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STUDY OF INFLUENCE OF MATERIAL MODELS ON OVALIZATION PREDICTION

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Abstract: The aim of this article is the study of the influence of the different material models as Prager, Prager combined with nonlinear isotropic hardening and Chaboche fitted on low carbon steel 11523. The influence of mentioned material model is examined on resulted ovalization for first and possible second load cycle. Parametric model includes wide range of possible pipe diameters as well as thicknesses. The resulting ovalization shows 3D dependency on mention geometry properties for each material models.

Keywords: ovalization; Chaboche model; bilinear kinematic hardening; nonlinear isotropic hardening

1 Introduction

The cross section of a pipeline under a bending load suffers ovalization. Furthermore, when the stress reaches the yield limit of the material, this flattening becomes permanent. The article deals with ovalization of the pipeline system which is laid on the bottom of the sea. During the reel lay process the pipe is plasticly bended during unreeling as well as in the aligning part (see Fig.1). This can be simplified to the several bending cycles. The aim of this study is to evaluate the influence of different materials models on predicted ovalization for wide range of pipe geometrical properties.

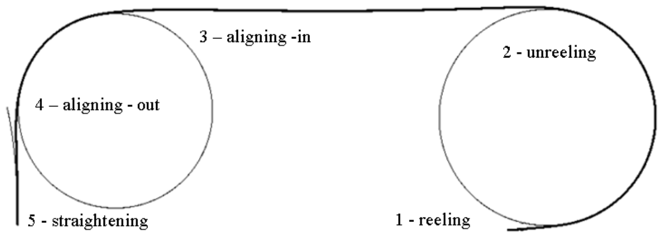

Figure 1: *Scheme of reel-lay system [1]*

2 Study of material models influence

2.1 Description of the material models

For the study purpose, three different material models were used:

- Bilinear material model with Prager rule (noted as BKIN, Bilinear Kinematic Hardening)
- Bilinear material model with Prager rule combined with nonlinear isotropic hardening rule (noted as BKIN NLISO, Bilinear Kinematic Hardening combined with Nonlinear Isotropic hardening)
- Chaboche material model combined with nonlinear isotropic hardening rule (noted as CHAB NLISO)

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2.2 Bilinear kinematic hardening rule

The simplest material model, but frequently used in industry for FE simulations, was developed by Prager in 1956 [2]. It is based on the so-called bilinear kinematic hardening rule, which describes the Bauchinger effect correctly. The bilinear kinematic hardening rule for uniaxial loading case is

$$d\alpha = Cd\varepsilon_p, \tag{1}$$

where C is a material parameter, $d\alpha$ is the backstress increment and $d\varepsilon_p$ is the plastic strain increment. The parameter C defines the slope of the line in the diagram that gives the axial stress versus axial plastic strain, thus it corresponds directly to the plastic modulus $C=h=d\sigma/d\varepsilon_p$.

2.3 Armstrong-Frederick nonlinear kinematic hardening rule

Armstrong-Frederick model contains so-called memory term in the Prager rule, which was published in [3]. The evolution of backstress was defined for uniaxial loading as

$$d\alpha = Cd\varepsilon_p - \gamma\alpha dp, \tag{2}$$

where C and γ are material parameters. The nonlinear kinematic hardening rule can be integrated and the following analytical solution is obtained:

$$\alpha = \psi\frac{C}{\gamma} + \left(\alpha_0 - \psi\frac{C}{\gamma}\right)e^{-\psi\gamma(\varepsilon_p - \varepsilon_{p0})}, \tag{3}$$

where α_0 and ε_{p0} are the initial values of the back stress α and the longitudinal plastic strain ε_p respectively and ψ is the scalar multiplier, which depends of loading direction ($\psi = 1$ for tension and $\psi = -1$ for compression). Therefore, considering yield condition the constitutive equation for the monotonic tension case can be written as:

$$\sigma = \sigma_Y + \alpha = \sigma_Y + \frac{C}{\gamma}(1 - e^{-\gamma\varepsilon_p}). \tag{4}$$

where σ_Y is the yield stress of material.

2.4 Chaboche nonlinear kinematic hardening rule

Rule, introduced by Chaboche [4], include back stress composed by several back stresses parts

$$\alpha = \sum_{i=1}^{M} \alpha_i. \tag{5}$$

The evolution equation of each back stress part is analogous to the Armstrong–Frederick model, i.e.

$$d\alpha_i = C_i d\varepsilon_p - \gamma_i\alpha_i dp, \tag{6}$$

where C_i and γ_i are material parameters. An analytical solution for M back stress parts can be written for non-zero material parameters in the form

$$\sigma = \sigma_Y + \alpha = \sigma_Y + \sum_{i=1}^{M}\frac{C_i}{\gamma_i}(1 - e^{-\gamma_i\varepsilon_p}). \tag{7}$$

In the case of cyclic plasticity modelling, Chaboche model may be calibrated from the cyclic stress–strain curve using the formula

$$\sigma_a = \sigma_Y + \sum_{i=1}^{M}\frac{C_i}{\gamma_i}tanh\left(\gamma_i\varepsilon_{ap}\right), \tag{8}$$

where $\sigma_a, \varepsilon_{ap}$ mean the amplitude of stress and the amplitude of plastic strain respectively.

2.5 Calibration of the cyclic plasticity models

On the basis of the experimental hysteresis loops, it is possible to visually compare the accuracies of the stress–strain predictions of above mentioned material models. Some attention was paid earlier to describing the constitutive models and explaining their behavior, especially under uniaxial loading.

2.5.1 Experimental data

For material calibration, there were used the results from a tension–compression cyclic plasticity test as well as uniaxial test results for 11523 steel (ST52) visible in Fig. 2.

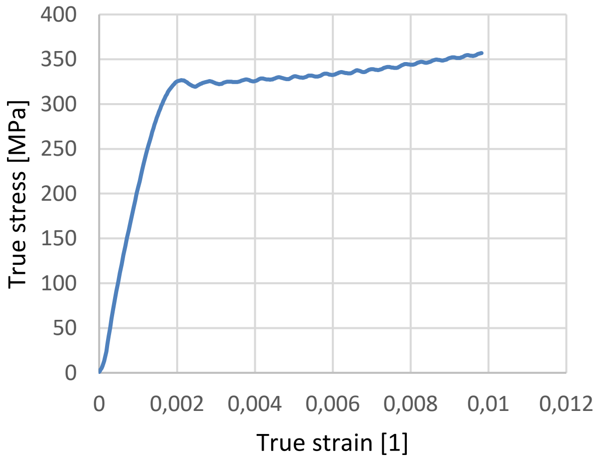


Figure 2: *Uniaxial stress-strain curve for 11523 steel*

2.5.2 Calibration of the cyclic plasticity models

The calibration of material models has been done on simple FE model including series of link elements loaded in tension and compression to get correct response for the comparison shown below on Fig.3-5. All calibrated material parameters used in further analysis are stated in Table 1.

The first considered material model is based on Prager´s kinematic hardening rule (BKIN). The bilinear response of the pure kinematic hardening model is clear from the Fig. 3. The closed hysteresis loop is obtained in the first cycle, as could be expected.

The next tested material model is based on Prager´s kinematic hardening rule combined with a nonlinear isotropic hardening law (BKIN+NLISO). The predicted uniaxial hysteresis loops are shown in the Fig. 4.

More complicated, however, in industry becoming more and more used, the Chaboche model (CHAB+NLISO) was tested too. This model is able to describe ratcheting and mean stress relaxation. Three back stress parts are considered (M = 3) in order to accurately describe the shape of the hysteresis loop. Cyclic hardening or softening of material is furthermore incorporated by combining it with a nonlinear isotropic hardening rule. The predicted uniaxial hysteresis loops are in the Fig. 5.

Model	*Material parameters*
BKIN	E = 188 GPa; ν = 0.3; $\sigma_y = 364$MPa ; $C = 3999$MPa
BKIN+NLISO	E = 188 GPa ; ν = 0.3; $\sigma_y = 314MPa$; $C = 3999MPa$; $R_0 = 0$; $R_\infty = 80MPa$; $b = 50$
CHAB+NLISO	E = 188 GPa ; ν = 0.3; $\sigma_y = 100MPa$; $C_{1-3} = 250000, 34860, 2670\ MPa$; $\gamma_{1-3} = 2500, 273, 0$; $R_0 = 0$; $R_\infty = 80MPa$; $b = 50$

Table 1: *Material parameters of the calibrated model*

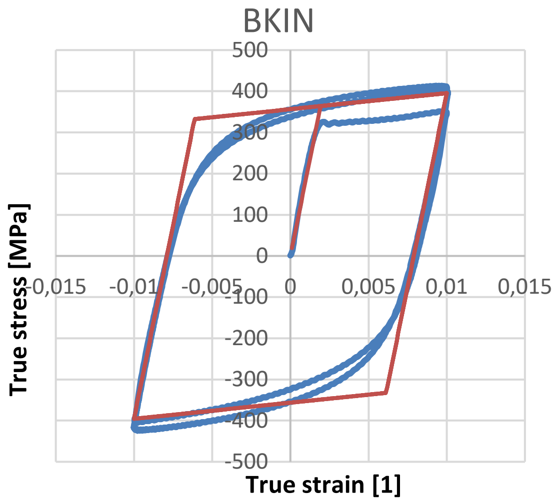


Figure 3: Experimental and FE data for BKIN model

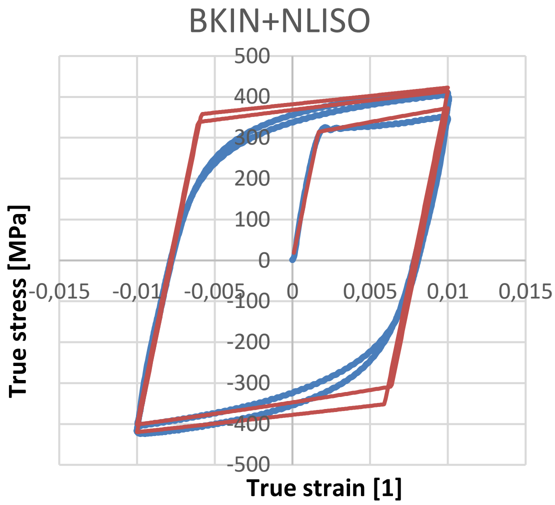


Figure 4: Experimental and FE data for BKIN+NLISO model

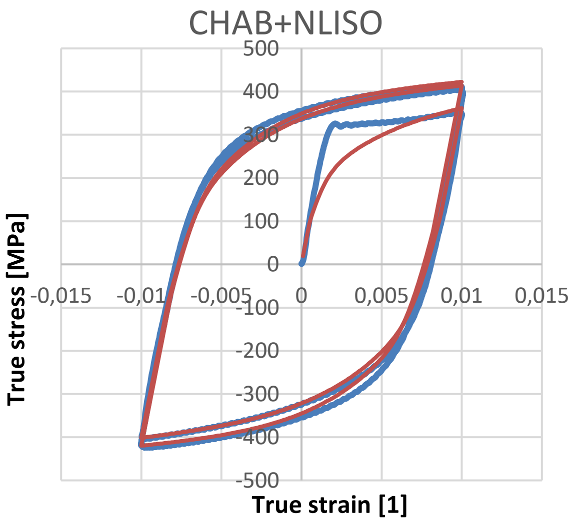
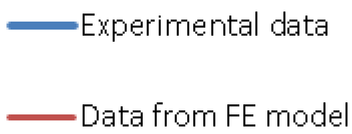


Figure 5: Experimental and FE data for CHAB+NLISO model



2.6 Finite element model

The analysis was performed in Ansys software (version 18.2). The model consists of SHELL281 elements and the reliability of used approach is proved in [1]. The pipe has been simplified with the symmetry boundary condition (depicted by red line on Fig.6 and by labels B and C). Remote rotation of 10° in X direction was applied to the other end as depicted by yellow colour and label A on the Fig.6, rotation in Z and displacement in X and Y were fixed. The resulted vertical ovalization has been evaluvated from points in the Fig.7 and the vertical ovalization was calculated as follow

$$\text{Ovalization} = y_{pointA} - y_{pointB}. \tag{9}$$

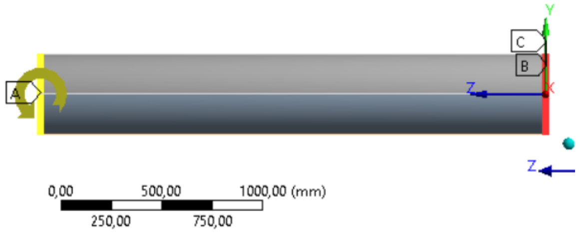


Figure 6: *Boundary conditions*

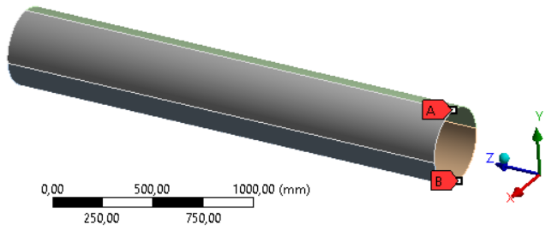


Figure 7: *Evaluation points*

3 Results

The presented ovalization prediction was obtained based on material inputs from Table 1 and above described boundary conditions for first loading cycle for constant pipe thickness. As it is obvious from the Fig. 8 all tested material models predict very similar ovalization in scenario of smallest pipe diameter. Bigger pipe diameter is resulting into higher ovalisation for Prager‘s model.

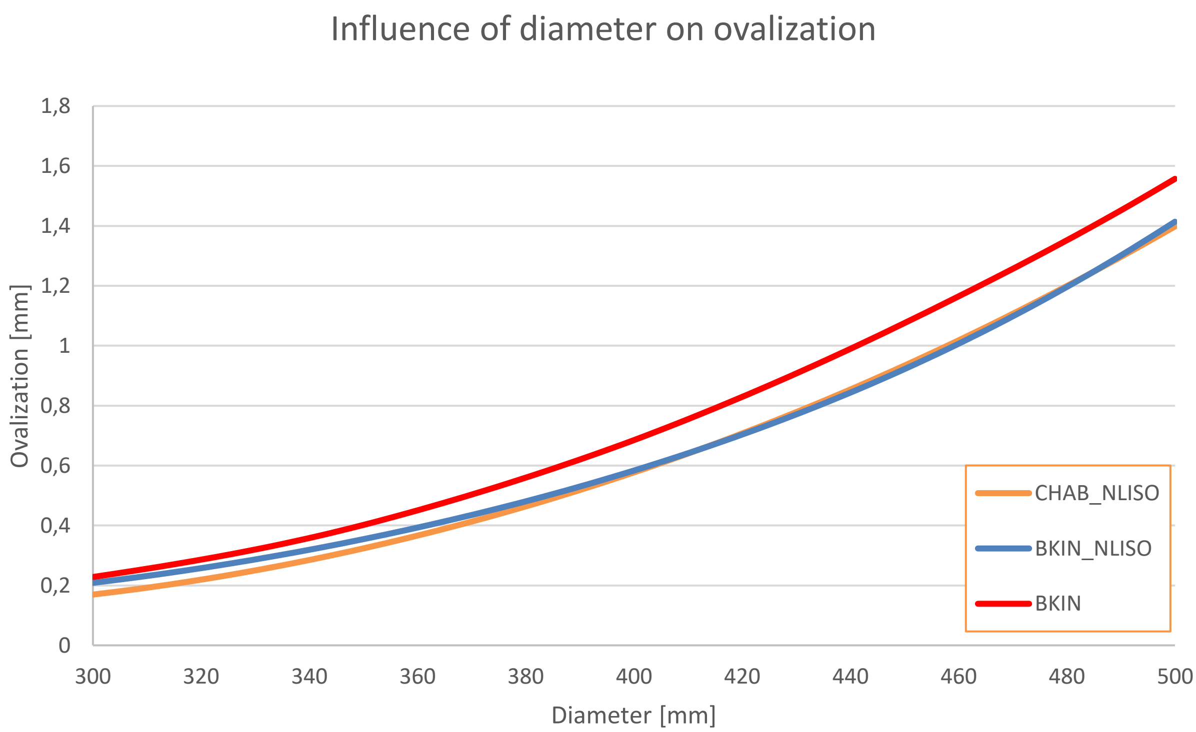


Figure 8: *Ovalization as a function of pipe diameter for the three material models*

Similar study has been done for pipe thickness as well. Therefore the influence of both geometrical parameters on predicted ovalization for all tested material models is plotted in the form of 3D charts, see Fig. 9-11.

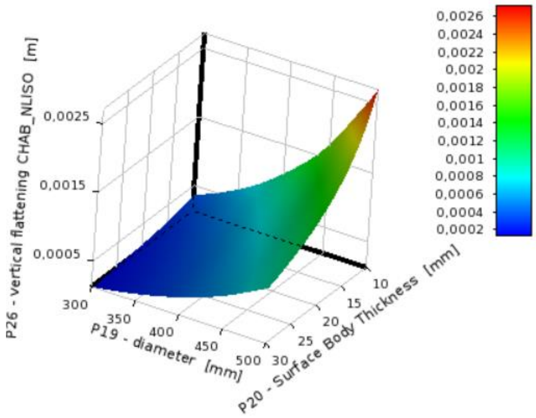


Figure 9: 3D chart for CHAB+NLISO model

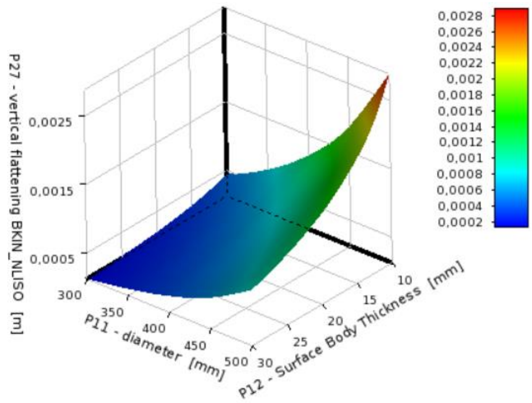


Figure 10: 3D chart for BKIN+NLISO model

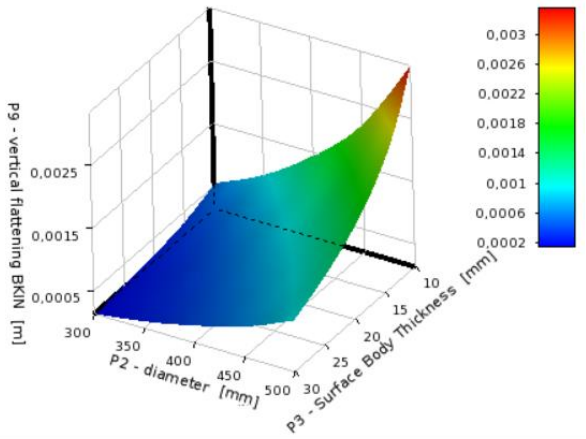


Figure 11: 3D chart for BKIN model

4 Conclusion

This study shows that material models has crucial influence on predicted ovalization as well as material parameters itself. In the technical practice the most used Prager model predicts highest ovalization from the tested material models however reports sensibility on combination of pipe diameter and thickness. This behaviour is necessary to study it more in detail with higher amount of design points. Presented results finally confirm that based on this study is necessary to perform real testing for several geometrical variants to evaluate accuracy in wide range of pipes.

Acknowledgement

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