LOCAL APPROACH IN MECHANICAL PROPERTIES PREDICTION

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Abstract

Indentation technique was focused on the prediction of the strain hardening behaviour of carbide steels. An improved technique to determine the plastic properties of material from the load-displacement curve from a ball indentation test was proposed. The time severity for the search for an optimal solution for a non-linear constitutive model is dependent on a number of design variables. Common methods like gradient methods or linear programming can fail due the fact that they drop to the local minimum. The advantage of a genetic algorithm does not require knowledge of the target function. Proposed method was applied to the data from the instrumented indentation technique. Results were found to be in good agreement with the data from conventional, standard tests, and in less time.

Keywords: Instrumented indentation test, material model, genetic algorithm

1. INTRODUCTION

Instrumented indentation method is one of the experimental methods that can estimate values of a material’s mechanical properties based on the record of dependence of indenter penetration depth on applied force. Evaluation of a construction material’s mechanical properties, such as steel where, for the reason of such small dimensions, the conventional mechanical test cannot be used, it can be realized through the use of indentation methods. The instrumented indentation test used in this case is based on the well known Brinell’s hardness test. Implementation of the testing machine with a system of exact force and indenter penetration depth recording enabled the development of mechanical properties estimation methods. Recently, techniques that reveal basic strength characteristics such as elastic modulus, yield stress and strain hardening exponent were evolved. The Automated Ball Indentation Test (ABI) is among the most widely used evaluation instruments; due to repetitive indentation of spherical indenter into one spot, estimation of real stress and deformation can be realized. Typical process of indentation test with the use of spherical indenter (Fig. 1) consists of loading part and unloading part.

Fig. 1. Indent imprint cross section

Elastic modulus (3) is determined from the unloading phase of indentation test process (Fig. 2). The value of elastic modulus is directly proportional to unloading curve slope.

\[
H = \frac{P_{\text{max}}}{A},
\]
Where $P_{\text{max}}$ is maximal loading force, $E_m$ and $E_i$ are tested material and indenter tip elastic modulus, $E_r$ is reduced indentation modulus.

Development of numerical modeling methods leads to their usage for material models’ parameters estimation. The material properties estimation method is based on searching for the minimum of function that expresses the difference between a measured and a calculated process of indentation test. Non-linear material model in the finite element method is used for the analysis of a contact problem.

**Fig. 2.** Force - displacement indentation curve

### 2. FINITE ELEMENT MODEL DESCRIPTION

For target function evaluation it is necessary to determine indentation dependence by means of a numerical model. The indentation test is being solved as a quasi-static axisymmetric problem with a non-linear material model. Finite element model assumes that a rigid spherical indenter is loaded with a normal force $P$ and penetrates into the surface of an axisymmetric homogenous specimen occupying the domain $\Omega \{0, 2\pi\}$ (Fig. 3). Uniaxial quasi-static indentation process is simulated by monotonically increasing the value ($h > 0$) of the penetration depth. Another condition is that this process runs without any additional moments and friction. As this is a symmetric problem, a consequential axisymmetric contact problem is modelled for penetration depth $h = \{0; h_{\text{max}}\}$. The indentation is modelled by the following contact problem finding the displacement field $u(x,y) = (u_1(x,y), u_2(x,y))$ the solution of the unilateral problem:

$$\begin{cases}
-\frac{\delta}{\delta x} (x\sigma_{11}(u)) - \frac{\delta}{\delta y} (x\sigma_{12}(u)) + \sigma_{11}(u) = 0, \\
-\frac{\delta}{\delta x} (x\sigma_{12}(u)) - \frac{\delta}{\delta y} (x\sigma_{22}(u)) = 0, \\
(x,y) \in \Omega \subset \mathbb{R}^2;
\end{cases}$$

The contact condition is:

$$\begin{cases}
u_1(x,y) \leq -h + \varphi(x), \\
u_2(x,y) + h - \varphi(x)\sigma_{22}(u) = 0, \\
\sigma_{12}(u) = 0, (x,y) \in \Gamma_0;
\end{cases}$$

and boundary condition are defined:

$$\sigma_{11}(u) = 0, \sigma_{12}(u) = 0, (x,y) \in \Gamma_\sigma;$$
\[ u_i(0, y) = 0, \sigma_{ix}(u) = 0, (x, y) \in \Gamma_i, \]
\[ \sigma_{ix}(u) = 0, u_x(x, 0) = 0, (x, y) \in \Gamma_u. \]

Where,
\[ \Omega = \{(x, y) \in \mathbb{R}^2 : 0 < x < l_x, 0 < y < l_y \}, \]
\[ \Gamma_\sigma = \{(l_x, y) : 0 < y < l_y \}, \quad \Gamma_0 = \{(x, l_y) : 0 \leq x \leq l_x \}, \]
\[ \Gamma_i = \{(0, y) : 0 < y < l_y \}, \quad \Gamma_u = \{(x, 0) : 0 \leq x \leq l_x \}, \]

and \( \phi(x) = \sqrt{R^2 - x^2} \) is function of the curve of the spherical indenter with the radius R.

Non-linear constitutive model (Fig. 4) used in analysis is:
\[ \sigma = \sigma_y + C_1 \varepsilon_{pl} + \gamma (1 - e^{-C_2 \varepsilon_{pl}}) \]

3. OPTIMIZATION ALGORITHM

An optimization method using a genetic algorithm is utilized for location of the target function minimum. Target function is composed of the measured indentation curve and indentation dependence calculated with a finite element model. The form of the target function proposed for this model:
\[ F(X_1, X_2, ..., X_m) = \sqrt{\prod_{i=1}^{m} (Y_i - Y_i)^2} \]
The genetic algorithms start with randomly chosen parent chromosomes from the search space to create a population. They work with chromosome genotype. The population “evolves” towards the better chromosomes by applying genetic operators modeling the genetic processes occurring in the natural selection, recombination and mutation. Selection compares the chromosomes in the population aiming to choose these, which will take part in the reproduction process. The selection occurs with a given probability on the basis of fitness functions. The fitness function plays a role of the environment to distinguish between good and bad solutions. The recombination is carried out after selection process is finished. It combines, with predefined probability, the features of two selected parent chromosomes forming similar children. After recombination offspring undergoes mutation. Generally, the mutation refers to the creation of a new chromosome from one and only one individual with predefined probability. After three operators are carried the offspring is inserted into the population, replacing the parent chromosomes from which they were derived, producing a new generation. This cycle is performed until the optimization criterion is met (Fig. 5).

Fig. 5. Flow diagram of genetic algorithm

4. EXPERIMENT

For verification of the proposed method a set of steel was selected on which experimental measurements were realized. Selected materials are listed in table 1. The experiment was processed with constant speed of loading. Samples surfaces were polished before the experiment until a mirror gloss was achieved.

Table 1: Specimens’ microstructure characterization

<table>
<thead>
<tr>
<th>Mark</th>
<th>Micro-structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>R7T</td>
<td>Ferrite + pearlite</td>
</tr>
<tr>
<td>34CrMo</td>
<td>Bainite</td>
</tr>
<tr>
<td>CrMoV</td>
<td>Bainite</td>
</tr>
<tr>
<td>11375</td>
<td>Ferrite + pearlite</td>
</tr>
</tbody>
</table>

5. DISCUSSION AND RESULTS

Material model parameters for steel samples are estimated on the basis of the proposed method and experimental test. Results of the analysis are summarized in table 2. Values of yield stress and ultimate tensile stress from uniaxial tensile test are stated in the right part of the table.

Table 2:

<table>
<thead>
<tr>
<th>Mark</th>
<th>€y</th>
<th>C1</th>
<th>y</th>
<th>C2</th>
<th>Re</th>
<th>Rm</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>R7T</td>
<td>532</td>
<td>345</td>
<td>419</td>
<td>27,8</td>
<td>552</td>
<td>949</td>
<td>6.1 %</td>
</tr>
<tr>
<td>34CrMo</td>
<td>1032</td>
<td>116</td>
<td>134</td>
<td>16,2</td>
<td>1053</td>
<td>1107</td>
<td>2 %</td>
</tr>
<tr>
<td>CrMoV</td>
<td>682</td>
<td>151</td>
<td>203</td>
<td>33,2</td>
<td>708</td>
<td>901</td>
<td>3.6 %</td>
</tr>
<tr>
<td>11375</td>
<td>232</td>
<td>453</td>
<td>202</td>
<td>26,2</td>
<td>252</td>
<td>422</td>
<td>8 %</td>
</tr>
</tbody>
</table>

The final processes of a single materials indentation curve are depicted and compared with loading parts processes calculated with numerical model (Fig. 6).
6. CONCLUSION

The proposed mechanical properties estimation method through the use of instrumented indentation test was verified on a set of construction materials. Optimization algorithm for searching of minimum of target function through evaluations techniques was proposed. This system accomplished a reduction of the number of iteration steps in the process of searching for optimal solution. Results reached with the proposed method were compared to a true stress and true strain curve process from uniaxial tensile test. Results of predicted properties are in good correspondence.

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REFERENCES