Sborník vědeckých prací Vysoké školy báňské - Technické univerzity Ostrava
číslo 1, rok 2008, ročník LIV, řada strojní
článek č. 1586

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RATCHETING SIMULATIONS OF S45C STEEL BY FEM

SIMULACE CYKLICKÉHO TEČENÍ OCELI S45C POMOCÍ MKP

Abstract

Two modifications of AbdelKarim-Ohno [Int. J. Plasticity 16 (2000) 225] cyclic plasticity model were proposed for better ratcheting simulations [Trans. VŠB-TUO Mech. Ser. (2006) 155]. The developed model was implemented into commercial FE software Ansys. In this paper, the model was verified on a set of axial/torsional loading paths taken from Chen et al. [Int. J. Plasticity 21 (2005) 161]. The model predicts ratcheting strain reasonably well for the almost all test cases.

Abstrakt

Dvě modifikace AbdelKarim-Ohno modelu cyklické plasticity [Int. J. Plasticity 16 (2000) 225] byly navrženy pro zpřesnění simulací cyklického tečení [Sbor. věd. pr. VŠB-TUO ř. stroj. (2006) 155]. Model byl implementován do komerčního konečnoprvkového programu Ansys. Ověření možností modelu bylo provedeno na experimentálních datech z Chen et al. [Int. J. Plasticity 21 (2005) 161]. Získané predikce cyklického tečení vykazují dobrou shodu s experimenty téměř u všech řešených případů.

1 INTRODUCTION

When materials are subjected to cyclic plastic loading with nonzero mean stress, strain usually accumulates in the direction of mean stress with the increase of the number of cycles. This kind of strain accumulation is called cyclic creep or ratcheting.

Ratcheting is an important factor in the design of structural components. The effect of ratcheting can occur for example in piping components [1] and rail/wheel system. Since ratcheting is the progressive deformation accumulating cycle by cycle, it is not easy to predict the development of ratcheting accurately. Classical models of cyclic plasticity, implemented into the most of FEM software, are very poor in predicting ratcheting [1]. Hence, searching for a more accurate model is necessary.

2 DESCRIPTION OF THE PROPOSED MODEL

Constitutive equations for the mechanical behaviour of materials developed with internal variable concept are the most expanded technique at the last two decades. In this concept, the present state of the material depends on the present values only of both observable variables and a set of internal state variables. When time or strain rate influence on the inelastic behavior can be neglected, time-independent plasticity is considered.

To solve engineering problems by means of the constitutive equations, it is necessary to perform incremental computations of the structure. The cyclic plasticity constitutive models employed for ratcheting analysis with the assumption of rate-independent material's behavior consist of von Mises yield criterion

$$f = \sqrt{\frac{3}{2}(\mathrm{s}-\mathrm{a}):(\mathrm{s}-\mathrm{a})} - \sigma_Y - R = 0 \,, \tag{1}$$

the plastic flow rule

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$$d\,\varepsilon_p = d\lambda \frac{\partial f}{\partial \sigma} \tag{2}$$

and the kinematic hardening rule

$$d\,\boldsymbol{a} = g\left(\boldsymbol{\sigma},\boldsymbol{a},\boldsymbol{\varepsilon}_p, d\,\boldsymbol{\sigma}, d\,\boldsymbol{\varepsilon}_p, etc.\right), \tag{3}$$

where, $\boldsymbol{s}$ is the deviatoric part of stress tensor $\boldsymbol{\sigma}$, $\boldsymbol{a}$ is the deviatoric part of back-stress $\boldsymbol{\alpha}$, σ_Y is the initial size of the yield surface, *R* is the isotropic variable, $\boldsymbol{\varepsilon}_p$ is the plastic strain tensor and $d\lambda$ is the plastic multiplier, which is equal to the equivalent plastic strain increment in the case of associated plasticity

$$dp = \sqrt{\frac{2}{3} d\,\boldsymbol{\varepsilon}_p : d\,\boldsymbol{\varepsilon}_p}\ , \tag{4}$$

where the symbol $:$ denote contraction, ie. using Einstain's summing rule $\boldsymbol{d} = \boldsymbol{b} : \boldsymbol{c} = b_{ij} c_{ij}$.

The time-independent cyclic plasticity models basically differ in the kinematic hardening rule they employ. For example, Chaboche [2] introduced "decomposed" nonlinear kinematic hardening rule in the form

$$\boldsymbol{a} = \sum_{i=1}^{M} \boldsymbol{a}_i\ ,\quad d\,\boldsymbol{a}_i = \frac{2}{3} C_i d\,\boldsymbol{\varepsilon}_p - \gamma_i\, \boldsymbol{a}_i\, dp\ , \tag{5}$$

where C_i and γ_i are material constants. Indeed, it was found by many researchers, that the Chaboche model overpredict biaxial ratchetting responses. On that account, AbdelKarim and Ohno [3] have proposed this modification of Chaboche nonlinear kinematic hardening rule

$$\boldsymbol{a} = \sum_{i=1}^{M} \boldsymbol{a}_i\ ,\quad d\,\boldsymbol{a}_i = \frac{2}{3} C_i d\,\boldsymbol{\varepsilon}_p - \mu_i \gamma_i\, \boldsymbol{a}_i\, dp - \gamma_i H\left(f_i\right)\left\langle d\lambda_i \right\rangle \boldsymbol{a}_i\ , \tag{6}$$

where

$$f_i = \frac{3}{2} \boldsymbol{a}_i : \boldsymbol{a}_i - \left(\frac{C_i}{\gamma_i}\right)^2\ , \tag{7}$$

and

$$d\lambda_i = d\,\boldsymbol{\varepsilon}_p : \frac{\boldsymbol{a}_i}{C_i / \gamma_i} - \mu_i dp\ . \tag{8}$$

In equation (6), the symbol $\langle . \rangle$ indicates the MacCauley bracket, i.e. $\langle x \rangle = \left(|x| + x\right)/2$. The parameters μ_i sets a ratcheting rate. The AbdelKarim-Ohno model could simulate well only ratcheting with steady-state [3]. Because of simplicity the only one parameter $\mu = \mu_i$ for all *i* is used as in author's previous paper [1]. In the first proposed modification large transient effect can be introduced assuming the ratcheting parameter dependent on equivalent plastic strain by these evolution equations

$$d\eta = d\eta_1 + d\eta_2\ , \tag{9}$$

where

$$d\eta_1 = \omega_1\left(\eta_{\infty 1} - \eta_1\right)dp\ ,\ d\eta_2 = \omega_2\left(\eta_{\infty 2} - \eta_2\right)dp\ . \tag{10}$$

Then, the six material constants η_{01}, η_{02}, $\eta_{\infty 1}$, $\eta_{\infty 2}$, ω_1, ω_2 should be determined by fitting an uniaxial ratcheting test.

Further, it is difficult to simulate simultaneously the uniaxial and the multiaxial ratcheting responses of S45C steel with the AbdelKarim–Ohno model as was found by Chen et al. [4]. This problem was removed by introduction of the nonproportional term into the ratcheting parameter.

$$\mu_i = \eta \left| \frac{\partial f}{\partial \boldsymbol{\sigma}} : \frac{\boldsymbol{a}_i}{\overline{a_i}} \right|^{\chi} , \quad \overline{a_i} = \sqrt{\frac{3}{2} \boldsymbol{a}_i : \boldsymbol{a}_i} , \tag{11}$$

where material constant χ should be established from a multiaxial ratcheting test.

Isotropic hardening was not assumed in this study because of negligible cyclic softening/hardening of S45C steel.

2 Comparison of simulations with experimental data

In the previous studies (for example [1]), the developed cyclic plasticity model described at the previous section was verified by virtue of experimental data obtained from axial/torsional tests under several biaxial loading histories with acting internal pressure. The present goal is to verify the proposed model by means of experimental data obtained from axial/torsional tests with different loading path shape published elsewhere [4].

The material used in the experiments was medium carbon steel S45C (Czech equivalent is 12050 steel). The specimen has a tubular geometry with outside and inside diameters of 12.5 mm and 10 mm respectively. Completely reversed, uniaxial and torsional tests were conducted at several strain amplitudes (Fig 1 and 2). The uniaxial hysteresis loop with largest strain range was used for estimation of model's parameters C_i , γ_i . More details about model calibration has been described in [1]. The developed model was implemented into FEM software Ansys 8.0. The benefits of the proposed model will be clear by comparative analysis using Chaboche model included in the FEM package. All neccesary parameters of both models are presented in Tab.1, with exception of the elastic constants E=206000MPa, ν=0,3.

The next simulated case was the uniaxial ratcheting test with stress amplitude σ_a=370MPa and mean stress σ_m =100MPa. The simulation was also used to the estimation of parameter γ_3 for Chaboche model (CHAB) and parameters η_{01} , η_{02} , $\eta_{\infty 1}$, $\eta_{\infty 2}$, ω_1 , ω_2 for proposed model (Modified AbdelKarim–Ohno model, MAKO). The proposed model shows better results then Chaboche model, see Fig 3).

Tab. 1 Parameters of used cyclic plasticity models

model	***parameters***
Chaboche (CHAB)	$\sigma_Y = 220 MPa, C_{1-3} = 300000{,}900\,00{,}7500\ MPa$ $\gamma_{1-3} = 3000{,}600{,}1$ $\eta_{01} = -0{,}2; \eta_{\infty 1} = 0{,}1; \omega_1 = 1{,}5; \eta_{02} = 0{,}27; \eta_{\infty 2} = 0; \omega_2 = 0{,}7; \chi = 0{,}75$
Proposed (MAKO)	$\sigma_Y = 220 MPa, C_{1-6} = 434968{,}745\ 44{,}39359{,}1\ 5263{,}6439,\ 8607\ MPa$ $\gamma_{1-6} = 6077{,}1551,\ \ 735{,}345{,}19\ \ 4{,}10$

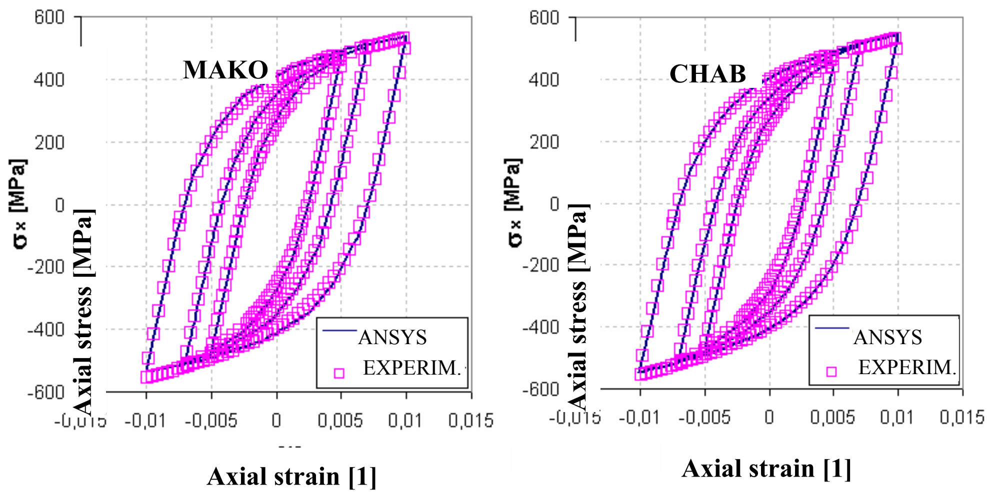

Fig. 1 Uniaxial hysteresis loops

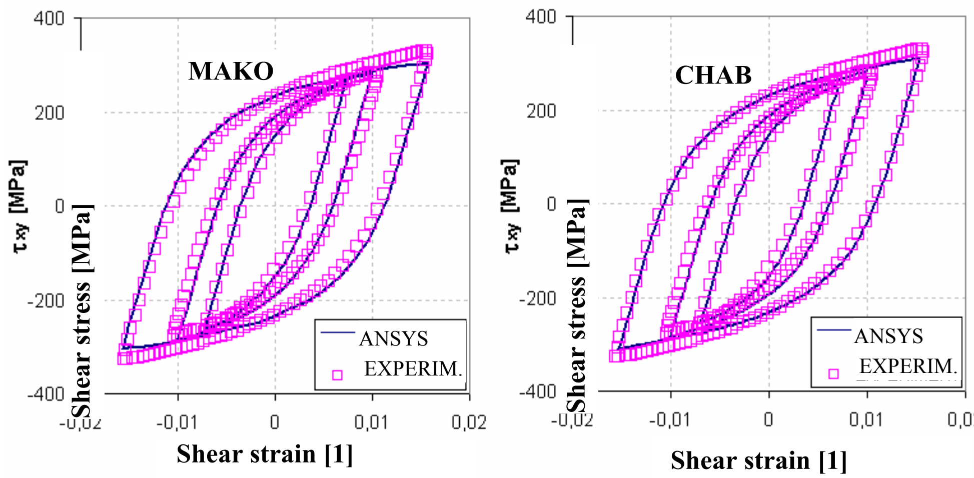

Fig. 2 Torsional hysteresis loops

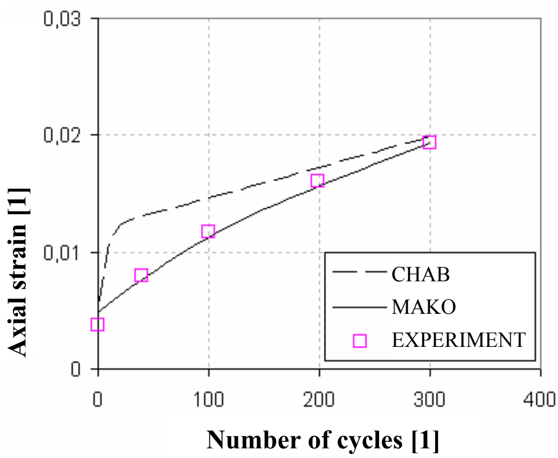

Fig. 3 Uniaxial ratcheting

Except the seven described cases with proportional loading the eight cases of tension/torsion combined loading with different loading histories (Fig.4) were simulated.

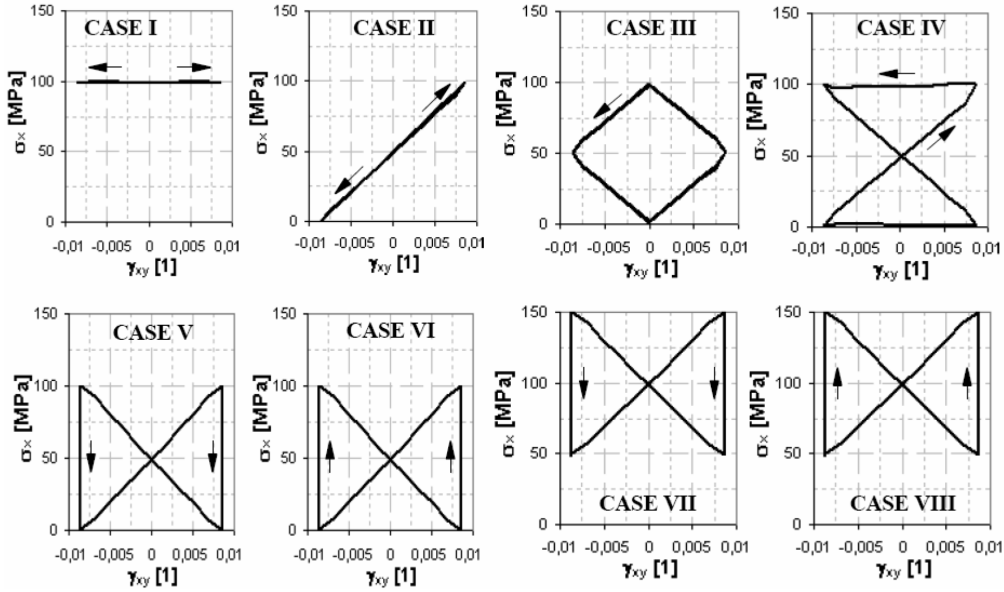

Fig. 4 Loading histories – nonproportional loading in tension/torsion

The results from simulations of the eight cases of nonproportional loading are presented in graphically at the Fig 5 and 6.

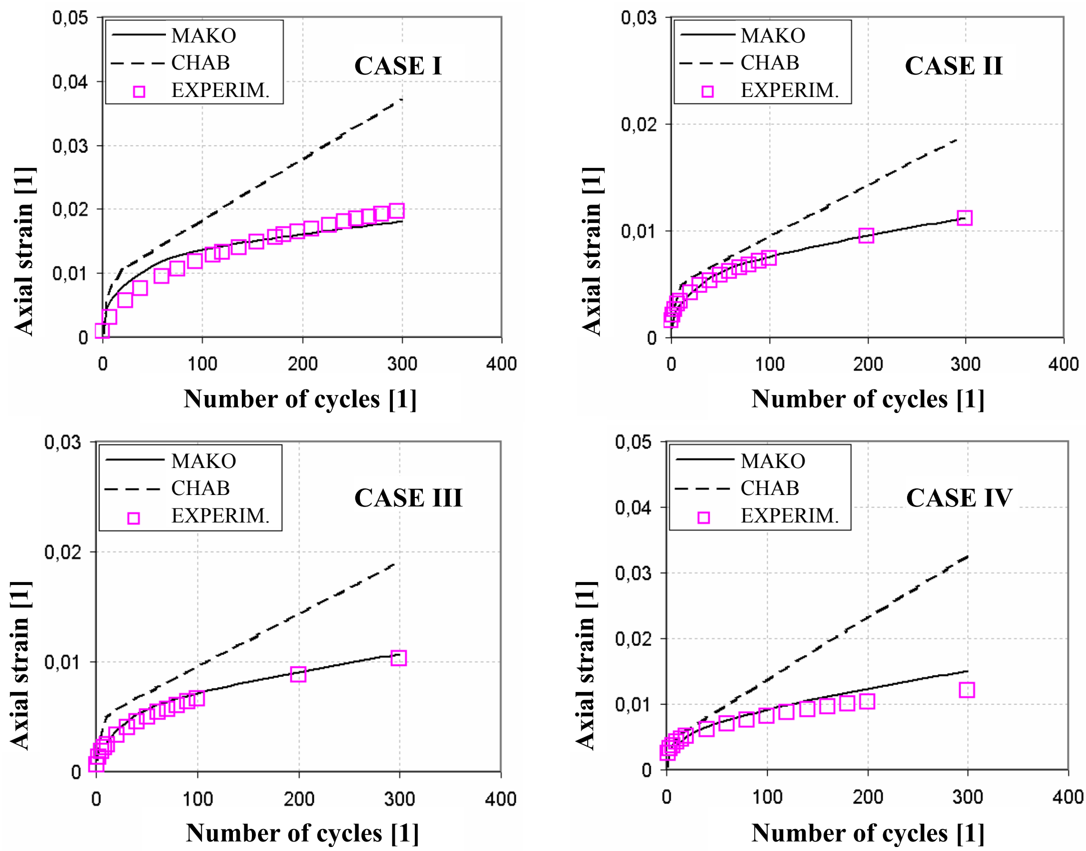

Fig. 5 Results of multiaxial ratcheting simulations

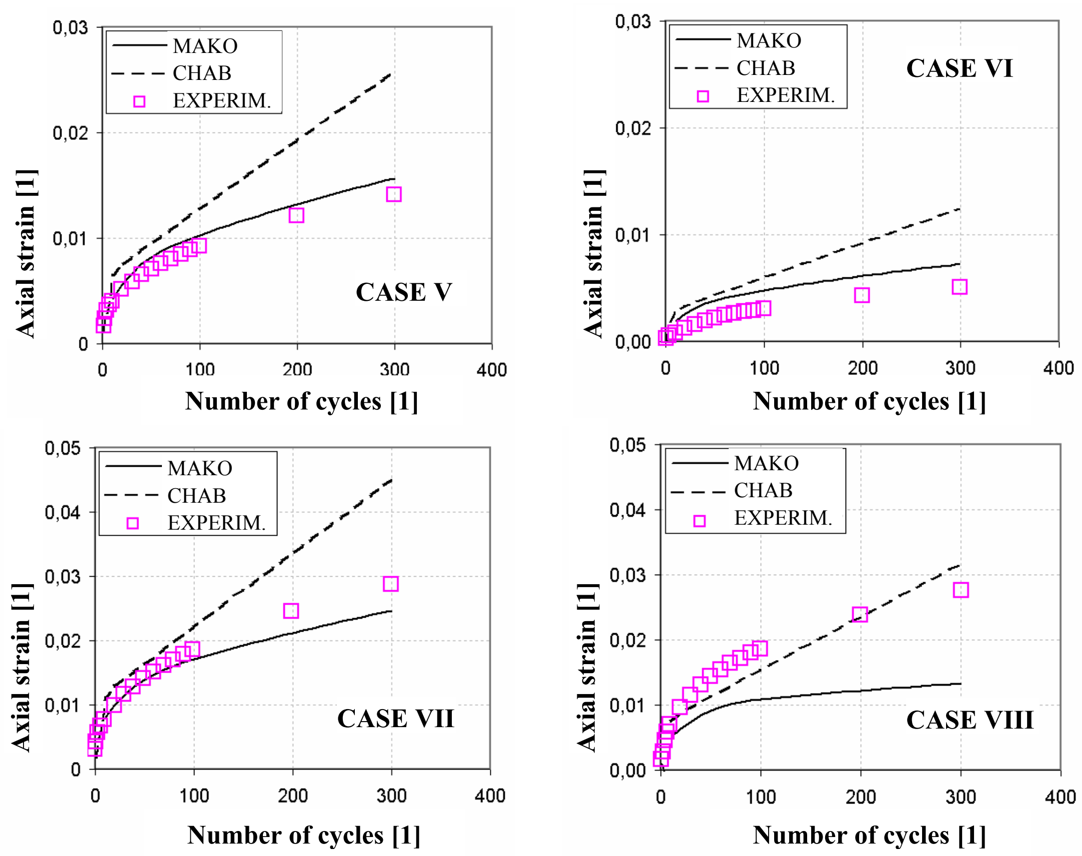

Fig. 6 Results of multiaxial ratcheting simulations (continuation of Fig 5)

4 Conclusions

The paper shows possibilities of the modified cyclic plasticity model AbdelKarim-Ohno in modelling uniaxial and multiaxial ratcheting under various load shapes in tension/torsion. For this purpose, experimental data were taken from [3]. The model was implemented into the FEM software Ansys and gives much better results than the Chaboche model, included in the SW package.

This research has been supported by the project MSM6198910027.

REFERENCES

[1] HALAMA, R. Ratchetting Simulations with Modified AbdelKarim-Ohno Cyclic Plasticity Model. *Transactions of the VŠB-Technical university of Ostrava, Mechanical Series*. 2006, LII, Nr. 1, p. 155-162. ISSN 1210-0471.

[2] ABDEL-KARIM, M. & OHNO, N. Kinematic Hardening Model Suitable for Ratchetting with Steady-State. *International Journal of Plasticity*. 2000, XVI, p. 225-240. ISSN 0749-6419.

[3] CHEN, X. & JIAO, R. & KIM, K.S. On the Ohno-Wang Kinematic Hardening Rules for Multiaxial Ratchetting Modeling of Medium Carbon Steel. *International Journal of Plasticity*. 2005, XXI, p. 161–184. ISSN 0749-6419.

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