theories. Recently, the necessity of development of specific theories for various metallic materials and their introduction to the computational fatigue analysis is evident [1].

The subject of our investigation is the R7T wheel steel, which is very often used in the railway industry. There are presented some interesting results of performed uniaxial and multiaxial experiments, including such important effects as ratcheting and nonproportional hardening. Developed cyclic plasticity model called MAKOC [2] was successfully applied in the FEM simulations for chosen cases to describe the stress-strain behaviour of examined material correctly.

Details of Experimental Study

There were realized low-cycle fatigue tests under strain as well as stress control in a laboratory at the VSB - Technical University of Ostrava. The specimens were subjected to tension-compression and tension-torsion tests on the reconstructed test machine INOVA 100kN/1000Nm as in the previous study performed on ST52 steel [3]. The extensometer EPSILON 3550 with 25.4mm gauge length was used to measure axial strain and shear strain.

The testing specimen has tubular testing part with outer diameter of 12.5 mm and with inner diameter of 10 mm.

Description of Numerical Simulations

Two cyclic plasticity model options were used in numerical simulations by FEM: AKO model (AbdelKarim-Ohno kinematic hardening rule and no isotropic hardening, see [1]) and MAKOC model (considering also Calloch isotropic evolution equations [2]). The second model makes possible good description of nonproportional hardening. Both models have been implemented into the ANSYS program [2], which was used for all FE computations. All uniaxial tests were simulated by use of LINK180 element, the multiaxial tests then using the PIPE288 element. Description of MAKOC model can be found in [2]. Here we use a reduced version of the MAKOC model. All used hardening rules are stated in Table 1. The parameters of both cyclic plasticity models are shown in the Table 2.

Table 1. Constitutive equations.

Kinematic hardening rule (AKO and MAKOC model)

$$\boldsymbol{\alpha}=\sum_{i=1}^{5}\boldsymbol{\alpha}_i,\quad \dot{\boldsymbol{\alpha}}_i=\frac{2}{3}C_i\dot{\boldsymbol{\varepsilon}}_{\mathbf{p}}-\mu_i\gamma_i\boldsymbol{\alpha}_i\dot{p}-\gamma_i H(f_i)\langle\dot{\lambda}_i\rangle\boldsymbol{\alpha}_i,\quad f_i=\frac{3}{2}\boldsymbol{\alpha}_i:\boldsymbol{\alpha}_i-\left(\frac{C_i}{\gamma_i}\right)^2,\quad \dot{\lambda}_i=\dot{\boldsymbol{\varepsilon}}_{\mathbf{p}}:\frac{\boldsymbol{\alpha}_i}{C_i/\gamma_i}-\mu_i\dot{p},$$

where $H(f_i)$ is Heavisides step function and the symbol $\langle x\rangle$ means Macaulay's bracket ($\langle x\rangle = x+|x|$).

Isotropic hardening rule (MAKOC model only)

$$\dot{R}=b(Q-R)\dot{p},\quad \dot{Q}=d\cdot A\cdot(Q_{AS}(A)-Q)\dot{p},\quad Q_{AS}(A)=\frac{gAQ_\infty}{gA+(1-A)},\quad A=1-\frac{(\mathbf{a}:\dot{\mathbf{a}})^2}{(\mathbf{a}:\mathbf{a})(\dot{\mathbf{a}}:\dot{\mathbf{a}})}.$$

Table 2. Material parameters of both cyclic plasticity models.

$$\sigma_Y=200MPa;\quad \gamma_{1-5}=3636,1290,615,284,35;\ C_{1-5}=325370,83235,34133,13219,14413MPa$$

$$d=90;b=10000;Q_\infty=100MPa;g=0.12;\ \mu_i=0.03\quad \textit{for all i}$$

Comparison of Numerical Results with Experiments

Firstly, results of a sequential uniaxial test and its FE prediction are presented in Fig. 1. The cyclically stable behavior of the R7T material at higher strain amplitudes is obvious.

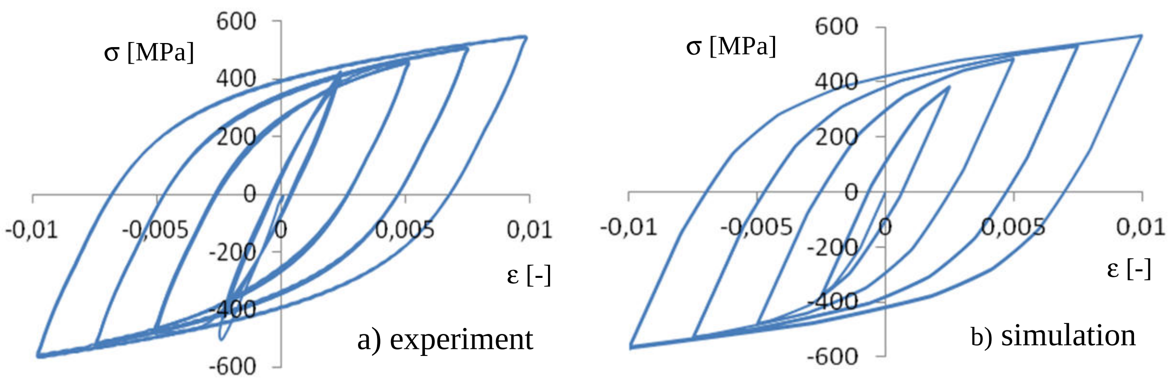

Fig. 1. Experimental and predicted uniaxial sequential test.

The force controlled test with amplitude of stress of 400MPa and mean stress of 100 MPa was simulated by AKO model, see Fig. 2. The model MAKOC in the presented version has the same prediction of plastic strain accumulation (so called ratcheting or cyclic creep).

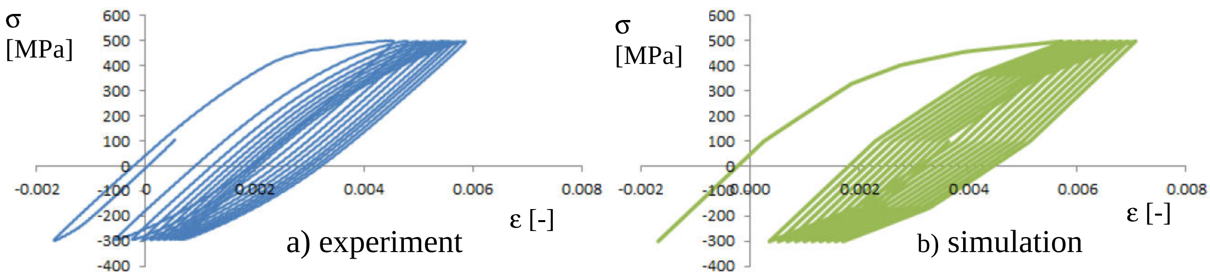

Fig. 2. Experimental and predicted uniaxial sequential test.

A multiaxial ratcheting test was also realized to can study ratcheting under nonproportional loading. Experimental results are shown with prediction in the Fig. 3.

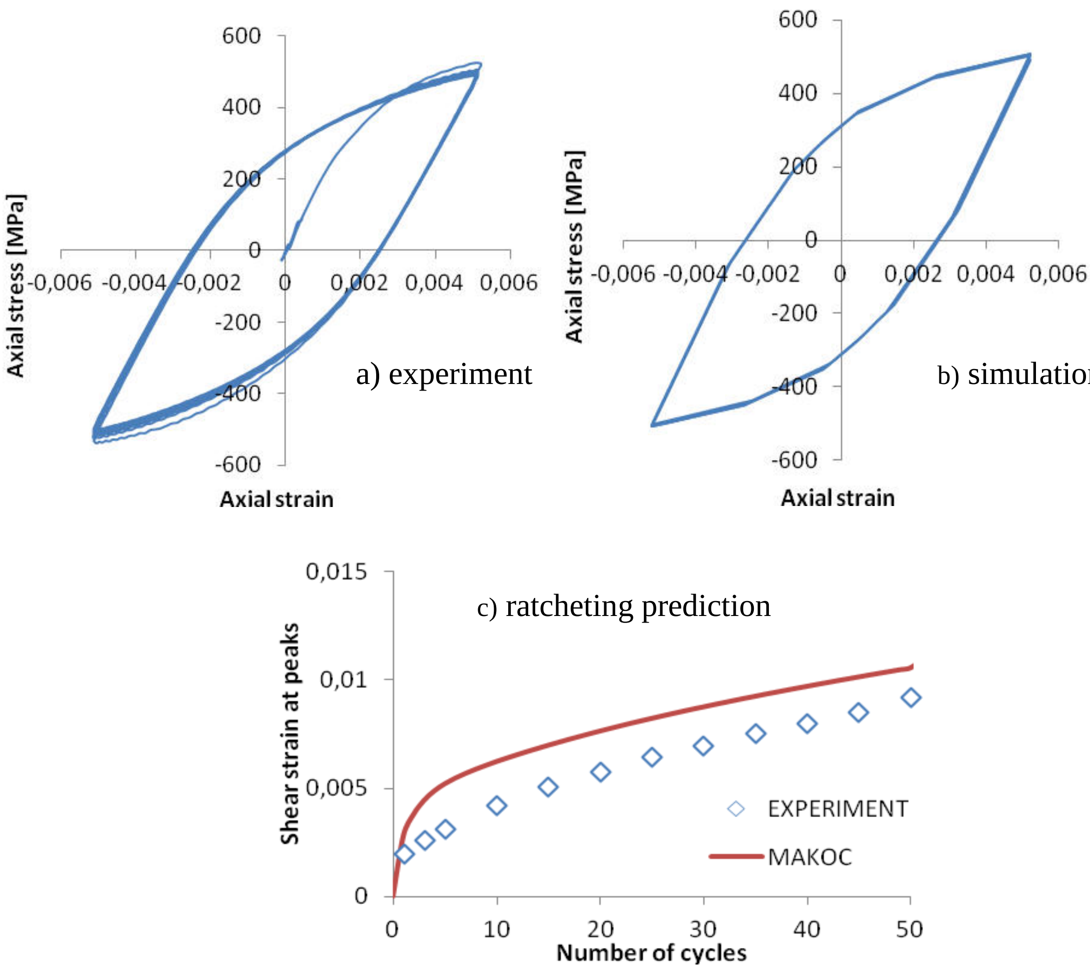

Fig. 3. Accumulation of shear strain in the test and simulation - multiaxial test with constant shear stress of 50MPa and with amplitude of axial strain of 0.8 %.

An additional cyclic hardening of R7T wheel steel was found under nonproportional loading under tension/torsion out of phase loading. It is obvious from the Fig. 4, where stable hysteresis loops from experiment and simulations corresponding to two steps of a multiaxial sequential test are confronted. AKO model, which cannot describe additional hardening gives less amplitude of stress then observed in experiment of about 100MPa (Fig.4b).

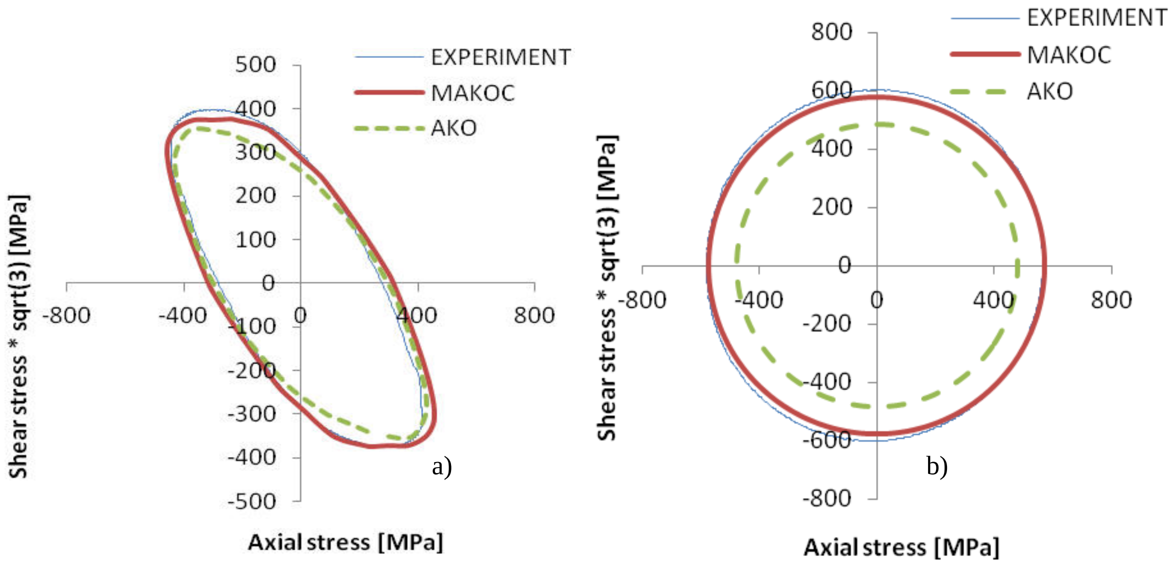

Fig. 4. Experimental and predicted multiaxial stress responses: a) elliptic strain path (166° out of phase test, ε_{aeqv}=0.5 %), b) circular strain path (90° out of phase test, ε_{aeqv}=0.75 %).

Conclusions

The stress-strain behavior of the R7T steel has been experimentally studied in this paper. Additional hardening due to nonproportional 90° out of phase loading is about 20% comparing to the amplitude of stress under equivalent uniaxial loading. Ratcheting effect of the wheel steel was also investigated under uniaxial and multiaxial loading. As a result we can conclude that the accumulation of plastic strain under proportional and nonproportional loading is comparable because AKO model can predict both test cases simultaneously. The results of realized tests and simulations allow us to conclude that it is necessary to consider a cyclic plasticity model with a nonproportional parameter for the correct description of stress-strain behaviour of the R7T steel even under room temperature. The MAKOC model was shown as a good candidate.

Acknowledgment

This work was supported by the European Regional Development Fund in the IT4Innovations Centre of Excellence project (CZ.1.05/1.1.00/02.0070) and by the OPVK project Opportunity for young researchers (CZ.1.07/2.3.00/30.0016) co-financed by the ESF.

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