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SELECTION OF MATERIAL MODEL OF CHOSEN PHOTOCURABLE RESIN FOR APPLICATION IN FINITE ELEMENT ANALYSES

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Abstract
In the paper, a numerical study of a photocurable material sample developed by additive techniques is presented. The main aim was to state which material model is appropriate for such kinds of matter. The Finite Element Method and the LS Dyna software was applied in the investigations. The results of calculations were compared with data coming from own experiment, also described in the paper. It was stated that the best data agreement may be obtained for the so-called MAT_168 model.

Keywords: additive manufacturing, photocurable material, Finite Element Method, constitutive models.

INTRODUCTION

The stereolithography (SLA) is one of the additive manufacturing techniques. The main idea of this method is a printing with the use of a photocurable resin, e.g. epoxy or acrylic one. During the crosslinking process the resin is exposed to a ultraviolet (UV) light of a specific wavelength. This physico-chemical process is known as a photopolymerization (DIZON, ESPERA, CHEN, ADVINCULA, 2018). In practice the SLA is carried out on 3D printers. Such printer working method is presented schematically in Fig. 1. The model for the printing is created in a CAD software (Fig. 1a), transformed to STL format (Fig. 1b), divided into slices (Fig. 1c) and printed. The printer is built of a moving platform (1 in Fig 1d) placed in a tank (2 in Fig 1d) filled with a liquid polymer (3 in Fig 1d). The light from an UV laser (4 in Fig 1d) cures a designed cross-sectional pattern of the sample (5 in Fig 1d) on the surface of the liquid polymer through a mirror (6 in Fig 1d). In the next step the platform moves and the curing cycle repeats. The part is built layer by layer of a designed thickness Δz (Fig. 1e), until the object is fully formed (VAEZI, SEITZ, YANG, 2013).
The SLA printed objects can have very complicated shapes, what can be the basis of using it for developing real constructions elements such as energy absorbers or connectors. This idea is also the purpose of designing such elements using finite element method (FEM).

In FEM, a very important problem is to choose and to verify a proper constitutive model for the analyzed material.

In this paper the possible models found in software libraries were reviewed as well as the approaches to such modelling found in the literature. Finally, the numerical analyses of tensile test of a selected SLA resin using different material models was shown.

Fig. 1. SLA printing scheme: a) CAD model, b) STL model, c) division into slices, d) printer setup (1 – moving platform, 2 – resin tank, 3 – liquid polymer, 4 – UV laser, 5 – printed object, 6 – mirror), e) printed model; Δz – layer thickness

SELECTED RESIN TENSILE TEST

To observe the specific mechanical behavior of the photocurable material, the Tough Resin (produced by Formlabs) was tested in tensile static process. The dog-bone samples were printed (Fig. 2) and post processed. The dimensions of the printed sample were set on the base of the standard titled: Plastics - Determination of tensile properties - Part 1: General principles (ISO 527-1:2012).

The samples were cleaned in isopropanol bath to remove the non-crosslinked resin.
Then the supports were removed mechanically. Finally, the samples were additionally harden in the UV chamber (2.5 hour) to achieve the maximum values of mechanical parameters and heated in 60ºC (2 hours) in accordance to producer’s guidelines. The direction of layering was not considered, because previous research showed that the material is negligibly orthotropic (Miedzińska, Gieleta, Malek, 2020).

The static compression test was carried out on the Zwick Roell Kappa 500 strength setup with the load speed of 10 mm/min.

The experimental results were achieved as the force-displacement charts. They were then recalculated to engineering stress and engineering strain on the base of the following equations:

- engineering stress:
  \[ \sigma_{eng} = \frac{P}{A_0} \]  

- engineering strain:
  \[ \varepsilon_{eng} = \frac{\Delta l}{l_0} \]

where: \( P \) is the value of measured force, \( A_0 \) is the initial cross section of the sample gage length, \( \Delta l \) is the change in the sample length, \( l \) is the initial gage length of the sample.

The test results were shown in Fig. 3 as engineering stress in the function of engineering strain.
The achieved characteristic is specific for thermoplastic polymers (Eisele, 1990), for which after achieving yield strength, the stress value decreases, because of a weakening of polymer chains links. Also it must be marked that there is no clear proportionality region.

**NUMERICAL APPROACH TO POLYMERS MODELLING – REVIEW**

Some approaches to numerical modeling of polymers can be found in literature, as well as in calculation software libraries. In the work described in the paper the LS Dyna computer code was used, so the material constitutive models implemented in this software were reviewed and shown below.

The easiest way to model elasto – plastic material, but without considering the chemical changes in polymer chain structure, is to apply the linear plasticity model (in LS Dyna it is *MAT_PIECEWISE_LINEAR_PLASTICITY - MAT_24 (Hallquist, 2007)). The material description is based on Young’s modulus, Poisson’s ratio, yield stress, hardening modulus, ultimate plastic strain, and time step size for element deletion. Also an arbitrary stress versus strain curve and arbitrary strain rate dependency can be defined. In this model deviatoric stresses are determined due to the yield function as:

$$\frac{1}{2} s_{ij}s_{ij} - \frac{\sigma_y^2}{3} \leq 0$$

The yield stress is calculated as:
\[ \sigma_y = \beta \left( \sigma_0 + f_h(\varepsilon_{eff}^p) \right) \]  \hspace{1cm} (4)

where: \( \beta \) is the strain rate effect parameter, \( f_h(\varepsilon_{eff}^p) \) is the hardening function and \( \varepsilon_{eff}^p \) is the effective plastic strain.

The other model that can be found in LS Dyna is MAT_168 (*MAT_POLYMER), available since version 971 (HALLQUIST, 2007). This model is based on the assessment that the polymer has two resistances to the deformation: an inter – molecular one, related to the relative moment between molecules (A), and the other one evolving anisotropic, which is connected to the molecules chains straightening (B). This model was is based on the study showed in BOYCE, SOCRATE, LLANA (2000). It can be schematically presented as the mechanical setup built of two springs and a damper (Fig. 4). A resistance of the spring A is described on the base of the Neo-Hookean law. On the base of this scheme the deformation gradient tensor is the same for A and B resistance:

\[ \mathbf{F} = \mathbf{F}_A = \mathbf{F}_B \]  \hspace{1cm} (5)

and Cauchy stress tensor is a sum of A and B resistances ones:

\[ \sigma = \sigma_A + \sigma_B \]  \hspace{1cm} (6)

Fig. 4. Schematic illustration of polymers two resistances to deformation: an inter – molecular one related to relative moment between molecules (A) and evolving anisotropic one connected with molecules chains straightening (B)

In LS Dyna also the following material models for polymers are available:
- *MAT_081 (MAT_PLASTICITY_WITH_DAMAGE),
- *MAT_089 (*MAT_PLASTICITY_POLYMER),
- *MAT_101 (*MAT_GEPLASTIC_SRATE_2000A),
- *MAT_112 (*MAT_FINITE_ELASTIC_STRAIN_PLASTICITY),
- *MAT_141 (*MAT_RATE_SENSITIVE_POLYMER).
MAT_081 (HALLQUIST, 2007) is the elasto-visco-plastic material description, where stress–strain curve or strain rate dependency can be defined. Damage is considered before rupture occurs. In this model the constitutive properties for the damaged material are obtained from the undamaged material properties. The amount of damage evolved is represented by the constant, \( \omega \), which varies from 0 (no damage) to 1 (complete rupture). For the uniaxial loading, the nominal stress, \( \sigma_{\text{nominal}} \), in the damaged material is given as:

\[
\sigma_{\text{nominal}} = \frac{P}{A}
\]  

where: \( P \) is the applied load and \( A \) is the surface area.

The true stress is given by:

\[
\sigma_{\text{true}} = \frac{P}{A - A_{\text{loss}}}
\]

where: \( A_{\text{loss}} \) is the void area.

The damage variable is defined as:

\[
\omega = \frac{A_{\text{loss}}}{A}
\]

In this model damage is defined in terms of plastic strain after the failure strain is exceeded:

\[
\omega = \frac{\varepsilon_{\text{eff}}^p - \varepsilon_{\text{failure}}^p}{\varepsilon_{\text{rupture}}^p - \varepsilon_{\text{failure}}^p} \quad \text{if} \quad \varepsilon_{\text{failure}}^p \leq \varepsilon_{\text{eff}}^p \leq \varepsilon_{\text{rupture}}^p
\]  

MAT_089 (HALLQUIST, 2007) describes the elasto-plastic material, for which also stress-strain or strain rate curve can be considered. This model can be applied when the elastic and plastic responses are not clear, as e.g. in metals. Also polymers brittle behavior in high strain rates can be considered. This model is only applicable for 2D elements. MAT_89 is similar to MAT_24 except the following points:

- loadcurve lookup for yield stress is based on the equivalent uniaxial strain, not the plastic strain,
- elastic stiffness is initial equal to Young modulus but will be increased according to the slope of the stress-strain curve,
- the failure strain depends on the strain rate.

The strain used for failure and damage calculation, \( \varepsilon_{\text{pm}} \), is based on an approximation of the greatest value of maximum principal strain encountered during the analysis:

\[
\varepsilon_{\text{pm}} = \max_{i \in \text{N}} (\varepsilon_{H}^i + \varepsilon_{V_M}^i)
\]
where: \( n \) is a current time step index, \( \max_{i \leq n} \) the maximum value attained by the argument during the calculation and:

\[
\varepsilon_H = \frac{\varepsilon_x + \varepsilon_y + \varepsilon_z}{3}
\]

\( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are the cumulative strains in the local \( x, y, \) and \( z \) direction, respectively,

\[
\varepsilon_{VM} = \sqrt{\frac{2}{3} \text{tr}(\varepsilon'^T \varepsilon')}
\]

\( \varepsilon' \) is a deviatoric strain tensor.

MAT_101 (HALLQUIST, 2007) is dedicated for thermoplastics. It was developed by General Electric Company to model commercial materials subjected to high strain rate loading. In this model yield stress is a function of strain rate. This model is described by the constitutive equation:

\[
\dot{\varepsilon}_P = \dot{\varepsilon}_0 \exp(A[\sigma - S(\varepsilon_P)]) \times \exp(-p\alpha A)
\]

where \( \dot{\varepsilon}_0 \) and \( A \) are rate dependent stress parameters, \( S(\varepsilon_P) \) – internal resistance (strain hardening) and \( \alpha \) is a pressure dependence parameter.

MAT_112 is almost similar to MAT_89, but the elastic response of the model uses a finite strain formulation so that large elastic strains can develop before yielding occurs.

Finally, MAT_141 is a model for isotropic ductile polymers modelling with consideration of strain rate effects. The constitutive equation for the model is as follows:

\[
\varepsilon_{ij} = D_0 \exp\left[-\frac{1}{2}\left(\frac{Z_0^2}{3K_2}\right)\right]\left(\frac{s_{ij} - \Omega_{ij}}{\sqrt{K_2}}\right)
\]

where: \( D_0 \) is the maximum inelastic strain rate, \( Z_0 \) is the isotropic initial hardness of the material, \( \Omega_{ij} \) is the internal stress, \( s_{ij} \) is the deviatoric stress component and \( K_2 \) is defined as:

\[
K_2 = \frac{1}{2}(s_{ij} - \Omega_{ij})(s_{ij} - \Omega_{ij})
\]

and represents the second invariant of the overstress tensor. The elastic components of the strain are added to the inelastic strain to obtain the total strain. The internal stress variable rate is defined as:

\[
\dot{\Omega}_{ij} = \frac{2}{3} q \Omega_m \dot{\varepsilon}_{ij} - q \Omega_{ij} \dot{\varepsilon}^l
\]

where: \( q \) is a material constant, \( \Omega_m \) is a material constant that represents the maximum value of the internal stress and \( \dot{\varepsilon}^l \) is the effective inelastic strain.

The interesting approaches to the modelling of the photocurable polymers can be found in the literature. The scientists use the micro-macro modelling as well as the global one. For example
the approach with consideration the micro and macro structure of a printed material using FEM (finite element method) can be found in Rodriguez, Thomas, Renaud (2003). The authors applied the elasticity approach to assess the stiffness of ABS material printed with Fused Deposition Modelling (FDM) additive technique. The asymptotic theory of homogenization was applied to predict unidirectional FD-acrylonitrile butadiene styrene material behavior.

In Ajoku, Hopkinson, Caine (2006) the Nylon printed in SLS (Selective Laser Sintering) technique was modeled using FEM, but the positively validated results were achieved only for the elastic range of the stress. The researched material showed a 7% porosity and voids were placed in the 2D geometric model used for the FE analyses. The authors postulated that the applied geometry is too idealistic to reflect the material behavior in the nonelastic stress rate.

In Zarbakhsh, Irvani, Amin-Akflaghi (2015) the sub-modeling approach and FEM were proposed to analyze the mechanical characteristics of 3D-printed parts, whereas the details of 3D printing patterns were included in sub-model.

FEM is not the only method used in modeling the printed materials behavior. In Sugavaneswaran, Arumaikkannu (2015) the rule of mixture and analytical approach were applied to estimate the elastic properties of the additively manufactured composite parts. The analytical method was validated with the use of the experimental results. The experimental and analytical methods have quite good agreement, hence methodology proposed can be used for estimating the elastic properties of additively manufactured multi material structures.

Another approach was presented in Wu (2018), where the evolution of the mechanical properties of the photopolymer during the photocuring process was investigated using theoretical modeling and experimentation. The chemical reaction kinetics was modeled using the first order reaction differential equations.

NUMERICAL MODELLING OF SLA PRINTED SAMPLE

To study which of the constitutive models can be apply for the mechanical behavior of the SLA printed resin (Tough Resin – see Fig. 3) modelling, three models – MAT_24, MAT_168, MAT_081 – were selected. The other models showed above are not suitable for 3D elements (MAT_089) or are not dedicated for thermoplastics (MAT_112 and MAT_141). MAT_102 can be used only after determining the coefficients with the methods only known by GE Company. The applied numerical model of the dog-bone sample was presented in Fig. 5. The model was built of the solid 8-nodal elements. It must be mentioned that for each material model the influence of mesh density was checked and the presented model meets the convergence criteria.
The material constants, implemented in each model, were selected on the base of the experimental tests results and were shown in Table 1. As it was previously mentioned, the tested material has no proportionality region. The Young modulus was calculated in accordance to ISO 527-1:2012 standard as:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

where: $\sigma_2$ is the value of stress measured for the strain $\varepsilon_2$ of 0.25% and $\sigma_1$ – the stress for the strain $\varepsilon_1$ of 0.05%. The scheme of Young modulus calculation was presented in Fig. 6.

The true stress – true strain curve was used in each model. It was achieved on the base of the experimental results presented in Fig. 3 using the following formulas:

- true stress:
\[ \sigma_{\text{true}} = \sigma_{\text{eng}} \cdot (1 + \varepsilon_{\text{eng}}) \]  

(19)

- true strain:

\[ \varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{eng}}) \]  

(20)

The effective plastic strain was 1.153.

The boundary conditions were assumed as the fixing nodes at one of the sample ends in the x direction (see Fig. 5) and the displacement of the nodes at the other end of the sample.

**RESULTS AND DISCUSSION**

The results of the calculations for the tensile test in comparison to the experimental results were presented in Fig. 7 as the engineering stress – engineering strain curves.

The results were achieved from the FE model as the reaction force in the fixed nodes and the displacement in the loaded nodes and then transformed into engineering stress and strain using Eq. (1) and (2).

The relative error was calculated as the average of difference of the results in each time step from the following formula:

\[ \delta = \frac{\sum_{i=1}^{n} \left( \frac{x_i - x_0}{x_0} \right)}{n} \cdot 100\% \]  

(21)

where: \( x \) – FE simulation result, \( x_0 \) – experimental result, \( n \) – number of timestep. The error for each analysis when comparing it to the experiment was presented in Table 2.

<table>
<thead>
<tr>
<th>Material constants for Tough Resin (MIEDZIŃSKA, MAŁEK, POPLAWSKI, 2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density [kg/m³]</strong></td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td><strong>Young modulus [MPa]</strong></td>
</tr>
<tr>
<td>2100</td>
</tr>
<tr>
<td><strong>Poisson’s ratio</strong></td>
</tr>
<tr>
<td>0.45</td>
</tr>
<tr>
<td><strong>Yield strength [MPa]</strong></td>
</tr>
<tr>
<td>45</td>
</tr>
</tbody>
</table>

Table 2. Errors of numerical analyses in comparison to experiment

<table>
<thead>
<tr>
<th>Applied material model</th>
<th>Error (Eq. 5) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT_24</td>
<td>12.1</td>
</tr>
</tbody>
</table>
SUMMARY

The presented research deals with the material model selection to reflect the tensile behaviour of the selected resin printed with the use of SLA method. The revision of the constitutive models for polymers was presented. The numerical model of the SLA printed sample was analysed using selected material models.

On the basis of achieved results it is visible that MAT_168 gave the best compatibility with the experimental results, so it’s usage for reflecting SLA resin in static loading is the most desired. For MAT_24, which has no algorithms characteristic for polymers behaviour built in, the difference in curve shape is the biggest. Especially, achieving the yield strength is different, as well as Young modulus value. The difference in the elastic range behaviour is also visible for MAT_081 model.

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Literature


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