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Numerical Simulations of Pipeline Bending Tests

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Abstract

The paper compares numerical solution with results of experimental solution of pipeline under cyclic loading in elastoplastic domain. The pipeline was subjected to internal pressure and bending moment. Firstly material parameters were estimated (for Besseling model, Chaboche model and Modified AbdelKarim-Ohno model) on the basis of uniaxial loading. The possibility of parameter identification of assumed models using multiaxial tests was tested too. FE program ANSYS was used for all computations. Modified AbdelKarim-Ohno model was implemented by writing own user subrutin in FORTRAN language. Chaboche model usually overpredicts ratcheting under multiaxial stress state in confrontation with experiments, when it is calibrated by uniaxial tests only. Modified AbdelKarim-Ohno model makes possible better calibration for both uniaxial and multiaxial loading cases.

Keywords: finite element method, AbdelKarim-Ohno model, cyclic plasticity, ratcheting

1. Introduction

The phenomenon called ratcheting (cyclic creep) can be described as accumulation of plastic deformation in a specimen or a real machine component under cyclic loading condition. The ratcheting occurred in components subjected to rolling contact (for example in rail/wheel system) or pipe components subjected to static internal pressure and cyclic bending, push-pull, torsion or its combination.

Chaboche model was one of the first cyclic plasticity models, which was able to describe the complex ratcheting behavior. Indeed Chaboche model usually fails in ratcheting predictions, when only uniaxial tests are used in calibration procedure. The model overpredicts ratcheting strain under multiaxial loading comparing with experimental results, see for example [5]. Appropriate solution of the problem can be done by an alternative method for identification of material parameters [9] or using a more complex material models ([6, 7] or others). But implementation of more robust models can be complicated [13].

2. Description of Material Models Used for Simulations

All solved cases were simulated three times, using three different kinematic hardening rules. Multilinear Besseling model, nonlinear Chaboche model and proposed modification of nonlinear model of AbdelKarim-Ohno were used in turn. For all material models von Mises plasticity condition was applied

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

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where $\boldsymbol{s}$ is the deviatoric part of stress tensor $\boldsymbol{\sigma}$, $\boldsymbol{a}$ is the deviatoric part of back-stress $\boldsymbol{\alpha}$ and σ_Y is cyclic yield stress. As it is well known, it is possible to consider pure kinematic hardening rule for description of Bauschinger effect [14]. Thus, no isotropic hardening was assumed for all material models in this study.

2.1. *Besseling Model*

Besseling (1958) supposed, that the material is composed of various portions (subvolumes), all subjected to the same total strain, but each subvolume having different yield strength. For a plane stress analysis, the material can be thought to be made up of a number of different layers, each with a different thickness and yield stress. Each subvolume has a simple stress-strain response (ideal plastic material) but when combined the model can represent complex material behavior. More details were published in [1]. The material model is very popular, but it can not describe ratcheting even under uniaxial loading. Six point of hysteresis curve served for identification of Besseling model. All material parameters necessary for performed computations are presented in Tab. 1.

Table 1. Parameters of Besseling model (ANSYS-model KINH)

Calibration	**Parameters**
Closed hysteresis loop	[0.001 432, 262], [0.001 6, 286.3], [0.002 374, 378.88], [0.004 874, 573.62], [0.004 99, 579.83], [0.752 2, 15 651]

2.2. *Chaboche Model*

Many other authors seek a simpler nonlinear term in kinematic hardening rule. Very important work in this respect is publication of Armstrong and Frederick from the year 1966 [2], where the memory term was added to Prager's bilinear kinematic rule

$$\mathbf{d}\boldsymbol{\alpha} = \frac{2}{3} C \mathbf{d}\boldsymbol{\varepsilon}_{\mathbf{p}} - \gamma \boldsymbol{\alpha} dp, \tag{2}$$

where C, γ are material parameters and dp is accumulated equivalent plastic strain increment. It is possible to describe only the ratcheting with steady state (constant ratcheting strain increment in every cycle) with Armstrong-Frederick model and correct stress - strain response characterization is difficult. To treat these disadvantages of Armstrong-Frederick model, Chaboche proposed in 1979 [3] the summing law for kinematic tensor

$$\boldsymbol{\alpha} = \sum_{i=1}^{M} \boldsymbol{\alpha}_i, \tag{3}$$

whereas evolution of each kinematic part is directed by Armstrong-Frederick rule

$$\mathbf{d}\boldsymbol{\alpha}_i = \frac{2}{3} C_i \mathbf{d}\boldsymbol{\varepsilon}_{\mathbf{p}} - \gamma_i \boldsymbol{\alpha}_i dp. \tag{4}$$

Practically, from two to five kinematic parts are usually used. For the case of $M = 2$ identification of material parameters is trivial as it has been depicted in [4]. As has been stated in abstract of the paper, Chaboche model overpredicts multiaxial ratcheting in confrontation with experiments, what shows for example study [5]. In this paper four kinematic parts ($M = 4$) are assumed. Parameters of Chaboche model from computations are presented in Tab. 2 and 3.

Table 2. Parameters of Chaboche_1 model

Calibration	**Parameters**
Closed hysteresis loop	$\sigma_Y = 262\,\text{MPa}$, $C_1 = 837\,130\,\text{MPa}$, $C_2 = 111\,700\,\text{MPa}$, $C_3 = 22\,060\,\text{MPa}$, $C_4 = 217\,080\,\text{MPa}$, $\gamma_1 = 43\,481$, $\gamma_2 = 552$, $\gamma_4 = 3\,789$
Uniaxial ratcheting test	$\gamma_3 = 0.5$

Table 3. Parameters of Chaboche_2 model estimated by the extended iteration algorithm

Calibration	**Parameters**
Closed hysteresis loop Uniaxial ratcheting test Multiaxial ratcheting test	$\sigma_Y = 272\,\text{MPa}$, $C_1 = 843\,200$, $C_2 = 112\,500$, $C_3 = 21\,350$, $C_4 = 200\,900$ $\gamma_1 = 42\,680$, $\gamma_2 = 472$, $\gamma_3 = 0.502\,2$, $\gamma_4 = 3\,250$

2.3. *Modified AbdelKarim-Ohno model*

New kinematic hardening rule introduced specially for ratcheting with steady state was published by AbdelKarim and Ohno [6]

$$\boldsymbol{\alpha} = \sum_{i=1}^{M} \boldsymbol{\alpha}_i, \quad \mathbf{d}\boldsymbol{\alpha}_i = \frac{2}{3} C_i \mathbf{d}\boldsymbol{\varepsilon}_\mathbf{p} - \mu_i \gamma_i \boldsymbol{\alpha}_i dp - \gamma_i H(f_i) \langle d\lambda_i \rangle \boldsymbol{\alpha}_i, \tag{5}$$

where C_i, γ_i and μ_i are material parameters, $H(f_i)$ marks Heavisides step function ($H(f_i) = 1$, if $f_i = 0$ and $H(f_i) = 0$ if $f_i < 0$), whereas the function f_i is defined by

$$f_i = \frac{3}{2} \boldsymbol{\alpha}_i : \boldsymbol{\alpha}_i - \left(\frac{C_i}{\gamma_i} \right)^2 \tag{6}$$

and

$$d\lambda_i = \mathbf{d}\boldsymbol{\varepsilon}_\mathbf{p} : \frac{\boldsymbol{\alpha}_i}{C_i/\gamma_i} - \mu_i dp, \quad 0 \le \mu_i \le 1. \tag{7}$$

The symbol $\langle x \rangle$ marks Macaulay's bracket ($\langle x \rangle = 0$, if $x < 0$ and $\langle x \rangle = x$, if $x > 0$). Parameters μ_i have a great meaning in the model. For example, if $f_i < 0$ or $d\lambda_i < 0$, $\mu_i = 1$ for all i the equation (5) becomes identical to (4), i.e. Chaboche model. On the other hand, if $\mu_i = 0$ for all i, AbdelKarim-Ohno model corresponds to Ohno-Wang I model, which always predicts plastic shakedown (no ratcheting) under uniaxial loading [7]. Thus, parameters μ_i influence ratcheting strain rate. The only one parameter $\mu = \mu_i$ is usually used for all i because of simplification.

AbdelKarim-Ohno cyclic plasticity model has some disadvantages too. It gives noncorrect results for multiaxial ratcheting when it is calibrated from uniaxial ratcheting test and vice versa. The second handicap is the possibility of simulations of ratcheting with steady state only if the parameter μ is constant during loading. Two modification of original AbdelKarim-Ohno model were proposed [1], but in this paper it was used with little differences.

The transient effect in initial cycles, which occurred for some materials, can be described by evolution of parameter μ using relation

$$d\mu = \omega(\mu_\infty - \mu) dp, \tag{8}$$

where μ_∞ is the target value of μ, ω is the evolution coefficient and the initial value of μ is μ_0. Next proposed modification of AbdelKarim-Ohno model is idea to express the parameters μ_i in following form

$$\mu_i = \mu \left\langle n : \frac{\boldsymbol{\alpha}_i}{\overline{\alpha_i}} \right\rangle^{\chi}, \tag{9}$$

where

$$\overline{\alpha_i} = \sqrt{\frac{3}{2}\boldsymbol{\alpha}_i : \boldsymbol{\alpha}_i}, \quad n = \frac{\mathbf{d}\boldsymbol{\varepsilon}_\mathbf{p}}{dp}. \tag{10}$$

The term in Macaulay's bracket is always less than 1 under nonproportional loading [15] and equal to 1 under proportional loading (tension-compression, torsion and so on). Now it is clear, that choice of multiaxial parameter χ influence only ratcheting under nonproportional loading. Sometimes it is useful to introduce the evolution rule (8) for multiaxial parameter too

$$d\chi = \omega(\chi_\infty - \chi)dp. \tag{11}$$

The described modified AbdelKarim-Ohno model had to be coded into the FE software ANSYS as a user material subrutine [1].

3. Experiments

Experimental data were taken from paper [8] and the reader is forwarded to it for more detailed description of experimental equipment and realized tests.

Test specimen was thin walled straight pipe with thickness 0.911 mm, outside diameter 31.85 mm, and length 711 mm made out of alloy steel 4 130. These tests were simulated (loading cases are graphically presented at the Fig. 1):

- Experiment 1 — symmetric axial strain controlled cycles of amplitude $\varepsilon_{xc} = 0.75\,\%$ — output axial stress-strain stable hysteresis loop.

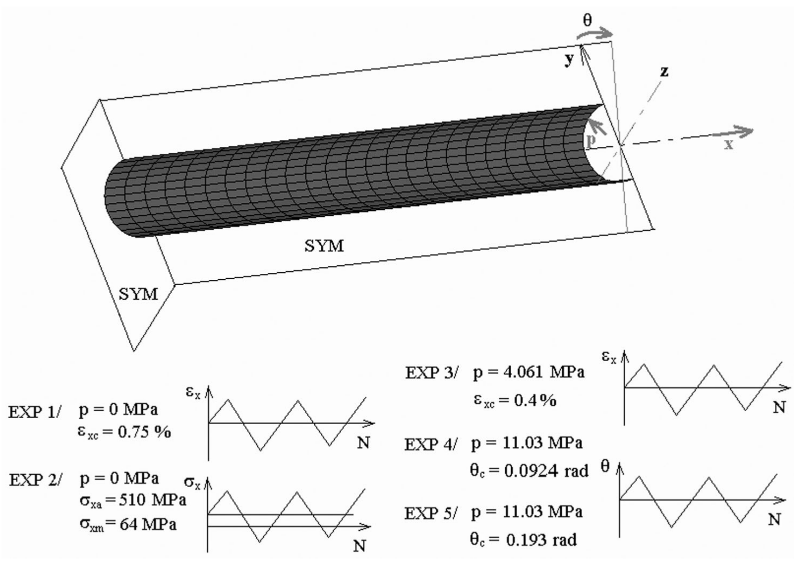

Fig. 1. FE model, boundary conditions and applied loading

- Experiment 2 — unsymmetric axial stress controlled cycles, mean stress $\sigma_{xm} = 64\,\mathrm{MPa}$, axial stress amplitude $\sigma_{xa} = 510\,\mathrm{MPa}$ — output axial strain-number of cycles (uniaxial ratcheting experiment).
- Experiment 3 — steady circumferential stress $\sigma_\theta = 71\,\mathrm{MPa}$ (internal pressure), and symmetric axial strain amplitude $\varepsilon_{xc} = 0.4\,\%$ — output circumferential strain-number of cycles (biaxial ratcheting experiment).
- Experiment 4 — internal pressure $p = 11.03\,\mathrm{MPa}$, and symmetric rotation controlled cyclic bending $\theta_c = 0.092\,4\,\mathrm{rad}$ — output mean in-plane diameter change, mean out-of -plane diameter change, mean of top axial strain peaks, mean of top circumferential strain peaks, amplitude of top axial strain peaks, amplitude of top circumferential strain peaks — number of cycles (biaxial ratcheting experiment).
- Experiment 5 — internal pressure $p = 11.03\,\mathrm{MPa}$, and symmetric rotation controlled cyclic bending $\theta_c = 0.193\,\mathrm{rad}$ — output mean in-plane diameter change, mean out-of-plane diameter change, mean of top axial strain peaks, mean of top circumferential strain peaks, amplitude of top axial strain peaks, amplitude of top circumferential strain peaks — number of cycles (biaxial ratcheting experiment).

4. Finite Element Model Characterization

Modeling of the pipe has been done in ANSYS utilizing the symmetry of the problem in both the longitudinal and circumferential directions, see Fig.1. The pipe was modeled using shell181 linear elements (*Besseling model, Chaboche model*) and shell93 elements with midside nodes (*Modified AbdelKarim-Ohno model*). Boundary conditions and loading for all solved cases are presented graphically at the Fig. 1.

5. Identification of Material Parameters

Material parameters of Besseling model (KINH) were gained by fitting the closed hysteresis loop (experiment 1), except values of Poisson's ratio $\nu = 0.302$ and Young modulus $E = 183\,000\,\mathrm{MPa}$ of course.

All material parameters of Chaboche model (Chaboche_1) were taken from literature [8] (genetic algorithm was used). An alternative approach is described elsewere [4]. Parameters were estimated using experiments 1 and 2.

The extended iteration algorithm (described for example in [9, 10, 11]) is firstly tested in low-cycle fatigue domain now. The algorithm uses FEM for identification of material parameters. It was applied only on Chaboche model (Chaboche_2, Tab. 3). In the calibration the first three experiments were used. It has been calculated and evaluated only ten loading cycles. The error of calculation was assumed as area between experimental curve and numerical one [11, 12] (graphs are presented in the next section, experiment 1 — graph at the Fig. 2, experiment 2 — graph at the Fig. 3, experiment 3 — graph at the Fig. 4). For error estimation in experiments 2 and 3 the equation (12) was used (in the first experiment the number of cycles N is replaced by corresponding values of stress σ).

$$Error = \frac{\sum_j \left\{ \left| \left(\varepsilon_j^{Exp} - \varepsilon_j^{FEM} \right) \cdot (N_j - N_{j-1}) \right| \right\}}{\sum_j \left\{ \left| \varepsilon_j^{Exp} \cdot (N_j - N_{j-1}) \right| \right\}}. \tag{12}$$

The total error corresponding to FEM for all three experiments was calculated as averaged mean (13).

$$Error\_total = \frac{Error\_\exp 1 + Error\_\exp 2 + Error\_\exp 3}{3}. \tag{13}$$

The complete calibration of proposed modification of AbdelKarim-Ohno model in case of five kinematic parts ($M = 5$) includes 18 parameters identification. The all material parameters are included in the Tab. 4.

Table 4. Parameters of modified AbdelKarim-Ohno model

Calibration	Parameters
Closed hysteresis loop	$\sigma_Y = 262\,\mathrm{MPa}$, $C_1 = 342\,610\,\mathrm{MPa}$, $\gamma_1 = 28\,292$, $C_2 = 208\,880\,\mathrm{MPa}$, $\gamma_2 = 3\,289$, $C_3 = 602\,30\,\mathrm{MPa}$, $\gamma_3 = 575$, $C_4 = 52\,800\,\mathrm{MPa}$, $\gamma_4 = 549$, $C_5 = 22\,670\,\mathrm{MPa}$, $\gamma_5 = 36.4$.
Uniaxial ratcheting test	$\mu_0 = 0.8$, $\omega = 35$, $\mu_\infty = 0.02$.
Multiaxial ratcheting test	$\chi_0 = 100$, $\chi_\infty = 1$.

6. Results of performed computations

The results of all performed simulations are shown at the Fig. 2–8 and are commented in the following section.

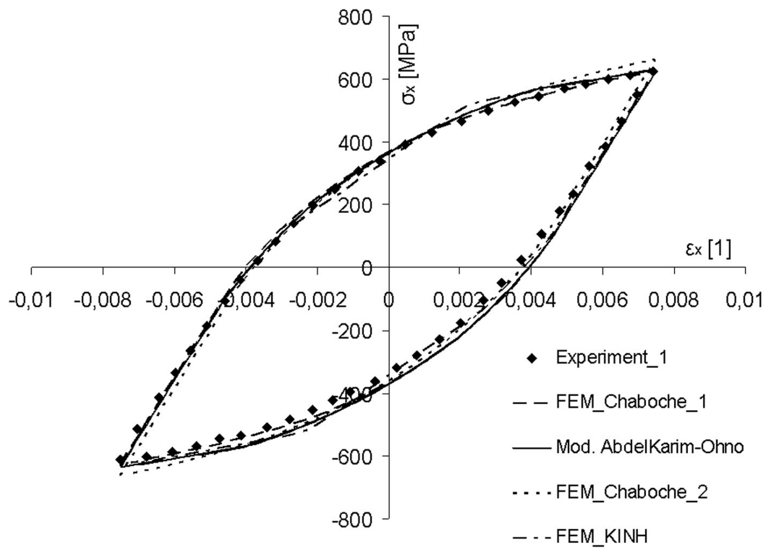

Fig. 2. Axial stress-strain closed hysteresis loop from a symmetric, axial strain controlled experiment for four tested material models (Experiment 1)

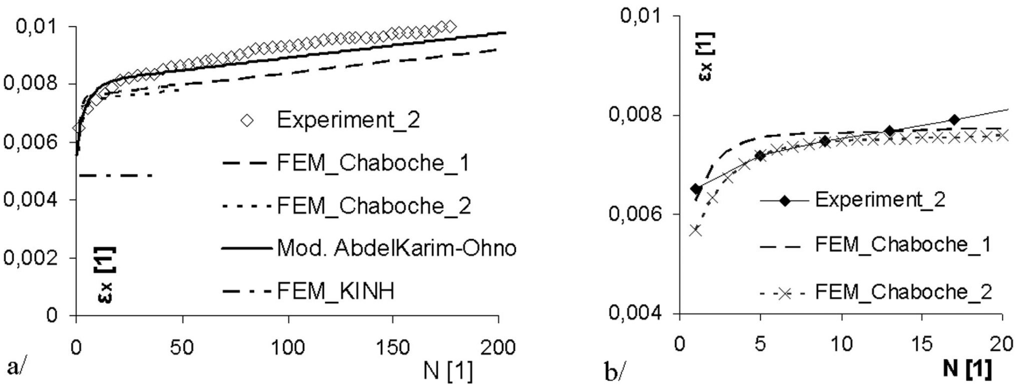

Fig. 3. Axial strains from uniaxial ratcheting test (Experiment 2) a) for four tested material models, b) detail for Chaboche model with two material parameters (FEM_Chaboche_2 — parameters identified for first ten cycles)

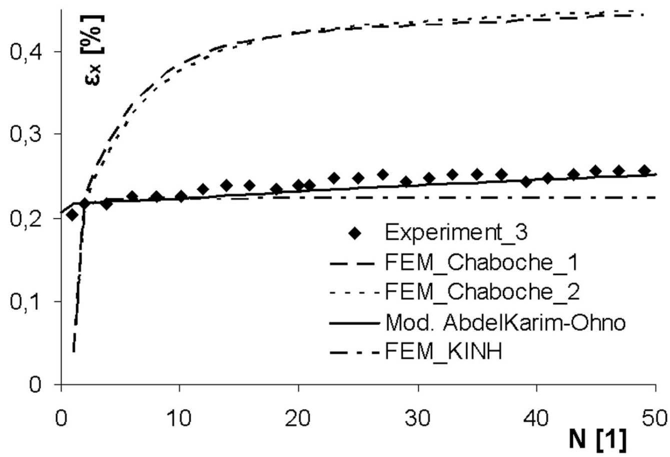

Fig. 4. Maximum circumferential strains from biaxial ratcheting test for four material models (Experiment 3)

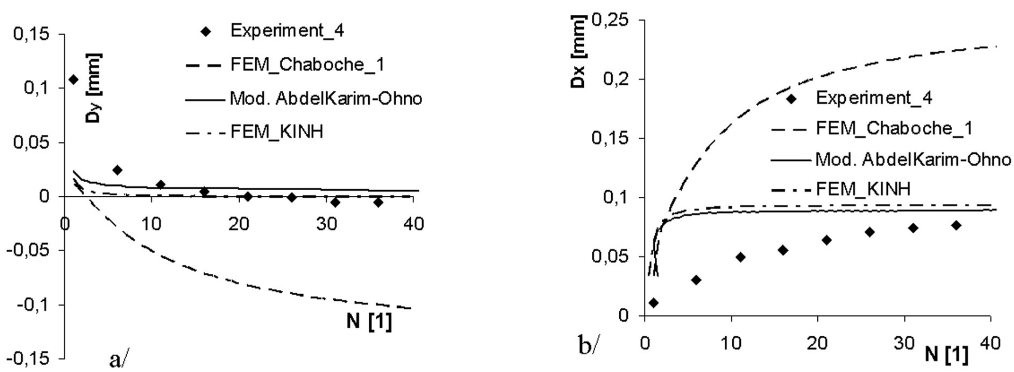

Fig. 5. Multiaxial ratcheting test a) mean in plane diameter change, b) mean out of plane diameter change for three material models (Experiment 4)

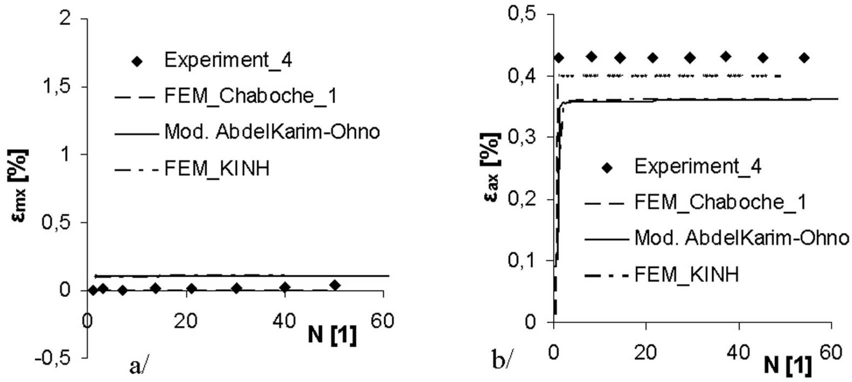

Fig. 6. Multiaxial ratcheting test a) mean in plane axial strain peak, b) amplitude in plane axial strain peaks for three material models (Experiment 4)

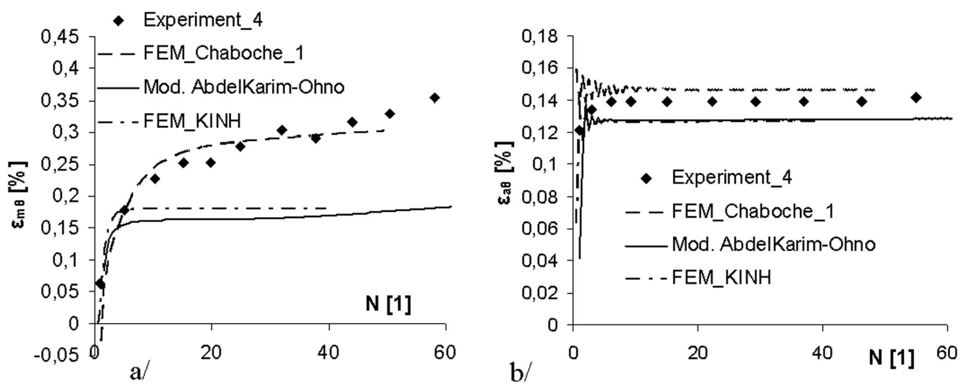

Fig. 7. Multiaxial ratcheting test a) mean in plane circumferential strain peak, b) amplitude in plane circumferential strain peaks for three material models (Experiment 4)

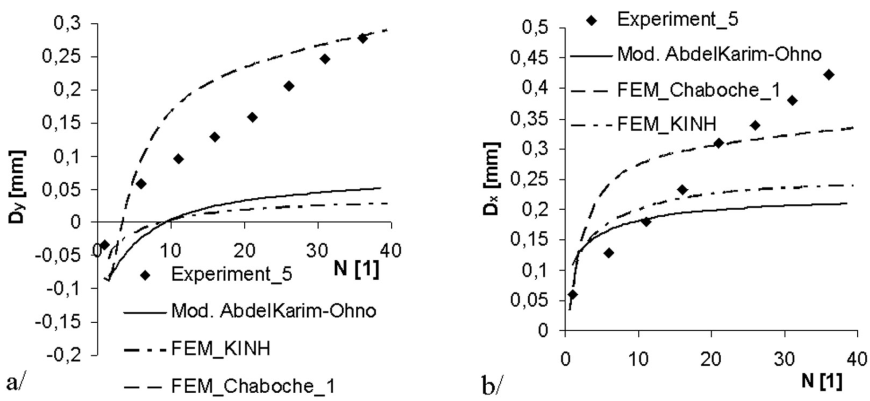

Fig. 8. Multiaxial ratcheting test a) mean in plane diameter change, b) mean out of plane diameter change for three material models (Experiment 5)

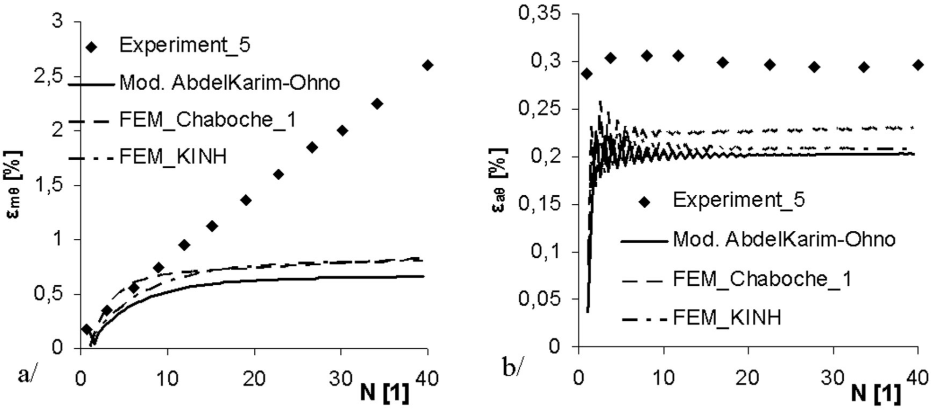

Fig. 9. Multiaxial ratcheting test a) mean in plane circumferential strain peak, b) amplitude in plane circumferential strain peaks for three material models (Experiment 5)

7. Conclusion

From the results of numerical simulations it can be concluded, that evaluated cyclic plasticity models shows very good correspondence with experiments, which were used for material parameter identification, see Fig. 2 (all models), Fig. 3 (Chaboche, AbdelKarim-Ohno), Fig. 4 (AbdelKarim-Ohno).

In experiments 4 and 5 the material tends to shakedown in axial direction (no ratcheting) and all evaluated material models give correct strain response (Fig. 6). Circumferential strain from simulations has good trend in the both cases, but the numerical results are strongly different for 5th experiment (Fig. 8).

Chaboche model predicts higher values in cases with lower ratcheting rate, see Fig. 4, Fig. 5, except circumferential strain prediction in Fig. 7. For higher ratcheting rate it gives better results than all other tested models (Fig. 8, Fig. 9).

The modified AbdelKarim-Ohno model gives the best results of all evaluated cyclic plasticity models (see Fig. 2–6). However, in simulations of experiments 4 and 5 it does not describe material behaviour correctly (see Fig. 7–9).

Numerical simulations of multiaxial ratcheting conducted by cyclic plasticity models described in the section 2 gives results (represented as graph curves) of the same order as experimental one for more solved cases. It is valid also for trends of the curves. All tested material models show significant stabilization of strain response in multiaxial ratcheting case, which is in conflict with experimental results of alloy steel 4130. Future research will be focused on hardening models testing, which do not show mentioned behavior. Further, a possibility of simultaneous material parameters identification from more experiments will be investigated (using FEM) [9, 16].

Acknowledgements

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