MULTISCALE MODELING OF SHORT FIBRE REINFORCED COMPOSITES AND IT’S RELATIONSHIP TO MODAL ANALYSIS OF MACHINERY PARTS

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Abstract: Although molding of thermoplastics is very productive method of machinery manufacturing, pure plastics are almost not used in so much quantity. Particle reinforced composites are more popular, because presence of solid inclusions reduces volume of organic matrix and usually improve strength and stiffness. Final properties are strongly influenced by manufacturing process which affects inner material structure. In composites where fibers are continuous in one direction or placed in layers, i.e. the fibers do not end inside the composite and it’s length is close to the dimension of machinery parts, elastic [1] [2] and thermal properties [7] can be predicted quite easily by Halpin-Tsai equations or derived simplified methods [2] with high accuracy. This paper is focused on prediction of density and material stiffness of composites, which are reinforced with very short glass fibers in thermoplastic matrix. In the first part we define the field of problem. Then we present simplified analytical calculus in compare to finite element method. We focus on ABAQUS 2018 and its features, which can be used for solving those problems. Estimation approaches such as representative volume element method and mean field homogenization are also studied. After this presented methods are confronted with selected material datasheet of Ultramid® A3WG6 [9] and Zytel® 70G35HSLRA4 [12] composite material. The effect of fiber randomization on material stiffness is introduced [4]. At the end of thesis we use previously calculated material data for modal analysis of real parts which are made from molded thermoplastic with short glass as well.

Keywords: MODAL ANALYSIS, ELASTIC PROPERTIES, SHORT FIBER, THERMOPLASTIC, COMPOSITE

1. Introduction

In the case of large thin-walled and low-ragged composite components, which are reinforced with long fibers, the volume representation and orientation of the reinforcement are constant. Prior to injection of the binder phase, the reinforcement is generally positioned and fixed in the mold such that during the production process to transfer the matrix was prevented from moving it. As the reinforcement position is known in advance, the assumed properties of actual products usually coincide well with the calculations and correspond to our expectations. The problem of molding short fiber reinforced composites stands on the opposite side of accuracy interval, because the order of the system is much lower than in case of long fiber composites.

In terms of access to the development process, it would be optimal if separate injection simulations were made for each type of material. In our article, we deal with the possibility that only one simulation is performed and only small variations in elastic material parameters would occur. We assume that fiber volume changes in percentage order will not lead to fundamentally different distribution and orientation results, while material parameters may have a more significant effect.

In this work, we have considered the primary objective of verifying the accuracy of material properties prediction in connection with injection simulation, followed by experimental modal analysis, because the problems of linear dynamics and elastic wave propagation are closely related.

2. Injection simulation

The simulation results are sensitive to the quality of the FE mesh and the type of used element. In this case, we consider the analyses contains output mesh of the injection simulation from Moldflow software. Because it is a flow problem where the mesh is stable in the space (it does not deform), but the mass moves inside, it is a description in Lagrange coordinates. The simulation provides information on the distribution, concentration and orientation of the material in the individual elements.

This type of mesh is often not suitable for distortion and stress analysis when individual nodes move and structure deforms, although in case of small strains, the model mesh can give satisfying results. However if there are large deformations or strains in the interval of plasticity, such a model can no longer be used, because the intermediate results will no longer meet the convergence criteria or give not good response to real problems. Therefore, the next step of work usually is to create a model mesh that would meet the least requirements. The flow model must then meet the solvency criteria and the possibility of transmitting some information so that the result is not affected.

3. Multiscale modelling of material properties

Each computational material model of composite material can be divided in few basic parts. The first section at the macroscopic level is usually a body or a machine component, consisting of a discretized network of elements representing a particular region. These are material properties that correspond to the microstructure level scale of the unit characteristic. It is important to mention that each of presented predictive theories reminded bellow works with another type of this elementary cell and therefore the results of the material characteristics differ from one another.

In order to study the effect of fiber randomization on material stiffness, we used previously calculated material data for modal analysis of real parts which are made from molded thermoplastic with short glass as well.
4. Short fiber reinforced composite materials

Parameters that have a key effect on material characteristics are fiber length ($l_f$), fiber diameter ($d_f$), shape and volumetric fraction of the reinforcements ($\phi$). The most important describing parameter is shape factor ($\zeta$) [1]. Physical parameters are given by material characteristics of components (Table 1). Since short fibers produced in a special machine are shortened by cutting or milling of long fibers and the length of each fiber is essentially unique, we must work with it as a statistical variable. For this instance, we consider the significant fiber length 120 $\mu$m ± 19 $\mu$m at 95% probability level. Fiber diameter is considered as constant value which is 10 $\mu$m. The relevant prediction of mechanical properties is therefore a rather complicated process where each of the variables we only predict with a certain degree of accuracy.

In this work we mainly deal with elastic properties of binary composites with polyamide matrix and reinforcement from E-glass. We took the properties of the matrix from the material sheet Ultramid® A3WG6 [8] and confronted with literature [2], glass properties were taken from [2] a [3]. In all the calculations, we consider the matrix as dry or low in moisture. We view both components as homogeneous isotropic materials.

For prediction of the composite material properties [9] [12] three basic methods were used. The traditional analytic method (AM) represents Halpin-Tsai equations (HT). The second was representative volume element method (RVE), which was applied on three basic cells with cylindrical and prolate reinforcement. It shows Fig. 4, while the effect of connected and disconected front boundary of cylinder was studied [2]. The last approach was mean field homogenization (MFH), when various formulations reminded in Table 2 were used and only ellipsoid-prolate inclusion was considered. In case of (HT), the properties were directly calculated by user written script. In case of (RVE) the ABAQUS CAE Micromechanics plugin was used. Parameters from MFH and RVE methods were derived from FE models when elementary tests applied and calculated. It shows Fig. 3. When we think composite as continual phase (MFH), elastic properties can be directly calculated from one element model following formulas (1), (2) and (3). When we consider material as separated entities (RVE) formula (4) should be used.

\[
(1) \quad E_{ij} = \frac{\sigma_{ij}}{e_{ij}} \quad i, j = 1, 2, 3
\]

\[
(2) \quad G_{ij} = \frac{\tau_{ij}}{2\epsilon_{ij}} \quad i, j = 1, 2, 3; i \neq j
\]

\[
(3) \quad \nu_{ij} = -\frac{\epsilon_{ij}}{\epsilon_{ij}} \quad i, j = 1, 2, 3; i \neq j
\]

\[
(4) \quad E_{ij}^C = \frac{\sum_{k=1}^{n}(e_{ik})(e_{jk})(\theta_{ik})}{((\epsilon^C)^2)(\nu^C)}
\]

![Connected front boundary](image1.png)
![Disconnected front boundary](image2.png)
![Connected front boundary](image3.png)

Fig. 4 FE model of material cell with bonded and unbonded front part of fiber boundary

5. Results mapping and FE model creation

When comparison of material prediction methods was finished and successful methods were selected, we created a trial workflow how to prepare FE models of real parts, which shows Fig. 5.

- **Mesh**
  - Mesh structure
    - From injection simulation
    - User created mesh with mapped orientation
  - Elements
    - 2nd o. elements

- **Elasticity**
  - From injection simulation
  - User defined
    - Analytic methods
      - Halpin-Tsai
    - Mean Field Homogenization
      - (Mori-Tanaka, Inversed Mori-Tanaka)

- **Material orientation**
  - From injection simulation
    - Orientation tensor

![Basic experiments applied on MFH and RVE models](image4.png)
First variant deals with possibility that original finite volume (FV) mesh generated by Moldflow is kept and directly used for past analysis (Fig. 6).

Possible permutations of model creation

First variant deals with possibility that original finite volume (FV) mesh generated by Moldflow is kept and directly used for past analysis (Fig. 6).

6.2 Experiment

Experimental modal analysis is the method which allows to obtain mathematical model of the vibration properties and behaviour of the structure by experimental means. The modal parameters are established by measuring and processing of frequency response function \( H(\omega) \), given as

\[
H(\omega) = \frac{X(\omega)}{F(\omega)}
\]

where \( F(\omega) \) is excitation and \( X(\omega) \) is response of the system, both in frequency domain. In our case we tested parts freely suspended in the center on rubber bands with low stiffness. For each part the experiments were done at 11 different positions of actuator while sensor position was fixed. Results were analyzes following literature [13].

7. Results

List of performed simulation variants show Table 3. Results of absolute values of modal frequencies for certain parts show Table 4 and Table 5. Eigen modal shapes show Fig. 8 and Fig. 9.

6. Modal analysis of real parts

6.1 Simulation

Task of this section was to verify the previously studied assumptions for real products, which shows Fig. 7 a), b). Present product, which consists of a two-piece assembly, was made by injection technology of short-fiber reinforced thermoplastic material [12]. The aim was to compare the results of modal analyses with different model mesh settings and engineering elastic constants. In this case, calculations have been performed in ways that were recognized as effective. In total, modal analysis of individual components were performed, then results were compared with the experimentally determined values. Temperature of surroundings was considered 23° C.

In second variant the successful (MFH) Mori-Tanaka was applied on user created mesh, when FE model was simplified in way that 9 elements thru thickness were reduced on 3 and the same distribution of material given by orientation tensor which was mapped on was used.

As third variant we considered the initially calculated distribution of material from Moldflow valid again and just mapped on user created mesh again, but this time material card was generated by using (HT) method.

List of performed analysis show Table 3. Results of absolute values of modal frequencies for certain parts show Table 4 and Table 5. Eigen modal shapes show Fig. 8 and Fig. 9.

<table>
<thead>
<tr>
<th>Material</th>
<th>Experiment</th>
<th>Moldflow</th>
<th>Halpin-Tsai</th>
<th>Mori-Tanaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh</td>
<td>-</td>
<td>Moldflow</td>
<td>User</td>
<td>User</td>
</tr>
<tr>
<td>Ori. tensor</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mapping</td>
<td>-</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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Table 4: Eigen modal frequency, Cover

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Experiment</th>
<th>Moldflow</th>
<th>Halpin-Tsai</th>
<th>Mori-Tanaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st [Hz]</td>
<td>442.4</td>
<td>578.0</td>
<td>470.2</td>
<td>470.3</td>
</tr>
<tr>
<td>2nd [Hz]</td>
<td>492.2</td>
<td>586.7</td>
<td>481.7</td>
<td>482.1</td>
</tr>
<tr>
<td>3rd [Hz]</td>
<td>984.4</td>
<td>1300.0</td>
<td>1069.3</td>
<td>1072.7</td>
</tr>
<tr>
<td>4th [Hz]</td>
<td>( \approx 3^{rd} )</td>
<td>1314.0</td>
<td>1073.4</td>
<td>1076.5</td>
</tr>
</tbody>
</table>

Table 5: Eigen modal shapes, Cover

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Experiment</th>
<th>Moldflow</th>
<th>Halpin-Tsai</th>
<th>Mori-Tanaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st [Hz]</td>
<td>424.8</td>
<td>562.7</td>
<td>492.5</td>
<td>484.9</td>
</tr>
<tr>
<td>2nd [Hz]</td>
<td>508.3</td>
<td>604.9</td>
<td>526.3</td>
<td>521.8</td>
</tr>
<tr>
<td>3rd [Hz]</td>
<td>1044.4</td>
<td>1295.2</td>
<td>1188.0</td>
<td>1144.0</td>
</tr>
<tr>
<td>4th [Hz]</td>
<td>( \approx 3^{rd} )</td>
<td>1323.1</td>
<td>1207.4</td>
<td>1170.2</td>
</tr>
</tbody>
</table>

Fig. 7 Machinery parts, a) Cover, b) Housing

Fig. 8 Eigen modal shapes, Cover

Fig. 9 Eigen modal shapes, Housing
8. Conclusion

Most of the methods did a well of predicting longitudinal modulus. The worst results are provided by MFH Prolate Inversed Mori-Tanaka method and we think material isotropic. Overall result with deviation from -38% for Zytel and 46.8% for Ultramid is unacceptable. Best deviation has been achieved using Prolate Mori-Tanaka. Halpin-Tsai equations reaches the boundary of deviation -5% and -8% for both materials. This can be considered also as sufficient. Deviance of other properties was found lower or same orders but not published.

Although the material settings of initial components were the same, modal frequency determined from original Moldflow model is influenced by largest error. The total average deviation from experimental is 25.2% (housing) and 27.3% (cover). In case of cover part the smallest deviation is obtained from model with user defined material card, which was mapped on user mesh. It is 5.7% in case of (HT) formulation. In instance of housing part the smallest deviation is obtained from model with mean field homogenization where Mori-Tanaka formulation was applied and which property distribution of fibers which is statistical value and low order of the system.

References