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PARAMETER IDENTIFICATION OF CHABOCHE MATERIAL MODEL USING INDANTATION TEST DATA AND INVERSE APPROACH

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Abstract. In this paper genetic algorithm and sensitivity analysis are used to identify 6 parameters of Chaboche kinematic hardening model using repeated Finite element (FE) simulations of indentation test. Five of them are material constants of Chaboche kinematic hardening model itself. The last one represents the stiffness of the foundation and the indenter. To obtain experimental data indentation test under cyclic loading on universal tensile testing machine was performed. Because for sensitivity analysis to obtain all possible combinations of parameters and its values large number of simulation have to be performed supercomputer Anselm hosted by IT4Innovation has been used. Advantage of using supercomputer is that every simulation could use multiple cores which will reduce computational time. Moreover, since each simulation is independent, computational time could be further reduced by performing multiple simulations at the same time. It is clear from the comparison of both methods that the genetic algorithm is very good choice for the parameter estimation.

1 INTRODUCTION

Although experimental measurement bears certain level of uncertainty and is influenced by error it is still the only way how to obtain material properties of any material. To describe the stress-strain behavior of any material under cyclic loading huge number of experiments has to be performed. In practice, it is sometimes very difficult to prepare specimens of the investigated material or application of standard testing method is unrealistic. The later occurs for example in the case of thin samples. Therefore, we need a new method to obtain stress-strain behaviour of investigated material. Numerical modelling and simulation could help to reduce number of physical experiments and also could give us better insight into the problematic

For sufficiently accurate FE modelling of cyclically loaded structures we need good representation of material behaviour. In the case of fatigue occurrence we should describe well cyclic plasticity phenomenon as Bauschinger effect, cyclic hardening/softening of material or the phenomenon called ratcheting (cyclic creep). Ratcheting can be described as the accumulation of any plastic strain component of strain tensor with increasing number of cycles. The ratcheting may occur in practice for instance in the rolling/sliding contact.

One of the first plasticity models, which can qualitatively capture ratcheting in numerical calculations, is Chaboche model [1]. Cyclic plasticity models have been extensively developed over the past three decades. The most popular kinematic hardening rules introduced into new constitutive theories are Ohno-Wang model II [2] and AbdelKarim-Ohno model [3]. For certain materials we can use Chaboche model with two backstress parts to capture all important effects in the simulation but for others it is necessary to implement a robust cyclic plasticity model into the FE code [4].

The main aim of this contribution is comparison of various approaches to cyclic plasticity model calibration from indentation tests performed on the wheel steel Class C. Two algorithms have been applied, the genetic algorithm and the sensitivity analysis to estimate 5 parameters of Chaboche model [1] and a stiffness of the indenter using experimental data from an indentation test with repeated loading. Results show very good prediction of the test using only two backstress parts in the Chaboche suporposition rule. The developed method can be advantageously used to compare various wheel steels from ratcheting point of view.

2 EXPERIMENTAL DATA

An indentation test was realized on testing machine TESTOMETRIC M500-50CT (FS_ZAZ_MR_11_009) at the VSB-Technical University of Ostrava to extract data for comparison of effectiveness of two different algorithms for material parameters identification. Our experiment was done by indeting of 5 mm steel ball into Class C wheel steel specimen. Applied force was between 5 and 2000 N increasing by force rate of 20 N/s. To obtain results for our calculations 10 cycles were performed and displacement as a function of applied force was recorded using a standard.

3 MODEL DESCRIPTION

Time-independent theory of elastoplasticity [5] was applied in this paper. Plastic behaviour is characterized by von Mises plasticity condition and could be described by the following equation

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

where $\mathbf{s}$ is the deviatoric part of stress tensor $\boldsymbol{\sigma}$, a is deviatoric part of kinematic tensor $\boldsymbol{\alpha}$ and $\boldsymbol{\sigma_Y}$ is the yield stress.

To describe Bauschinger effect [6] pure kinematic hardening rule could be considered. Thus, no isotropic hardening was assumed for material model in this study.

Memory term introduced by Armstrong and Frederick in [7], added to Prager's bilinear kinematic rule could be written in following form:

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

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 a superposition rule in [8] for backstress

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

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

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

Practically, from two to five kinematic parts are usually used. In this paper two kinematic parts are assumed, thus it is necessary to estimate material parameters C_1, γ_1, C_2, γ_2, and also the yield stress σ_Y.

4 METHODS DESCRIPTION

To perform parameter identification several methods such as random gradient, genetic algorithm, and sensitivity analysis could be used [9] [10]. In this paper genetics algorithm and sensitivity analysis are used to find material constants of Chaboche kinematic hardening model using repeated FE simulations of indentation test. Results from FE analysis are compared with experimental measurements.

Advantage of genetics algorithms is that for well-defined problem number of iteration needed to reach global minimum is usually very low. Detailed description of genetic algorithm could be found in [11]. In principle it is iterative process which is repeated until global minimum is found. In our case global minimum is defined as difference between measured and calculated values.

Sensitivity analysis due to high number of possible combinations could be seen as an inadequate approach. Number of all possible combinations for N number of parameters, and P values for each parameter could be calculated as

$$V_N^P = N^P. \tag{15}$$

In our case, we have 6 parameters and 5 values for each parameter, therefore number of all possible combinations is

$$V_5^6 = 5^6 = 15\,625. \tag{16}$$

The disadvantage of sensitivity analysis i.e. high number of simulations could be balanced by better understanding of how final results depend on input parameters and their combinations.

To reduce computational time needed for performing of high number of simulations supercomputers could be employed. In our case we used supercomputer Anselm hosted by IT4Innovation to run simultaneously several FE simulations.

5 NUMERICAL EXPERIMENTS

Numerical model reproducing experimental set-up was created using commercial FE package ANSYS. Numerical model of specimen was created using approximately 2000 axisymmetric structural elements (PLANE 182). The element has plasticity, hyperelasticity, stress stiffening, large deflection, and large strain capabilities. In our numerical simulation indented ball was considered as absolutely rigid. Numerical model of specimen and indented ball is shown at Figure 1.

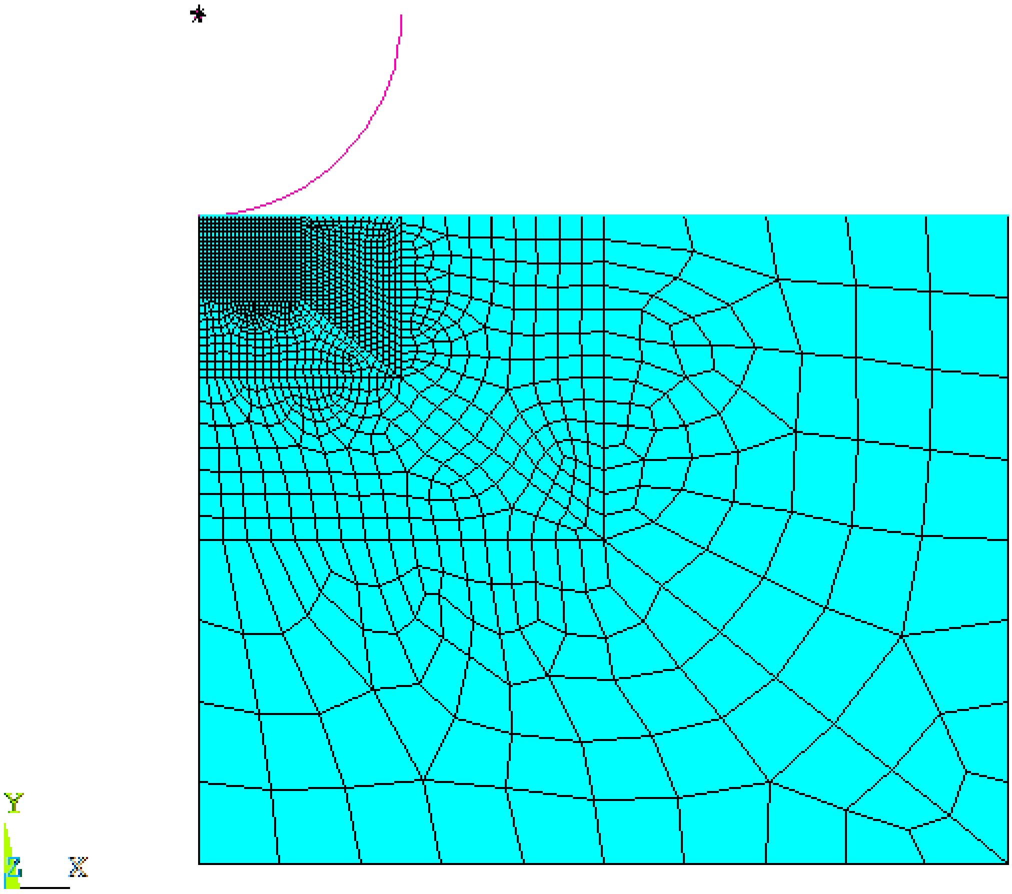

Figure 1: FE model of specimen and indented ball.

As boundary conditions axisymmetric boundary condition (displacement in x direction is set to zero) is used for left boundary and displacement in y direction was set to zero for nodes at the bottom of the specimen. Nodal forces in y direction were applied according to experiment.

The values of searched parameters for genetic algorithm are listed in Table 1, where the first iteration (second row of table) is the initial state and in the next two rows are values of parameters in 600 and 1452 steps. The convergence of genetic algorithm is depicted in Figure 2.

Tabulka 1: Values of parameters for genetic algorithmm

Iteration	σ_Y	C_1	γ_1	C_2	γ_2	rigidity	error
1	450.0	120 000	400	10 000	5.0	120 000	0.17400
600	337.0	113 601	552	7 496	5.6	104 998	0.00847
1452	354.9	107 336	582	7 146	5.5	103 920	0.00750

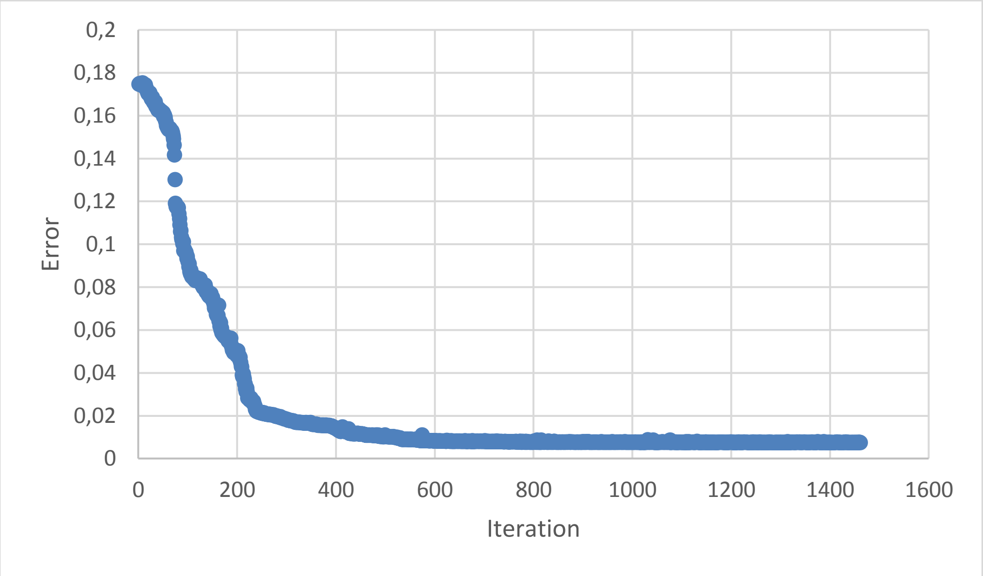

Figure 2: Convergence of genetic algorithm.

Material model used for numerical experiment is described in previous section. For sensitivity analysis values of parameters C1, C2, C3, C4, C5, and C6 are listed in Table 2.

Table 1: Values of parameters for sensitivity analysis

C1	80 000	90 000	100 000	110 000	120 000
C2	350	375	400	425	450
C3	60 000	75 000	90 000	105 000	120 000
C4	200	250	300	350	400
C5	10 000	12 500	15 000	17 500	20 000
C6	1	2	3	4	5

Since number of iteration of sensitivity analysis is apriori known we will be interested whether this method will be able to give us results which will satisfy our accuracy criteria. We decided that satisfactory results will be results for which difference between measured and calculated results is less than 1%. In case of genetics algorithm where we will run as many iterations as needed to fulfil accuracy criteria we will be interested in number of iterations as well.

For genetics algorithm 991 number of iterations in total were needed to obtain combination of parameters which leads to the solution satisfying our criteria described above. Fig. 3 shows comparison between numerical solution and experimental results. Maximal error is 0.75% and optimal values for input parameters are listed in Table 3.

Sensitivity analysis needed 15 625 iterations, as explained in previous chapter, to test all possible combinations of the parameters. The error for best combinations of the parameters is 1.0% and optimal value of input parameters are listed in Table 3. Fig. 4 shows comparison between experimental results and results obtained from numerical simulation. On Figure 5 comparison between both numerical approaches i.e. genetic algorithm and sensitivity analysis could be seen and detail is depicted in Figure 6.

Table 2: Comparison of the best value for genetic algorithm and sensitivity analysis

Parameter	Gen. Alg.	Sens. Anal.
C1	103919.9	110000
C2	354.9	425
C3	107336.7	10500
C4	582.1	400
C5	7146.3	12500
C6	5.53	5

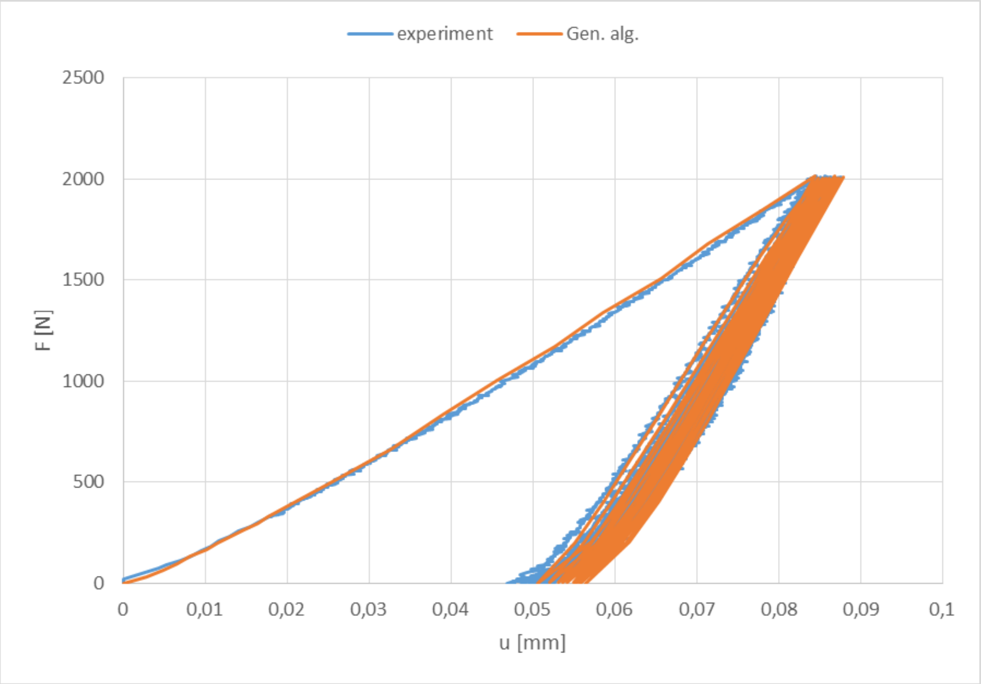

Figure 3: Comparison between numerical simulation by genetic algorithm and experimental data (F – force [N], u-depth of indentation [mm]).

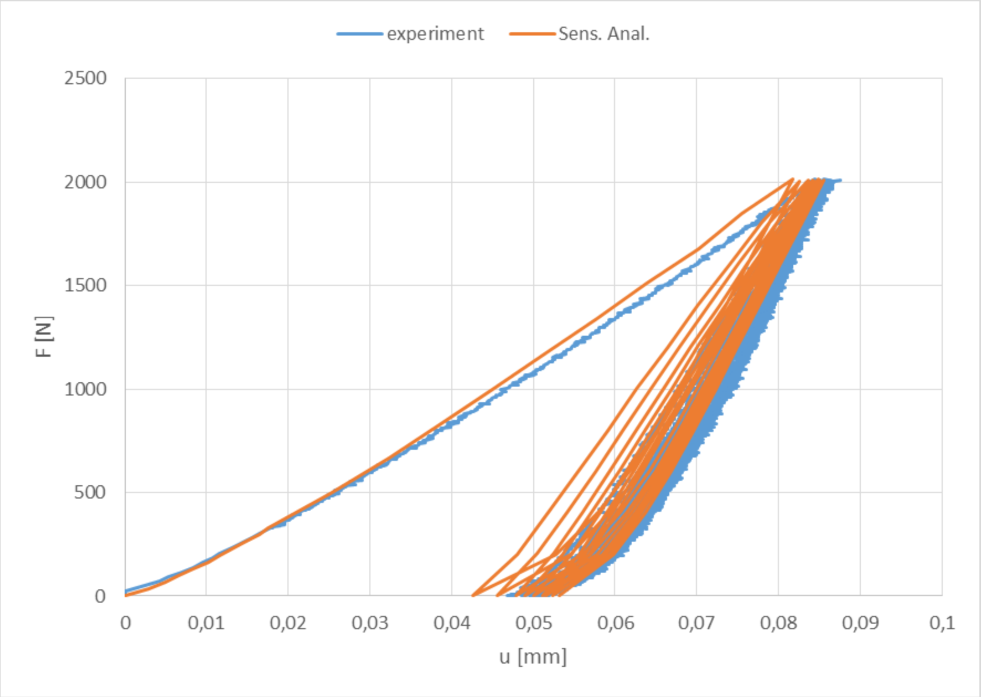

Figure 4: Comparison between numerical simulation by sensitivity analysis and experimental data (F – force [N], u-depth of indentation [mm]).

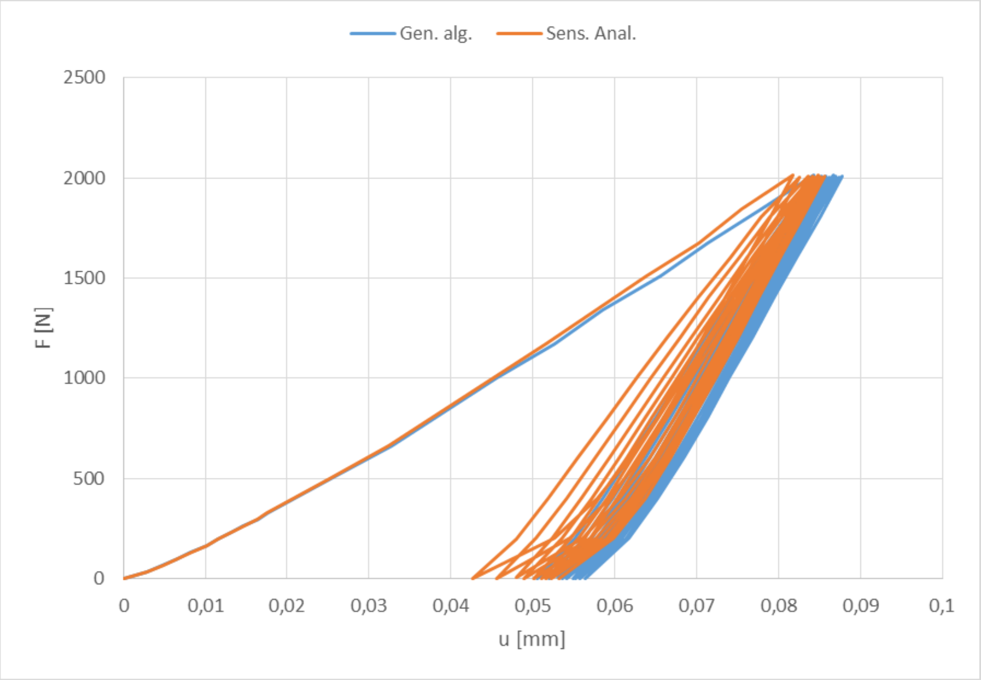

Figure 5: Comparison between numerical simulations by genetic algorithm and sensitivity analysis (F – force [N], u-depth of indentation [mm]).

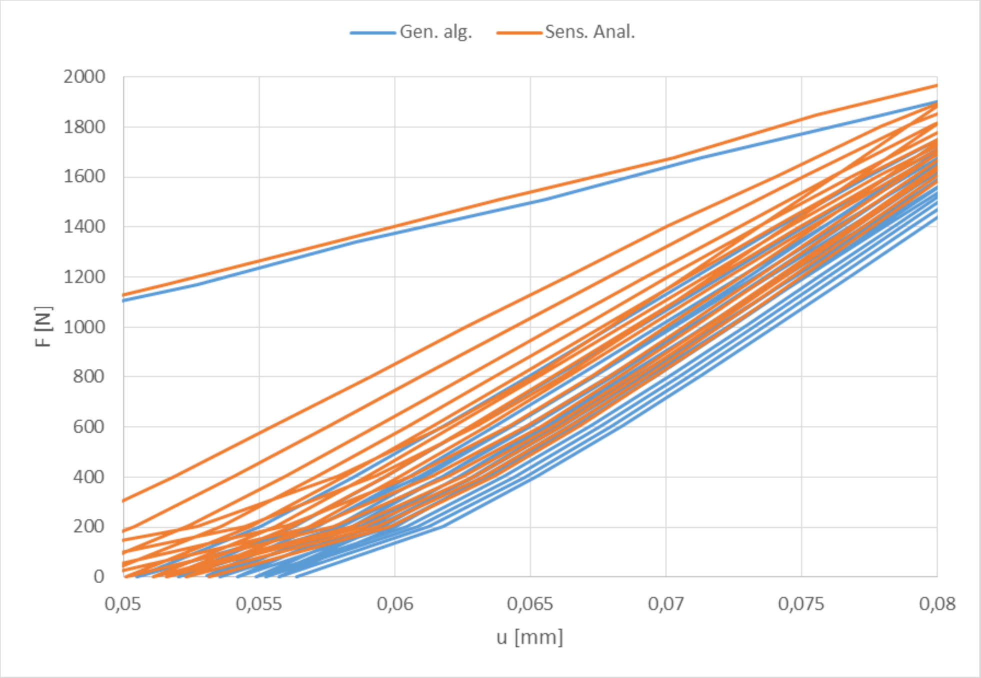

Figure 6: Detail of Figure 4 (F – force [N], u-depth of indentation [mm]).

6 CONCLUSIONS

Results presented in this paper shows that both methods i.e. genetics algorithm and sensitivity analysis are able to produce results with required precision. It is clear that genetic algorithm needs much smaller number of iterations to obtain satisfactory results. This advantage will be even more eminent if we increase number of parameters we would like to identify. A disadvantage of the sensitivity analysis is also the necessity of value interval estimation, which requires extensive experience with the used cyclic plasticity model. The paper was focused mainly on the inverse algorithm evaluation, a case study showing the correctness of estimated parameters for subsequent cyclic plasticity modelling will be discussed in a future paper.

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