EAN 2017
55th conference on experimental stress analysis

Tuning the material models for the nonlinear dynamic simulations by considering the exact material properties

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Keywords: *material models, strain-rates, Krupkowski law, dynamic bending test, simulations*

Introduction

In the automotive and ground transportation industry simulations have been replacing prototype tests for quite some time. The ”digital twin“ is required to acredibly copy the physical properties of the actual prototype. For the non-linear dynamics analyses it is necessary to choose the realistic physical properties of elastic-plastic materials. The goal is to have the simulation achieve the best correlation compared with the results of the experimental tests.

In this article we will show how optimizing the material parameters can significantly reduce the computational time while offering the same quality results. The aim of this article is to compare the results obtained when using two highly advanced material models, the hardening curves and the Krupkowski law [3]. The results of the simulations in both cases were compared to the results of the experimental dynamic bending tests carried out on test samples with a cross section size of 50x50 [mm], wall thickness of 5 [mm], where the material is steel class S355 and it is manufactured by hot rolling.

1. Creation of material cards

The first step of the „digitization“ of the material properties for the numerical simulation purposes is the acquisition and adjusting of the basic mechanical properties of the given material. Those we obtain by means of static tensile tests according to the STN EN ISO 6892-1 standards. At this stage it is necessary to create a model of the tensile specimen with a fine meshing into a finite elements and to carry out the tensile test with the given simulation software. In this case, it is best to use the 4 nodes shell or 10 nodes tetrahedron elements, depending on whether the material is tuned for the volume or shell elements. In case of volume mesh it is necessary to check the numerical material model thanks to which we intend to count elastoplastic behaviour of steel. Some elements have the tendency to be too soft (supple – for example hexahedrons), others can exhibit very high stiffness resulting in locking. At any case, the real and computed tensile curve must show compliance in the whole elastic-plastic domain. If this is not the case, it is necessary to adjust the characteristic variables (parameters) of the material models so that the difference is in the range of acceptable values.

Next, it is necessary to proceed with the tuning of the material properties to the size of the computation mesh. Although the speed at which computers perform is constantly improving , currently we are not able to calculate large models and large-scale tasks with a fine mesh size. To hammer out the results within a reasonable time, it is necessary to use a coarser mesh grid that is determined by the optimal characteristics of the meshing. In practice, for steel it means that instead of 5 mm mesh size for the dynamics tasks (with large deformations), a mesh with a size of 10 to 20 mm is used. Of course it is necessary to adjust and tune the material cards for that computational mesh size. The basic parameters of the material cards for the computational mesh size are also the tensile test results. In this step we prepare another set of the tensile test samples but this time with the element size that corresponds to the computational mesh size. At this stage it is necessary to adjust the parameters of the material model in such a way so that the tensile curves of both simulations (thus fine and real – computational mesh size) are in compliance. It should be emphasized that in all cases we have to compare the real, and not the engineering tensile curves.

2. Elastic-plastic material models

In the case of dynamic tasks most often two material models are used – the Krupkowski law and the strain-rate curves for the elastic-plastic description of the material behaviours.

The Krupkowski material model characterizes the behaviour of the material in the elastic-plastic domain which also implies isotropic and kinematic behaviours of the flexible bodies. The material model is described by the following equation:

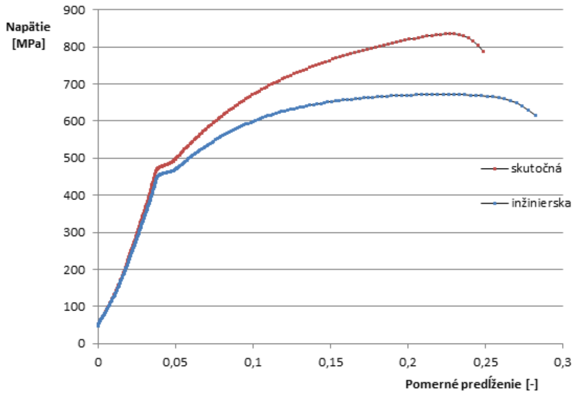
$$\sigma = K(\varepsilon_0 + \varepsilon)^n \tag{1}$$

where:

K – material constant (hardening coefficient)
n – strain hardening exponent, which has a value of <0,1>
(0 – isotropic hardening, 1 – kinematic hardening)
ε_0 – initial strain on the limit of elasticity

Constants K and n of the material model are obtained through the approximation of the tensile diagram, while engineering stress and strain values are recalculated into real values and thus construct a curve. We do this because the Krupkowski equitation better approximates the actual curve of stress and strains than the measured engineering curve value. The main benefit of the Krupkowski material model is the correct description of the material behaviour between the limits of proportionality and strength. Therefore for the search of constants of this material model we use that part of the tensile curves which describes this plastic area. The course of the real and engineering tensile curve is shown in figure Nr. 2.

Within the parameter settings the goal is to find the constants thanks to which the mathematical approximation is as close as possible to reality. Based on the calculated constants a curve is generated together with the plastic part of the real tensile curve are described in figure Nr. 3. The Krupkowski material law is tuned for a **specific loading speed**.



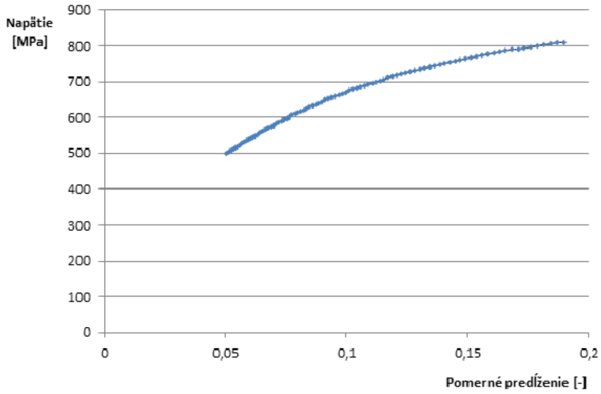


Fig. 1 The real and engineering tensile curve (left) and the plastic part of the real tensile curve (right)

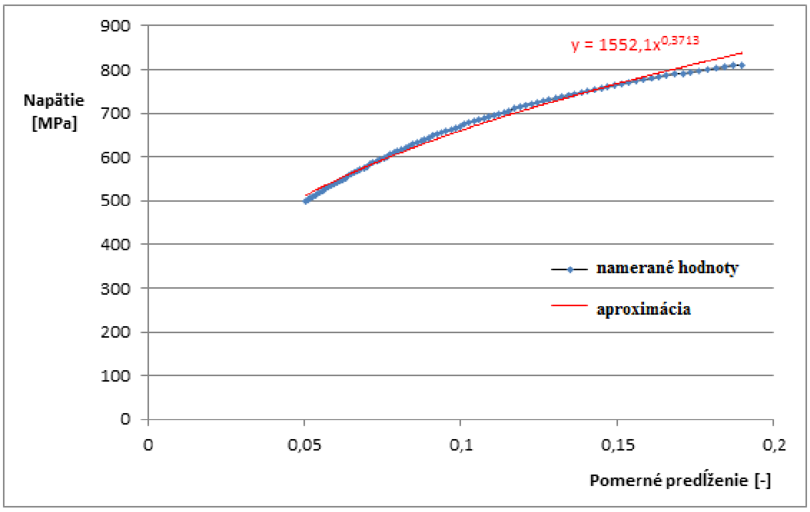


Fig. 2 the plastic part of the real tensile curve (blue) and its comparison with the computation by using the tuned Krupkowski law and given mesh size (red)

Another option to describe the material behaviour in the whole elastic-plastic domain is to use the strain-rate curves for a given range of speeds. This means that in this case it is necessary to experimentally measure the elastic-plastic behaviour of the material for different load speeds. These curves describe the strain rate influence on the plastic strain response for the given load speed. The number of curves that can be used as an input for a given material is usually limited by the specific software only – in the case of Virtual Performance Solution of ESI it is possible to define 8 different curves. These curves describe the strains ε depending on the strain rates $\dot{\varepsilon}$ the software interpolates the values σ (ε, $\dot{\varepsilon}$) from the specified curves. The first curve representing the basic stress-strain law $\dot{\varepsilon} = 0$ must always be defined.

3. Three-point dynamic bending

Static tensile tests and their execution by means of simulations help us create the basic material cards. For the dynamic calculations it is necessary to check the behaviour of a material under a dynamic loading of which impact velocity is typical for this particular problem. In case of elastic-plastic materials such verification can be done by using the dynamic bending test.

The dynamic bending test is characterized by a load of known weight *m*, which is impacting the test sample from a predetermined height. Since the value of the track of the free fall is known, the impact speed can be determined with a very high precision. The system must be set so that the impact velocity replicated that speed we require to perform the virtual test.

The weight of the impactor can be selected so that permanent deformation of the test specimen is approaching the expected deformation of the realtest. The scheme of the dynamic bending test si shown in figure nr. 4.

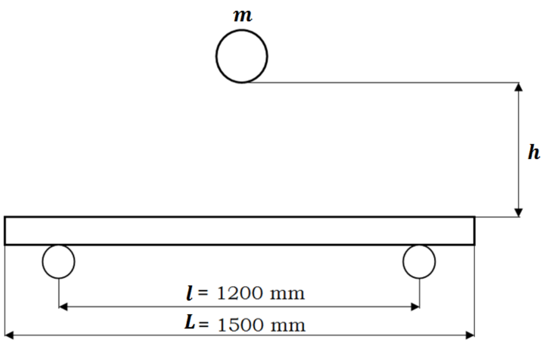


Fig. 3 The scheme of the dynamic bending test

After the impact, the impactor of a given mass *m* falls onto the test piece which bents and then after the impact and springback it results in a permanent deformation $\boldsymbol{y_d}$. The magnitude of this distortion can be expressed by the following formula:

$$y_D = \frac{G_D \cdot l^3}{48 \cdot E \cdot Jz} \qquad y_d = \frac{G_D . l^3}{48 E J_z} \tag{2}$$

An established method of obtaining the material data necessary for the simulation is performing dynamic bending tests on real samples and also on a computer model. Then these tests are compared to see whether they match up. The acceptable tolerance band is is up to 10%.

4. Experimental tests

Our experimental tests were carried out on test specimen of the square cross-section with dimensions of 50x50 [mm], with a wall thickness of 3 [mm] and a length of 1500 [mm]. The test specimen were made of steel of class S355. The impactor mass is 60 [kg] and its impact speed pn the test specimen were v_d = 8 [m.s^{-1}].

Substituting the appropriate values into the formula (2) we can estimate that the theoretic value of the maximal bending deformation after springback, without taken into account the hardening of the material, is

$$y_D = 56.14\ [mm] \tag{3}$$

In our case it is very difficult to measure the maximum deformation of the test specimen. Although the whole course of the test is recorded by a high-speed camera with a speed of 1 picture for a millisecond, the maximum deformation under our conditions can on;y be read and changed only with an accuracy of two-tenths of a millimetre. Hence we decided to evaluate the value of the permanent deformation of the test specimen. The actual experiment we conducted on 10 identical test specimen, while residual deflection was measured in 3 places of each one sample, The first measurement point was right in the middle of the sample, the second and the third were at a distance of ¼ L from the underpinning points towards the centre of the test piece. For the footage of f the carried out experiment, see Figure no. 5.

Fig. 4 Realization of the experiment: Impactor moment of contact with the test specimen (left) and the beginning of the springback

We used an identical approach in the case of virtual tests. In the modul VisualMESH™ of the software Virtual Performance Solution™ we prepared a finite element model with the identical bending test conditions. The model was prepared using mid surfaces, then we have given geometry divided into a finite network. For the discretization we used 4-nodes shell elements. Subsequently onto the prepared model we applied the initial and boundary conditions coincide with the real conditions of the experiment.

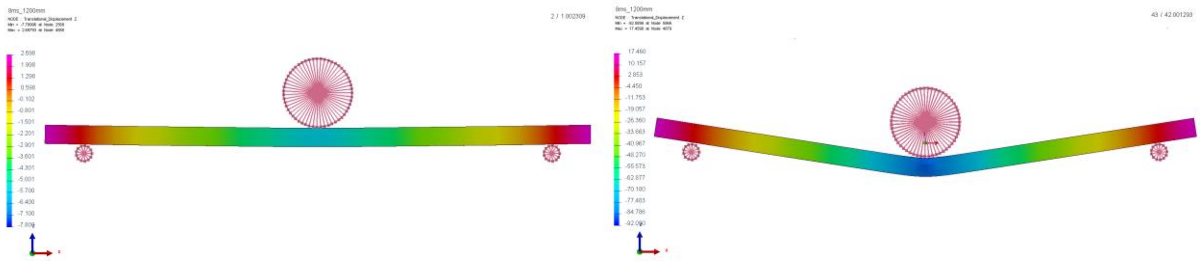


Fig. 5 Outputs of the simulation: Impactor moment of contact with the test specimen (left) and the beginning of the springback

5. Obtained results

The aim of this work was to analyze the extent to which it is possible to use simplified material models for complex calculations of dynamic events. For a more complete picture, we compared the two most widely used material models with experimental results in 3 characteristic points of the test specimen. The test results have been included in the following table:

The used test method	Deformations in the characteristic point of the test sample		
	1	**2**	**3**
Measured experimental data	-8,1	-45,6	-8,2
Computation through strain-rate curves	-8,4	-47,9	-8,4
Computation using the Krupkowski law	-8,8	-48,7	-8,7

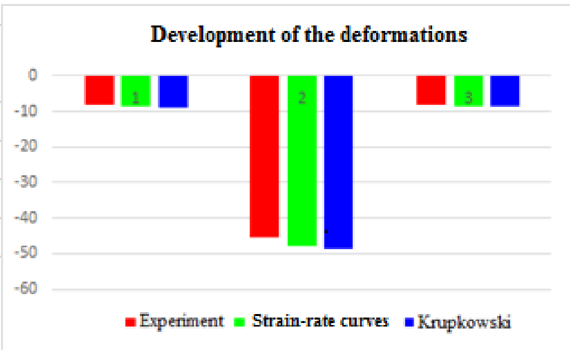


Fig. 6 Comparison of the results of the experiment and computations

Based on the obtained results we can conclude, that the maximum value of the percent deviation of the experiment and calculation when using the Krupkowski law is 8.6%. If we compare simulation results with the use of strain-rate curves, the maximum value of the percent deviation of the experiment and calculation is 5.0% .

If we compare the results obtained by calculations with two different material models, we can conclude that the maximal percent deviation is up to 2%.

Conclusions

The present article discusses the use of various flexible-plastic material models for simulation of nonlinear dynamic events. The subject is to optimize the material parameters to minimize the computational time in compliance with the quality requirements of the numerical calculation results. Based on the obtained results we can conclude, the two methods are fully applicable, and provide the result in the frame of the permitted tolerance margin percentage deviation. In areas with a strong plastic deformation the difference of the results of the computations using the Krupkowski law and the strain-rate curves is only 1.6%, while the latter method is financially much more expensive. Experiments to measure the strain-rate curves have of an order of higher costill there?
s. The computation time for the solution with the Krupkowski law is only 6% longer in comparison of the computation using the strain-rate curves.

Using the Krupkowski material model, it is possible to finalize the results quickly and efficiently, and the results thus obtained are consistent with the results obtained by experimental tests.

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