Analysis of short fiber reinforced plastics/composites using ABAQUS-Moldflow interface.

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Abstract: Injection molded short fiber reinforced thermoplastics play very vital role in automotive industry due to their low cost, high strength to weight ratio and corrosion resistance. Mechanical properties of Injection molded part are not uniform across the part. The properties of the Injection molded part vary to a great extent depending on the orientation of the fibers. For completely random orientation of the fibers the material behavior is isotropic where as for highly aligned fibers the material behavior is anisotropic. Considering isotropic properties for stiffness evaluation of such parts will tend to give erroneous results. Injection molding simulation can be performed in moldflow to determine the local fiber orientations. From these local fiber orientations local mechanical properties of unidirectional composites can be derived using micromechanics models such as Tangdon weng model. These predicted mechanical properties with unidirectional fibers are subsequently used in determining the mechanical properties with actual fiber orientations (derived from mold filling analysis) using orientation averaging.

Abaqus interface for Moldflow requires identical mesh from Moldflow to be used for Abaqus structural analysis. This usage restricts Analyst while selecting element type, size and quality; reflecting in poor results quality and higher solution time.

This paper presents how the fiber orientations and material properties from fine meshed mold flow model are mapped on to dissimilar abaqus model and how fiber orientations derived from Moldflows mold filling analysis can be used to generate the orthotropic properties required for structural analysis. Two case studies of accelerator pedal and engine head cover are presented.

Keywords: Short fiber reinforced composites, micromechanics, fiber orientation tensor, orientation averaging.

1. Introduction

The automotive industry is a very competitive and fast growing industry with huge emphasis on weight and cost reduction, and plastics play a very vital role in achieving this objective. Initially plastics were used mainly because they offered good mechanical properties combined with excellent appearance and the possibility of self-coloring.

Major benefits of using plastics in automotive parts

- Plastics are low cost compared to steel or aluminum.
- Plastics are durable and strong and are resistant to impact and corrosion
- Plastics are versatile allowing freedom in moulding design and are best suitable for parts with many packaging constraints.
- Plastics are light-weight which leads to energy saving and subsequently lesser emissions. Using 100 kg of plastics in a car can replace between 200 - 300 kg of traditional materials. Over the average lifespan of a vehicle every 100kg of plastics will reduce fuel consumption of the vehicle by 750 liters. It is estimated that every 10% reduction in vehicle weight results in 5% to 7% fuel saving. Thus for every kilogram of vehicle weight reduction, there is the potential to reduce carbon dioxide emissions by 20kg.

- Plastics make the manufacture and assembly of cars easier - single molded components only possible with plastics reduce the need for multiple parts connected with complex fasteners.

Different types of plastics are used in automotive industry. Table 1 shows these plastics in various automotive parts. Reinforced thermosetting resins are finding increasing use among these plastics. Our discussion in this paper is constrained to these fiber reinforced thermosetting plastics.

Component	Main type of plastics	Weight in average car(Kg)
Bumpers	PS,ABS,PC/PBT	10.0
Seating	PUR,PP,PVC,ABS,PA	13.0
Dashboard	PP,ABS,SMA,PPE,PC	7.0
Fuel systems	HDPE,POM,PA,PP,PBT	6.0
Body	PP,PPE,UP	6.0
Under-bonnet components	PA,PP,PBT	9.0
Interior trim	PP,ABS,PET,POM,PVC	20.
Electrical components	PP,PE,PBT,PA,PVC	7.0
Exterior trim	ABS,PAPBT,POM,ASA,PP	4.0
Lighting	PC,PBT,ABS,PMMA,UP	5.0
Upholstery	PVC,PUR,PP,PE	8.0
Liquid reservoirs	PP,PE,PA	1.0

Table 1. Plastics used in typical car.

2. Short fiber reinforced composite

Composites are materials in which a homogeneous “matrix” component is “reinforced” by a stronger and stiffer constituent that is usually fibrous but may have a particulate or other shape.Fibrous filler in a Short Fiber Reinforced Composite increases the tensile modulus of the composite along the direction of the fiber orientation, but hardly changes the properties in the transverse direction. This increase in tensile modulus along the direction of the fiber orientation is attributed to the very high stiffness of the fibers. Refer Table 2 for tensile modulus of various fibers used in composites.

Material	E(GPa)	σ_b(GPa)	ρ(Kg/mm^3)	E/ρ(MJ/Kg)	$\sigma_{b/\rho}$(MJ/Kg)
E-glass	72.4	2.4	2540	28.5	0.95
S-glass	85.5	4.5	2490	34.3	1.8
Aramid	124	3.6	1440	86.0	2.5
Boron	400	3.5	2450	163	1.43
HS graphite	253	4.5	1800	140	2.5
HM graphite	520	2.4	1850	281	1.3

Table 2. Properties of commonly used fibers in composites.

With short fiber reinforcement, the fiber length is on the order of 100 times the fiber diameter which is in microns. Short fiber reinforced thermoplastics tends to be manufactured by mixing the fibers into the molten thermoplastic using injection molding process. The fiber length and random orientation within the matrix make it relatively easy to achieve a good wet-out with this method.

3. Anisotropic behavior of short fiber reinforced composites.

Mold filling process results in non-uniform fiber orientations across the molded part. In addition to different local fiber orientation over the part, fiber orientation also varies in direction of wall thickness (Figure 1). The orientation of the glass fibers mainly results from the complex melt flow during filling of the mould cavity.

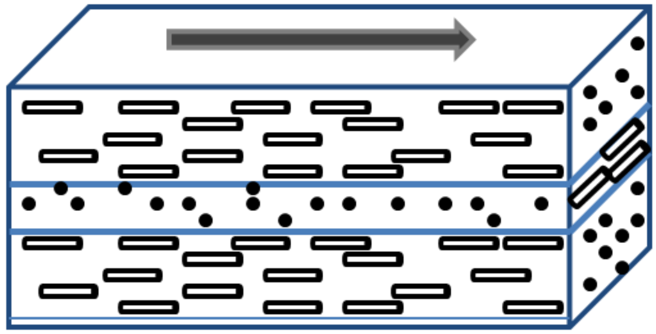


Figure 1. Fiber orientation distribution within the part.

The fibers in the outer layers of a thin walled part are aligned along the fluid flow of the polymer. The fibers of the center layer of the part are aligned rather perpendicular to the flow direction. Since there are major differences in the material properties in the fiber direction and transverse to it , this results in non-uniform elastic constants across the molded part. If there are three orthogonal planes of symmetry in the material- as it can be found for short fiber reinforced thermoplastics - the material behavior is denoted orthotropic (orthogonal anisotropy) with nine elements in the elasticity modulus tensor. The constitutive relation for orthotropic material is shown below.

$$\begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & \frac{-\nu_{31}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & \frac{-\nu_{32}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_{11}} & \frac{-\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ & & & \frac{1}{G_{23}} & 0 & 0 \\ & symmetric & & & \frac{1}{G_{13}} & 0 \\ & & & & & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix}$$

Figure 2. Constitutive equation for orthotropic material.

Determining these nine elements of the elasticity modulus tensor from the matrix, fiber properties and fiber orientation is elaborated below.

4. Determination of orthotropic properties from fiber orientation and matrix, fiber properties.

The properties of a short fiber reinforced composite can vary between isotropic and highly anisotropic. Maximal anisotropy is achieved when all g. fibers are unidirectional aligned. In this case we observe a maximum reinforcement for fibers in the longitudinal direction. If the fibers are randomly oriented throughout the matrix, the composite shows macroscopically isotropic behavior. It was found that the anisotropy of several material properties (elastic stiffness, thermal conductivity, viscosity) can be directly related to the orientation state of the fibers.It is very critical to understand the orientations of the fibers after the injection molding process so as to design the mold and to control the process parameters so that the fibers are oriented in the direction of principal stress. Commercial software packages like Moldflow can be used to simulate the mold filling process and at the same time to determine the local fiber orientation states in a finished injection molded part after cooling. Figure 3 below shows the fiber orientations in a composite pedal after the injection molding process.

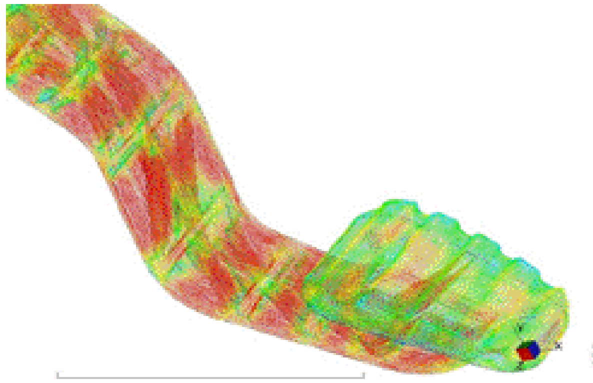


Figure 3. Fiber orientations predicted through Moldflow simulation.

4.1 Micromechanics models

Given the linear material properties of the constituents (Matrix and fibers), the micromechanical models can be used to predict the response of the composite material on the basis of the geometries and properties of the individual phases.Once the fiber orientations are calculated with mold filling simulation, micromechanical models (Tandon-Weng, Halpin-Tsai model) can be used to calculate the thermoelastic properties of a unidirectional short fiber reinforced unit. The equations used in these two models for determining the properties of a unidirectional short fiber reinforced unit can be found in "(. P. Tandon, G. J. Weng, 1984.)."

4.2 Orientation Averaging

Micromechanical models provide the properties of a composite with fully aligned fibers. Properties of composites with any given fiber orientations need to be derived from these properties of a composite with fully aligned fibers. Methods have been developed which can be used to determine the anisotropic properties of materials based on the orientation state of the fibers in a composite. The orientation averaging scheme proposed by Advani and Tucker is one of the methods to predict the overall properties of a known orientation state of fibers in which the elastic constants of a short fiber composite with any given fiber orientation distribution can be obtained by averaging the elastic constants of a composite with fully aligned fibers, weighted by the fiber orientation distribution. The fiber orientation distribution can be derived from the fiber orientation tensor. Detailed discussion about fiber orientation tensor is given below.For a composite with fully aligned fibers the properties along the other two perpendicular directions will be similar (transversely isotropic). Let ϵ_1, ϵ_2, ϵ_2 are the properties along the fiber orientation and perpendicular to the orientation respectively. Then the properties of composite with given fiber orientation distribution after orientation averaging can be written as

$$\langle \boldsymbol{\epsilon}_{\mathbf{ij}} \rangle_{eff} = (\epsilon_1 - \epsilon_2).\ \mathbf{a}_{\mathbf{ij}} + \epsilon_2 \boldsymbol{\delta}_{\mathbf{ij}}$$

Where $\boldsymbol{\delta}_{\mathbf{ij}}$ is the Kronecker Delta operator. $\boldsymbol{\delta}_{\mathbf{ij}} = 1$ when i = j and $\boldsymbol{\delta}_{\mathbf{ij}} = 0$ when $i \neq j$.

$\mathbf{a}_{\mathbf{ij}}$ is the 2nd order fiber orientation tensor.

The linear-elastic and the thermoelastic properties, however, require knowledge of both the 2nd and the 4th order orientation tensor because the elastic properties are characterized by a 4th order tensor. The orientation averaged elastic tensor $\langle \mathbf{C}_{\mathbf{ijkl}} \rangle$, is defined as:

$$\langle \mathbf{C}_{\mathbf{ijkl}} \rangle = \boldsymbol{B}_1 \mathbf{a}_{\mathbf{ijkl}} + \boldsymbol{B}_2(\mathbf{a}_{\mathbf{ij}}\boldsymbol{\delta}_{\mathbf{kl}} + \mathbf{a}_{\mathbf{kl}}\boldsymbol{\delta}_{\mathbf{ij}}) + \boldsymbol{B}_3(\mathbf{a}_{\mathbf{ik}}\boldsymbol{\delta}_{\mathbf{jl}} + \mathbf{a}_{\mathbf{il}}\boldsymbol{\delta}_{\mathbf{jk}} + \mathbf{a}_{\mathbf{jk}}\boldsymbol{\delta}_{\mathbf{il}} + \mathbf{a}_{\mathbf{jl}}\boldsymbol{\delta}_{\mathbf{ik}}) + \boldsymbol{B}_4(\boldsymbol{\delta}_{\mathbf{ij}}\boldsymbol{\delta}_{\mathbf{kl}}) + \boldsymbol{B}_5(\boldsymbol{\delta}_{\mathbf{ik}}\boldsymbol{\delta}_{\mathbf{jl}} + \boldsymbol{\delta}_{\mathbf{il}}\boldsymbol{\delta}_{\mathbf{jk}})$$

Where

B_1-B_5 are five scalar constants related to the elastic constants $<C_{ijkl}>$ of a transversely isotropic orientation state with fully aligned fibers

$$B_1 = C_{11} + C_{22} - 2C_{12} - 4C_{66}\,,\ B_2 = C_{12} - C_{23}\,,\ B_3 = C_{66} + (1/2)\,(C_{23} - C_{22})\,,\ B_4 = C_{23}$$

$$B_5 = (1/2)(C_{22} - C_{23})$$

4.3 Fiber orientation tensor.

The orientation of a fiber is defined by a direction unit vector **p** with components p_1, p_2, p_3 in a cartesian coordinate system (Figure 4). One of the most general but nevertheless most concise descriptions of fiber orientation can be made by using orientation tensors. The orientation state of a set of fibers, for example, can be defined by an infinite series of even order orientation tensors.

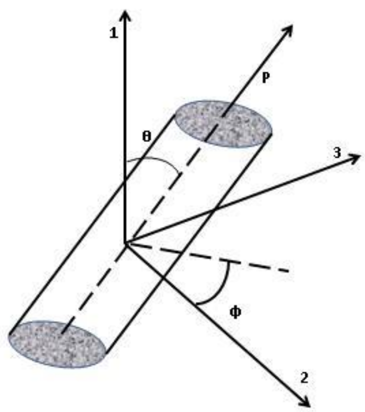


Figure 4. Fiber orientation.

The 2nd order orientation tensor is determined by forming dyadic products with all possible direction unit vectors **p** and integrating the product of the resulting tensors with the distribution function $\psi(\mathbf{p})$ over all possible directions of **p**.

$$a_{ij} = <p_i p_j> = \oint \mathbf{pipj}\ \boldsymbol{\psi}(\mathbf{p})\mathbf{dp} \quad \Rightarrow \quad a_{ij} = \begin{vmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{vmatrix}$$

$\mathbf{a_{ij}}$ is the fiber orientation tensor.

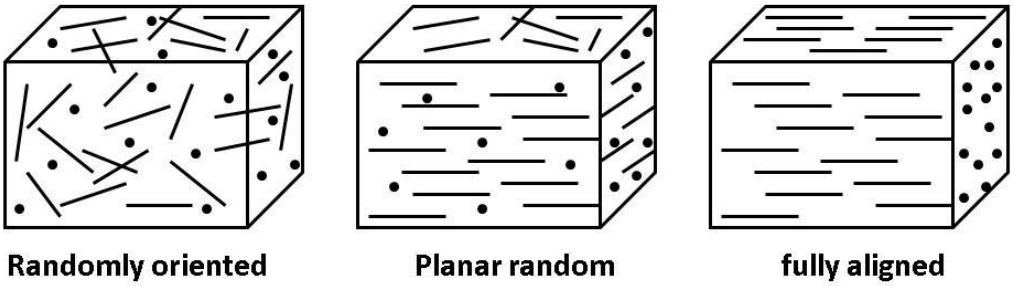
The indices i, j, run from 1 to 3.

1. In the flow direction.
2. Transverse to the flow direction.
3. In the thickness direction.

In a finite element sense it can be expressed as

$$<\mathbf{a_{ij}}> \frac{\sum_n (pi)n(pj)n}{\sum_n Fn} \qquad \mathbf{F_n = (1/cos\theta_n)}$$

The diagonal components of a fiber orientation tensor represent the strength of alignment in the respective directions. The values of diagonal components range between 0 and 1, and the sum of all three diagonal components is 1. The off-diagonal components of a fiber orientation tensor represent the amount that alignments vary from the coordinate axes, and they are zero when coordinate axes coincide with the principal directions of the orientation tensor. Interpretation of the fiber orientation tensor components is shown in Figure 5.



$$a_{ij} = \begin{vmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{vmatrix} \qquad a_{ij} = \begin{vmatrix} 1/2 & 0 & 0 \\ 0 & 1/2 & 0 \\ 0 & 0 & 0 \end{vmatrix} \qquad a_{ij} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}$$

Figure 5. Interpretation of the fiber orientation tensor components.

Eigen vectors and values extracted for this tensor give the principal directions and proportions of fibers along these principal directions respectively(Figure 6). The first principal direction represents the direction along which the most fibers are aligned, and the third principal direction represents the one along which the fewest fiber are aligned. The larger the principle value is, the stronger the alignment in the corresponding principal direction is.

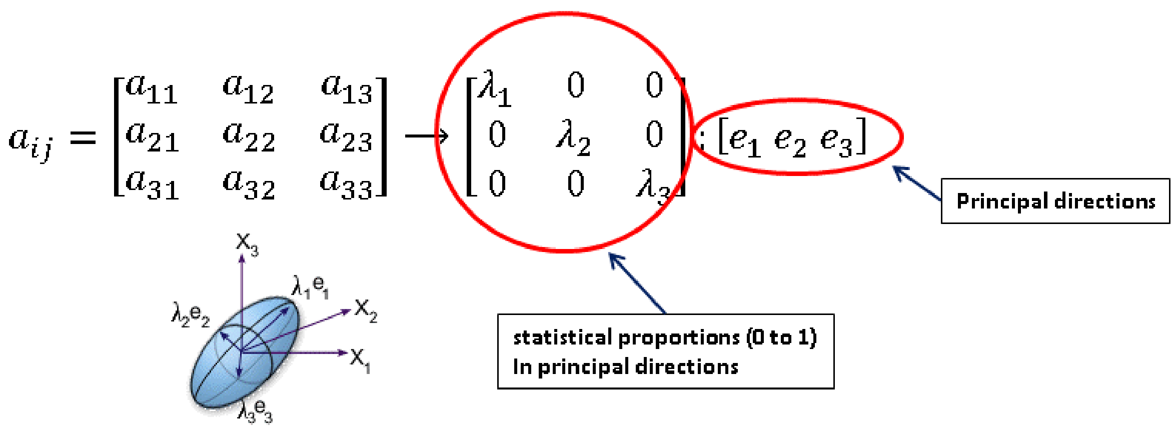


Figure 6. Principal directions and proportions along principal directions.

These principal directions (e_1, e_2,e_3) are used to define the material coordinate system along which the properties are defined. And the statistical proportions (λ_1, λ_2, λ_3) along these principal directions are used in orientation averaging to determine elastic properties of a known orientation state of fibers from that of fully aligned fibers.The whole process of determining orthotropic properties from fiber orientation and matrix, fiber properties is shown in figure 7.

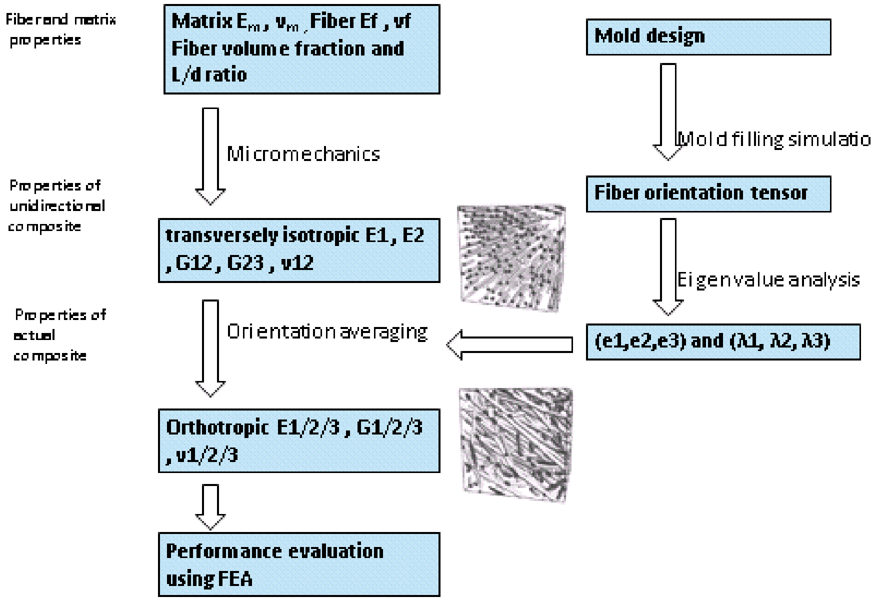


Figure 7. Process of determining orthotropic properties.

5. Abaqus Interface for Moldflow

Moldflow Plastics Insight can be used to model the mold-filling process. The results of a Moldflow simulation include calculations of material properties and residual stresses in the plastic part. Moldflow comes with a VB script (mpi2abq.vbs) which when executed generates all the orthotropic material properties, fiber orientations and initial stress in each element in different xml files. Abaqus Interface for Moldflow translates finite element model information from these xml files into a partial Abaqus input file. Figure 8 summarizes the typical usage of the Abaqus Interface for Moldflow.

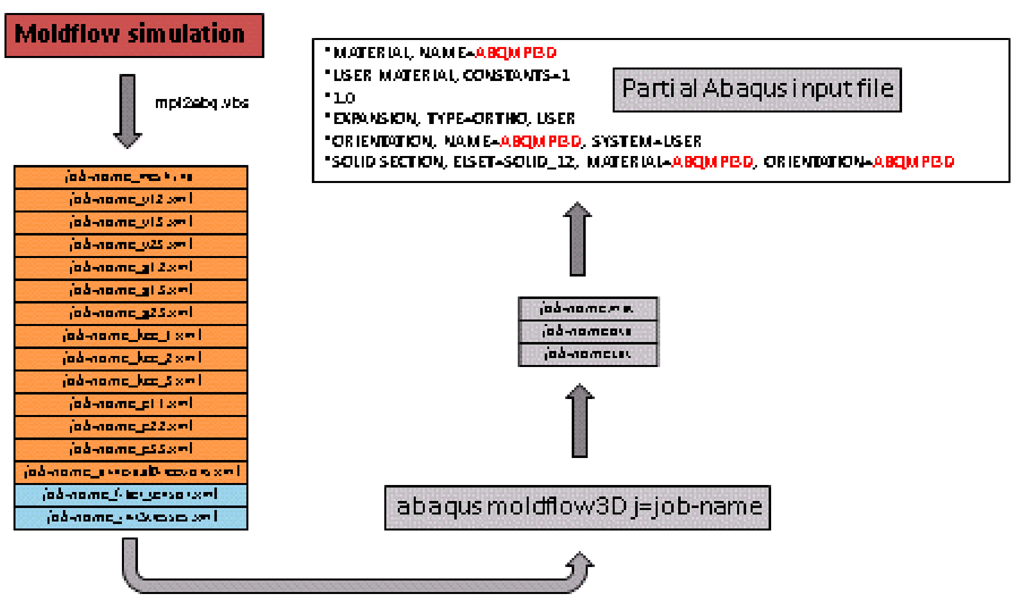


Figure 8. Workflow with Abaqus Interface for Moldflow.

Abaqus Interface for Moldflow requires the same mesh used in Moldflow to be used in the Abaqus analysis also. If there is a requirement to use a different mesh for the Abaqus analysis then AMSA plug-in can be used. This method requires the Abaqus mesh to be avalible before the Moldflow simulation is performed. Figure 9 shows the workflow using AMSA plug-in.

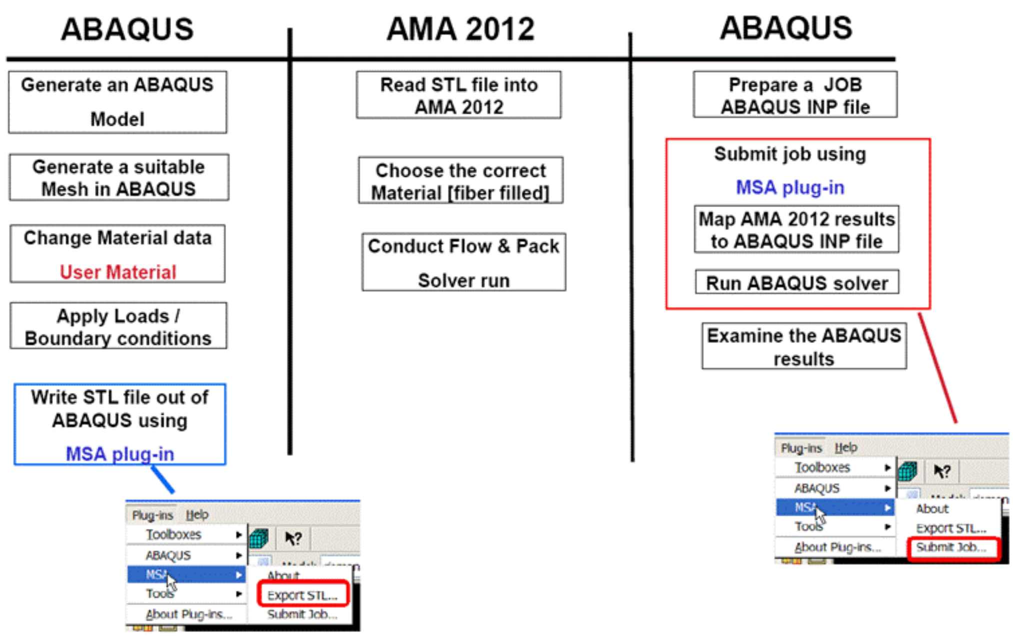


Figure 9. Workflow using AMSA plug-in.

6. Mapping orthotropic properties on to different mesh.

Many a times the analyst has reservations in using the mesh used for Moldflow simulation to be used in structural simulation. Using the same mesh to a great extent restricts the analyst in the selection of type, density and quality of mesh used, which subsequently reflects in the results quality and solution time. Typical cases where a different mesh is required for structural analysis are,

- When an explicit analysis is carried out where the element critical length plays a critical role in smallest time increment.
- Corse mesh requirement to cut down the solution time (Usually very fine mesh is used in a mold filling analysis).
- Node and element numbering requirements of automation tools in post processing.
- Matching mesh requirement between matting parts in assemblies.
- Conflicting element and node numbers when assembles are involve

For case studies show in this paper the following approach was used to map the orthotropic properties on to a different mesh.

1. Fiber tensor information from the xml interface file is written as tensor into a post processor readable file using shell scripts.
2. This fiber tensor was mapped on to a target mesh in suitable post processor.
3. The mapped fiber tensors are again rewritten to an xml file similar to the xml interface file generated by Moldflow using shell scripts.
4. Principal directions and proportions of fibers along these principal directions are calculated by extracting the Eigen vectors and Eigen values respectively in octave and written to the principal directions xml file.
5. Steps 1-3 are repeated elastic modulus and poisson's ratios also treating them as tensor components**. (Theoretically the elastic modulus, poisson's ratios should be calculated using micromechanics and orientation averaging (explained earlier) approach after evaluating principal directions and proportions from the fiber orientation tensor.)
6. Abaqus moldflow translator used to generate the .mpt,.opt,.tpt files to be used for abaqus analysis.

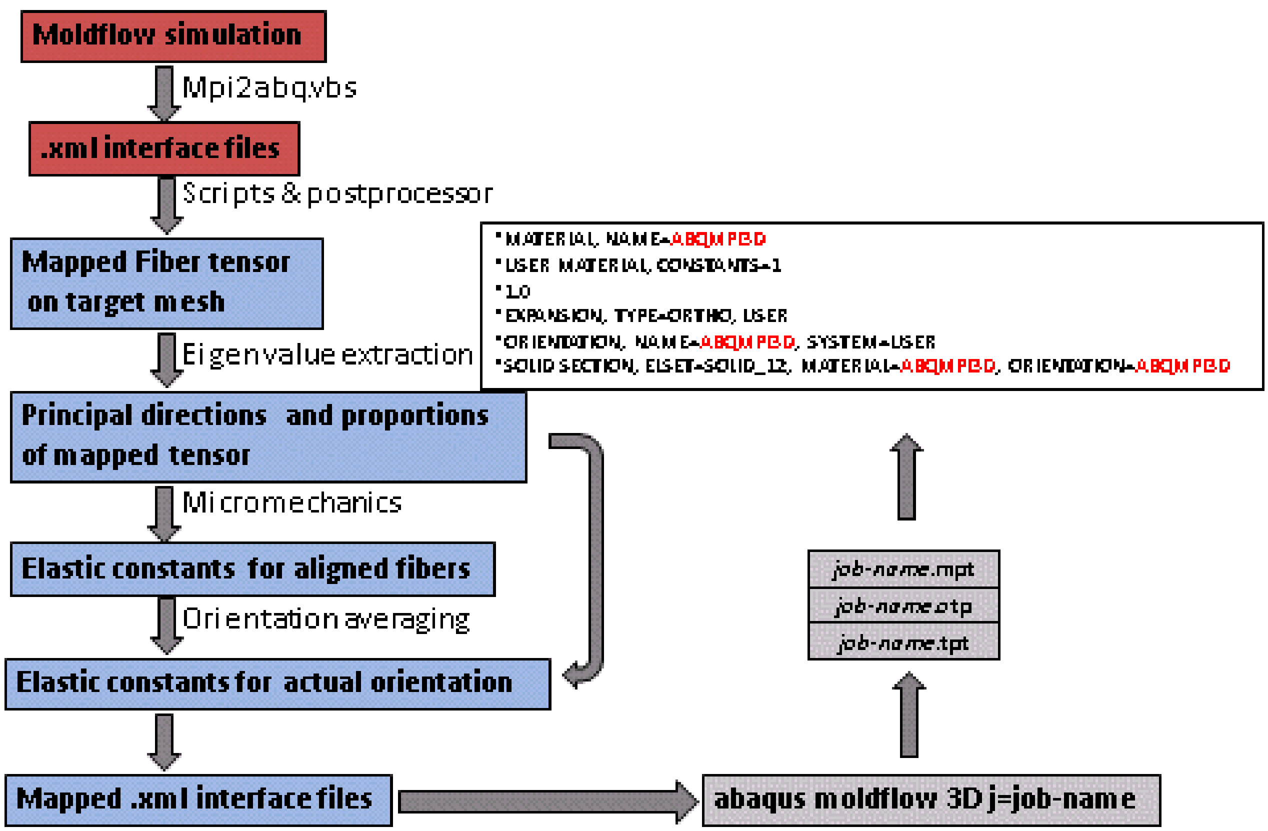


Figure 10. Process of mapping fiber orientations and elastic constants on to target mesh.

7. Case study

Two case studies, 1) accelerator pedal and 2) cylinder head cover are presented here to illustrate process.

7.1 Case study 1: Accelerator pedal.

Objective of the analysis was to predict the accurate deflection and stresses of the accelerator pedal with specified loads and boundary conditions and check if this deflections and stresses are under acceptable limits. Figure 11 shows FE-Model of the pedal with loads and boundary conditions. Figure 12 shows the fiber orientations inside the pedal after mold filling simulation.

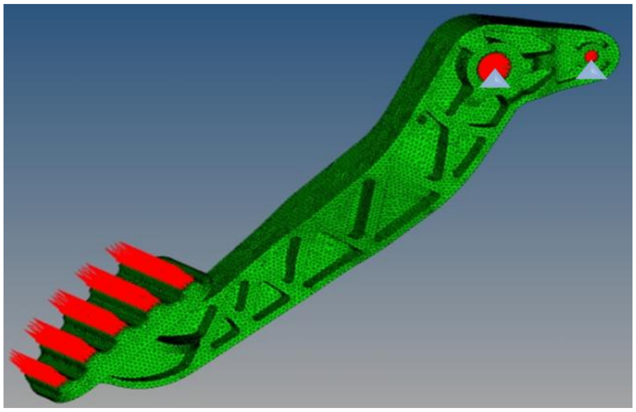


Figure 11. FE-model of pedal with loads and boundary conditions.

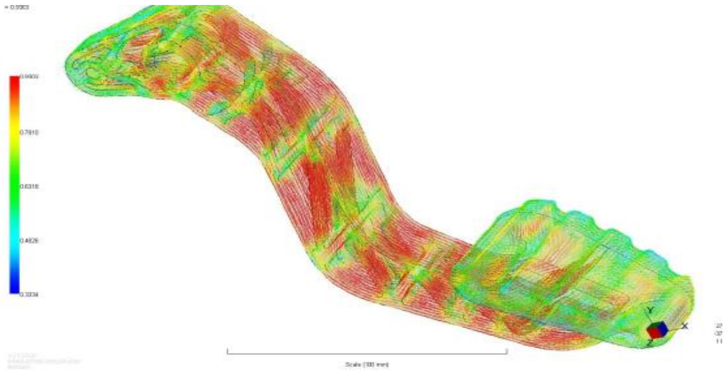


Figure 12. Fiber orientation distribution in the pedal.

Figure 13 shows the deflection results of the pedal considering isotropic properties (Matrix properties) and anisotropic properties due to fiber reinforcements. It is observed that the deflection evaluated considering the anisotropic properties is around half of that while considering isotropic properties, which is quite substantial and justifying the need to use anisotropic properties for short fiber reinforced composites. Accuracy of the results needs to be ascertained after testing of actual physical part which is still under progress. Stress results don't show any visible difference considering orthotropic material properties. Further fatigue analysis has considerable effect due to fiber orientations.

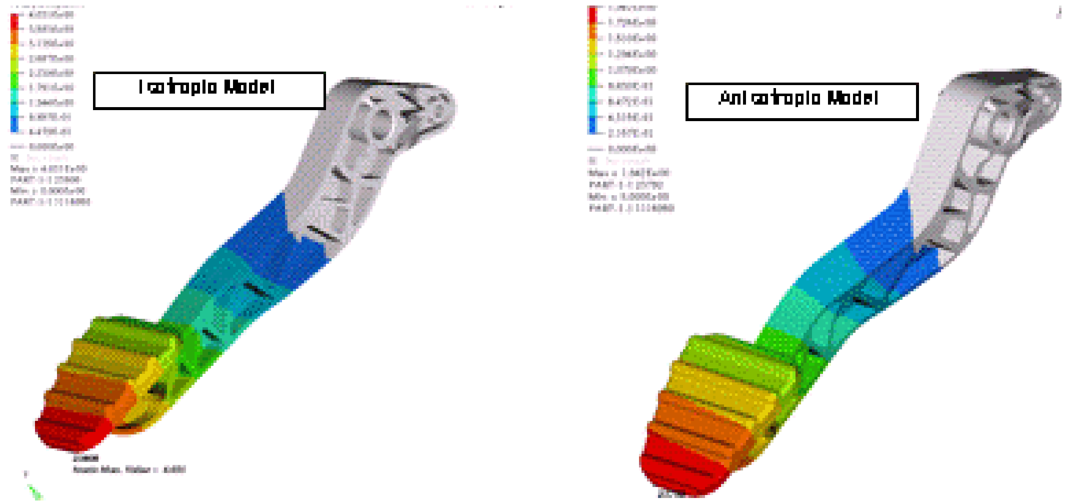


Figure 13. Displacement results considering isotropic and anisotropic properties.

7.2 Case study 2: Cylinder head cover.

One of the primary purposes of the engine cover is to stop the lubricating oil from seeping out. Objective of this analysis is to check the deflections of the cover, and sealing behaviour of the cover gasket assembley under bolt pre loads. Since the oil sealing between the head and the cover depends to a great extent on the stifness of the cover and its intraction with the gasket, it is of outmost importance to capture the head cover stiffness accurately, necessiating the need to use the anisotropic material properties for the cover. Main aim is to restrict the warping of the cover under blot preloads and under prolonged usage (creep).

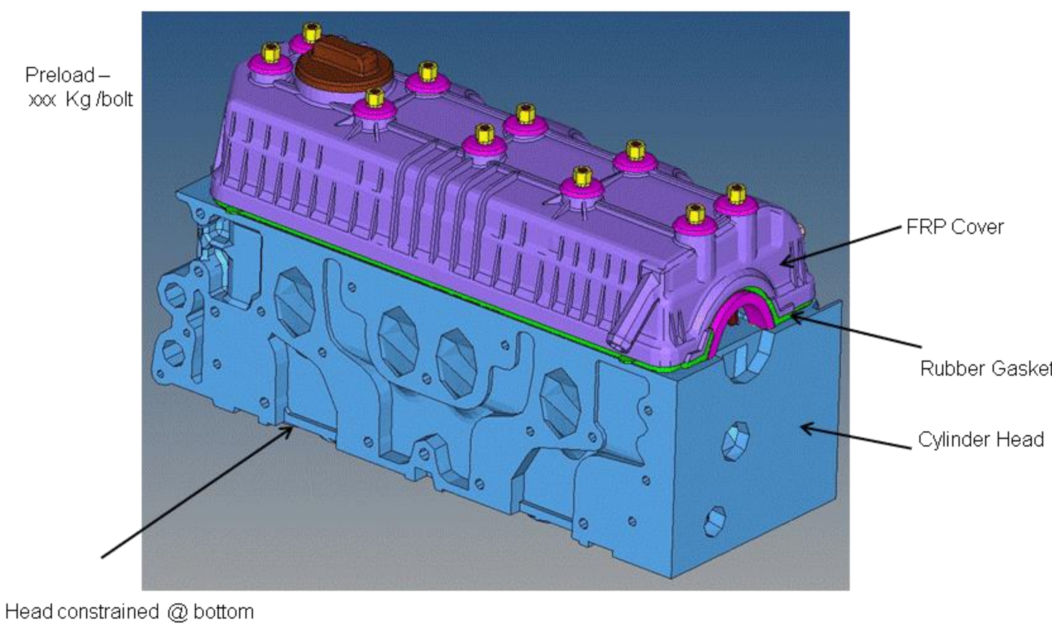


Figure 14. FE Model set-up of FRP cylinder head cover

Initial design was showing excessive deflections than acceptable of the engine cover in lateral direction under preloads. Suitable design modifications were carried to reduce the deflections of the cover and at the same time improve the contact distribution over the gasket.

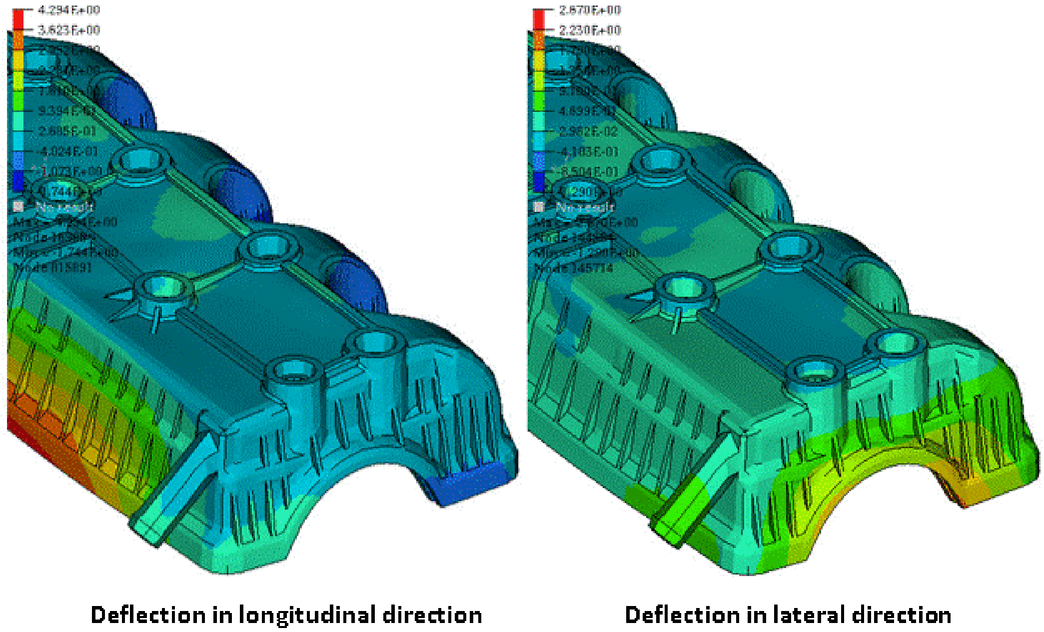


Figure 15. Deflections of cover in modified design

Figure 15 shows defections of modified cover in longitudinal and lateral directions. Figure 16 below shows sealing performance in final design.

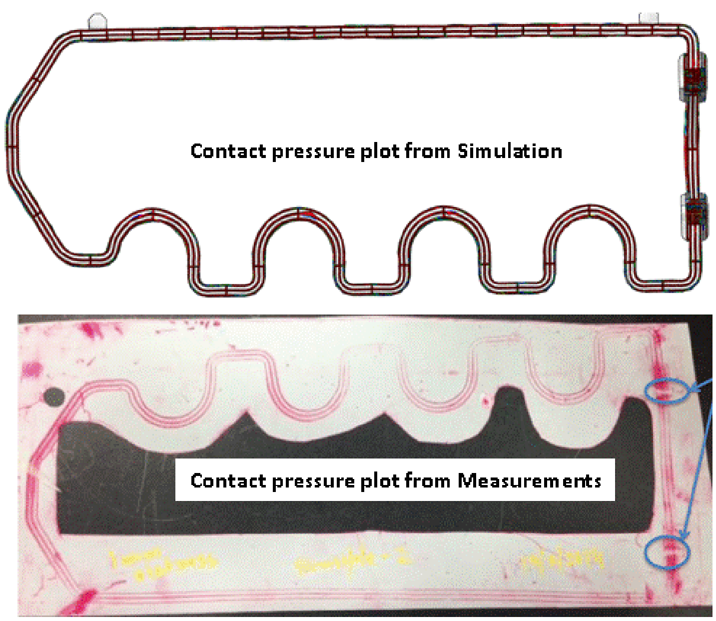


Figure 16. Contact pressure distributions showing proper sealing

After design has required sealing performance it was checked for deflections under operating conditions and prolonged usage. Creep in plastics has shown dominant effect and deformations in longitudinal directions are found to be increased significantly during defined creep cycle.

8. Future scope

All the work shown in this paper is inclined towards more accurate prediction of stiffness of short fiber reinforced composites. We have achieved test correlation in some projects and building on confidence in the process. Our future scope is to build confidence in method through multiple case studies and fine tuning the process. Also it is planned to map the anisotropic properties on to target mesh by using micromechanics and orientation averaging approach instead of map the mapping the elastic constants as tensor components as done in this case study.

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10. References

1. Abaqus Interface for Moldflow User's Manual.
2. Andrei A. Gusev, “Computer-aided design of structural parts from short fiber reinforced composites”.
3. Autodesk Simulation Moldflow Insight reference manual.
4. British Plastics Federation http://www.bpf.co.uk/Innovation/Automotive.aspx.
5. F.P. Gerstle, “Composites,” Encyclopedia of Polymer Science and Engineering, Wiley, New York, 1991.
6. G. P. Tandon, G. J. Weng, *Polym. Comp.* 1984.
7. H. R. LUSTI, “Property Predictions for Short Fiber and Platelet Filled Materials by Finite Element Calculations”.
8. J. D. Eshelby, *Proc. Roy. Soc. A* 1957.
9. Katarína SZETEIOVÁ, “Automotive materials plastics in automotive markets today”.
10. S. G. Advani, C. L. Tucker, J. Rheology 1987