Measurement and FE prediction of glass fibre orientation distributions for injection moulded products of increasing complexity.

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Abstract

The use of injection-moulded glass-fibre reinforced thermoplastics for load-bearing applications is ever increasing. However, the use of reinforced composites poses a problem during the design of the part, because these materials cannot be assumed to possess isotropic mechanical properties. The stiffness and strength of the material are determined by the orientation of the reinforcing fibres, which in turn is dependent on the manner in which the polymer melt fills the mould. This requires that, during the design of a new product, the processing details must be taken into account so the fibre orientation and resulting mechanical behaviour of the part can be confidently predicted.

In this study, components with different levels of complexity were chosen for comparison of the measured fibre orientation and subsequent mechanical properties with those predicted by a commercial injection-moulding software package (Moldflow Rel. 9.5).

The components considered include a simple tensile test component, a ribbed plaque and a prototype automotive clutch pedal. The fibre orientation was measured at chosen locations in the components using an advanced image analysis system developed at the University of Leeds. Where possible mechanical tests were performed on the specimens for comparison with property predictions from both theoretical models and Moldflow stress analysis.

The tensile component has a simple planar structure. The ribbed plate consists of the intersection of two planes and the clutch pedal is made up of a number of intersecting planar surfaces. This gives a sequence of increasing complexity in the components and allows general conclusions about the behaviour of fibre orientation to be made.

Introduction

Recent years have seen a large rise in the number of applications for engineering thermoplastics within the automotive industry. Injection moulded, fibre reinforced parts are replacing structural metallic components because they offer a good strength-to-weight ratio, are durable, and can be produced for a lower total cost.

The majority of engineering composites utilised within the injection moulding industry consist of a polymer matrix containing short (<1mm) reinforcing fibres. Typically, electrical quality glass (E-glass) is used for the fibres although carbon and Kevlar are also used for applications where increased performance is desirable, despite the higher cost. Similarly, the choice of polymer used within the composite is determined by a number of factors such as mechanical properties, cost, heat resistance and the ability to bond well with the reinforcing fibres.

It can be shown that the orientation of the fibres has a major influence upon the properties of the composite as a whole, but the nature of the injection moulding process means that it is very difficult to control the fibre orientation within the part. The fibre orientation is determined by the way the polymer flows through the mould, which is affected by such factors as the rheology of the material, moulding conditions and the geometry of the mould. This poses many problems for an injection moulder because it suggests that *once a part design has been finalised, the manner in which the part is produced has an impact upon the final mechanical properties of the part*. Consequently, the design stage of the part must include processing details which can be used to produce a reliable estimate of the fibre orientation after the part has been manufactured. Otherwise the worst possible orientation state must be assumed, and over-engineering and correspondingly high production costs will result.

Commercial software packages which simulate the injection moulding process and contain fibre prediction algorithms are currently available. However, these are usually based upon finite element (FE)/finite difference (FD) solutions of Hele-Shaw flows, which are approximations assuming the cavity to be both thin and flat and only consider in-plane flows. This is combined with a fibre prediction model which includes other approximations therefore care must be taken to assess the accuracy of the result. The software has the potential to be an extremely useful tool, but like many FE packages it requires a skilled user who understands where the solution may lose accuracy and the effect this may have upon the final output.

This paper presents work performed on four components of varying complexity which compares both measured fibre orientation distribution with that predicted by the software and also the results of mechanical testing with corresponding strains predicted using the MFStress component of the software.

The first part is a simple tensile test specimen, which has a geometry which can be accurately modelled using a two dimensional mesh within the simulation software. The second and third components are both ribbed plaques with very similar dimensions, but containing ribs mounted parallel with and perpendicular to the flow direction. The final component is an actual commercial prototype clutch pedal which contains a high level of complexity. These components were chosen because they offer a range of complexity with which to test the accuracy of the software.

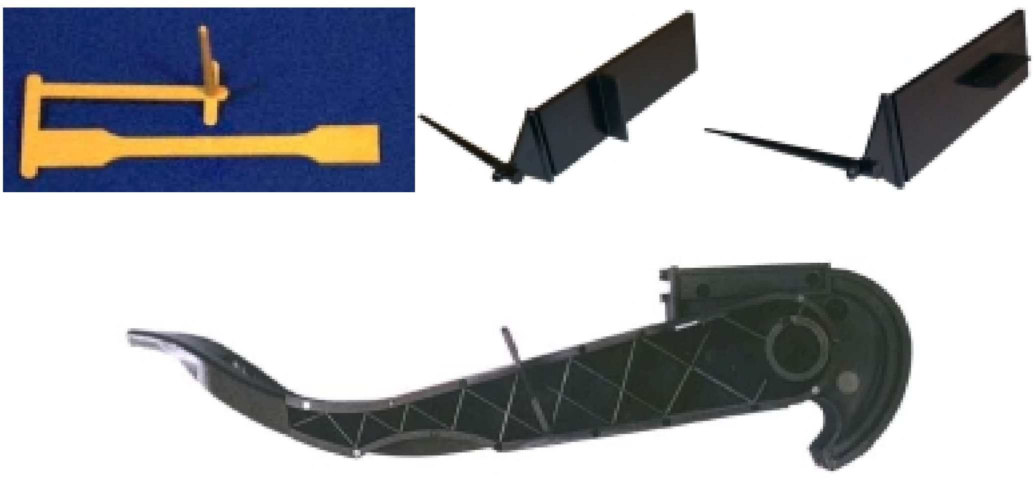


Figure 1 The four components used in this study.

Experimental

Moulding Details

Both the tensile test bar and the two ribbed plaque geometries were moulded using the facilities at the University of Bradford. The clutch pedal was moulded at Birkbys Plastics Ltd due to the dimensions of the mould which required a larger moulding machine than those available at Bradford.
Both the tensile test bar and plaques were moulded using a cassette tool system. The cassette used to mould the plaques is a modular system which contains a number of separate components as shown in Figures 2 and 3. The cassette holds an insert which contains the cavity and a replaceable runner system which allows the use of a number of different gating configurations. Two 1/4 inch cooling channels are bored through the tool to ensure a constant mould temperature during moulding runs and 4 ejector pins to assist removal of the sample.
The advantage of a system such as this is that a number of similar cavities can be manufactured, without having to engineer a new cooling, ejection or gating system, thus radically reducing the time taken to produce a new component.

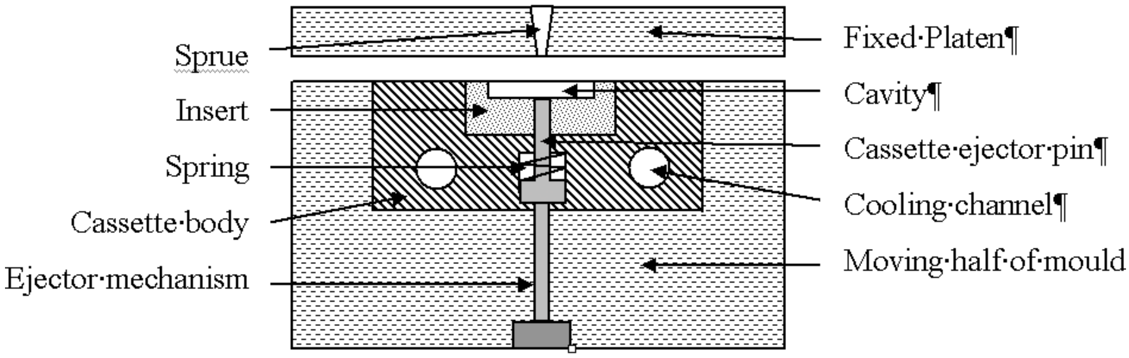


Figure 2 Schematic of the ribbed plaque mould.

Figure 3 Photograph of the cassette tool arrangement showing the main cassette with cooling channels and ejector pins, the cavity insert and the replacable gating insert..

The test bar was moulded using a Amoco Amodel polyphthalamide containing 33% Glass fibre reinforcement. The plaques and clutch pedal were moulded using a Rhodia C218 (Nylon 6) resin with 40% GF reinforcement. Machine settings for all the components can be seen in Appendix [1].
The moulding runs for all the components were monitored using a Polymer Insights Intelligent Monitoring Module, which ensured that any parts which were made during a cycle which produced an unusual Pressure/Time trace could be highlighted and set aside if necessary. A series of short shots were also produced for each component which allowed the accuracy of the filling geometry predicted by the software to be assessed.

Orientation Measurement

The fibre orientation within the components was measured using a reflective microscopy-based system located at the University of Leeds. The system is described in detail elsewhere and only a brief description will be given here.. The image analysis system uses a section cut from an area of interest using a fine saw. The sample is polished and then scanned using a PC-controlled microscope. The system allows samples containing tens of thousands of fibres to be analysed and characterised within hours.

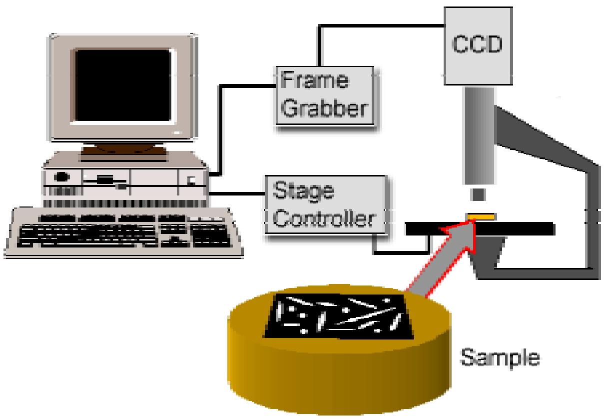


Figure 4 The FOD analysis equipment

The orientation of each fibre is characterised using the two angles θ and ϕ.

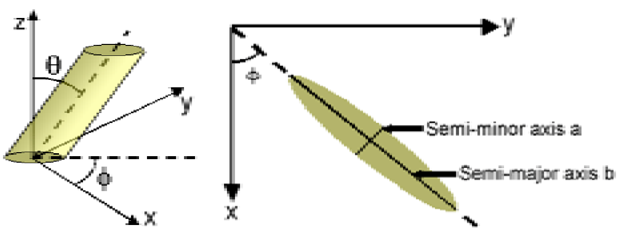


Figure 5 Description of angles θ and ϕ.

The data from each fibre can be combined to produce an orientation tensor which has 6 independent components. In the results discussion four of these will be presented which are the a_{xx}, a_{yy}, a_{zz} and a_{xy} components, which describe the proportion of orientation in the x y and z directions and the angle of the fibres in the x-y plane respectively.

A common fibre orientation distribution found in injection moulded parts is what is known as the skin-shell-core distribution. This can be explained as follows.

The skin region consists of material which flows from the flow front directly onto the mould wall, causing it to freeze almost instantaneously without experiencing any shear-led orientation effects. Fibre orientation within this layer therefore depends entirely upon the orientation state at the polymer flow front.

The shell region is found in the region of high shear in a cavity accounting for the majority of material between the mould wall and central plane of the section. Shear-led orientation dominates in this region and a correspondingly high level of orientation in the flow direction is produced.

The core region is the region in the vicinity of the central plane of the sample which experiences minimal shear, and contains a correspondingly lower level of orientation in the flow direction.

Mechanical test information

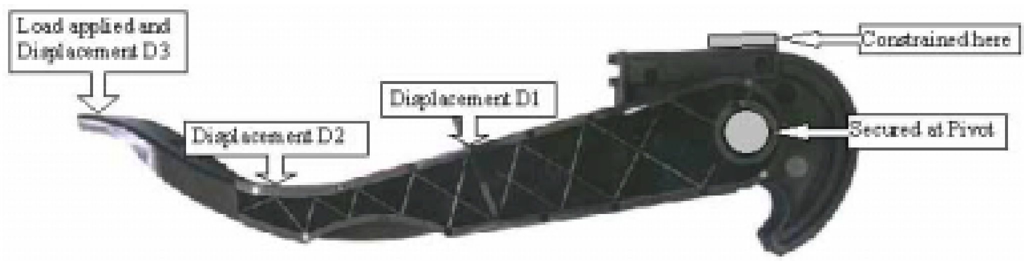


Figure 6 Pedal test setup

The tensile test bars and plaques were tested using a simple pull test using an Instron testing machine. The clutch pedal was tested by constraining it in the pivot region and then using the testing machine to apply a force to the footplate as shown in Figure 6. The tests were performed on three samples of each geometry and then the mean values were taken.

Results.

Flow Prediction

The Moldflow software accurately predicted the flow front through each of the components. Even the flow through complex structure of the clutch pedal was accurately modelled, as can be seen in Figure 7.

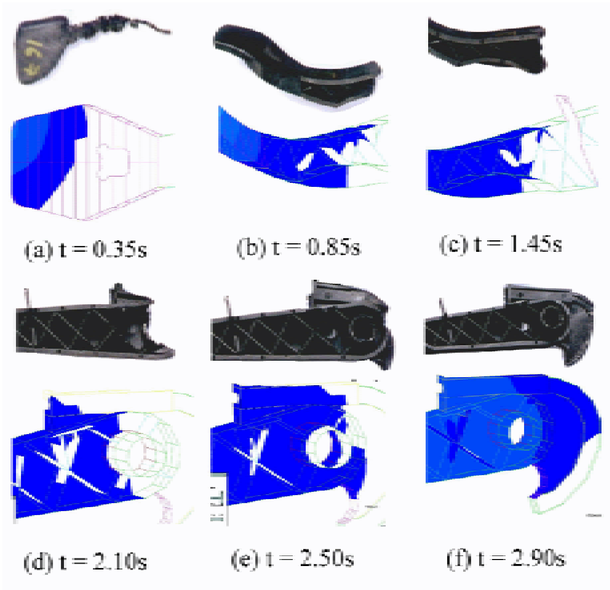


Figure 7 Comparison of short shots with Moldflow filling simulation.

Fibre orientation

The orientation was measured in the centre of the main gauge section of the tensile test bar. A scan was performed at one quarter depth through the sample and compared with the Moldflow result. The Moldflow data suggested a high degree of alignment in the flow direction. The experimental data also indicated high orientation in this direction, but also a random core region in the centre of the sample, which the software failed to predict.

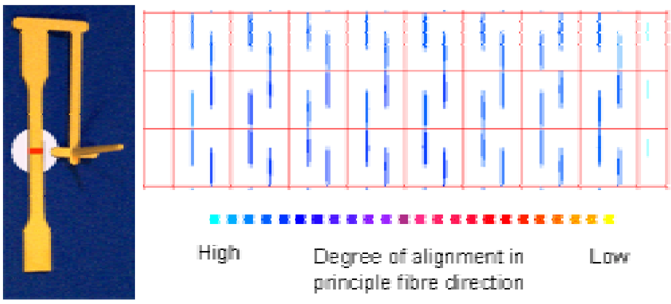


Figure 8 Moldflow fibre orientation results

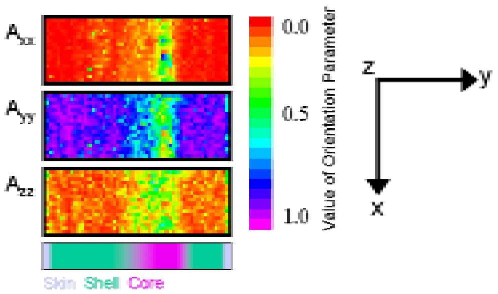


Figure 9 Measured fibre orientation.

The measured fibre orientation data taken from the line of symmetry at the rib intersection of the transverse ribbed plaque can be seen in Figure 10.

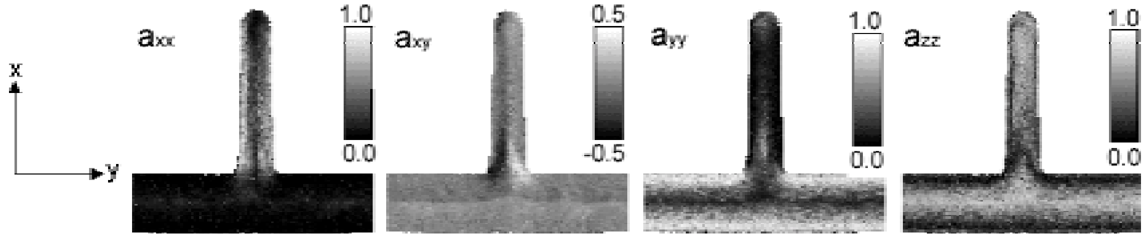


Figure 10 Measured fibre orientation data for transverse ribbed plaque.

A point was chosen 10mm upstream of the rib and the variation in orientation through the thickness was plotted against the MF prediction.

Figure 11 Orientation Parallel to flow direction in 4mm plaque.

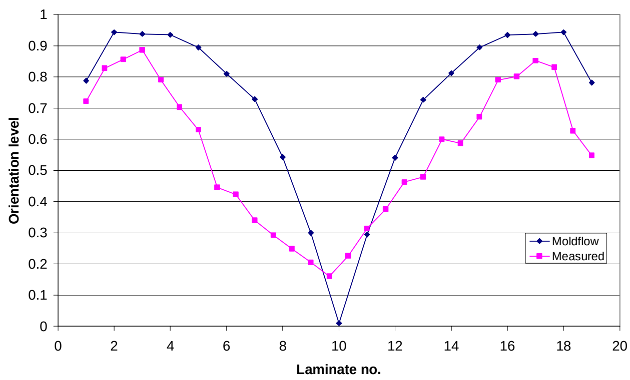


Figure 12 Orientation perpendicular to flow direction in 4mm plaque

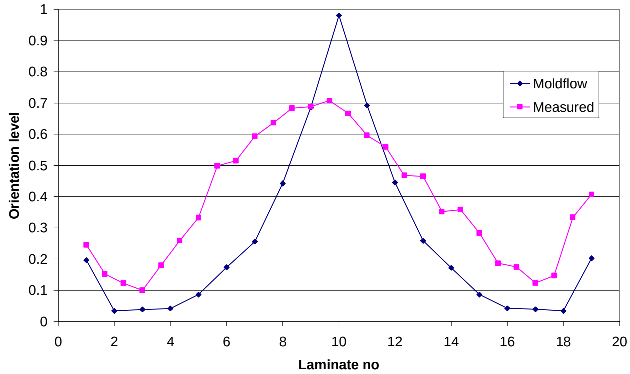
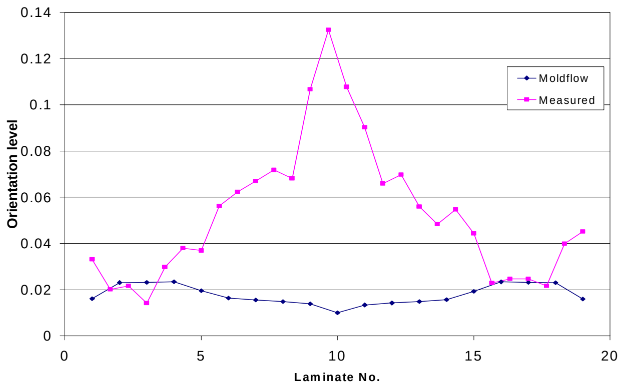


Figure 13 Out of plane orientation through thickness of 4mm plaque



These results show that the general distribution of fibre orientation predicted by Moldflow follows the measured data well. The out-of-plane orientation is under-predicted, but both MF and experimental values are low enough that it is doubtful that the discrepancy will have a noticable impact upon the mechanical property calculation for the part.

The fibre orientation within the longitudinally ribbed plaque was measured at a point halfway along the rib, perpendicular to the flow direction. The data is shown in Figure 14.

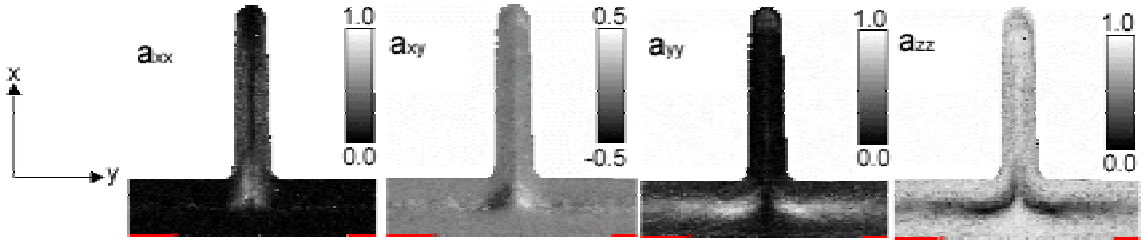


Figure 14 Measured fibre orientation data for the logitudinal ribbed plaque.

Once again the core region can clearly be seen in the plaque, but there is no evidence of a similar region in the rib. The rib contains a high level of orientation parallel with the flow direction. The Moldflow laminar data for the rib is displayed in Figure<<>>

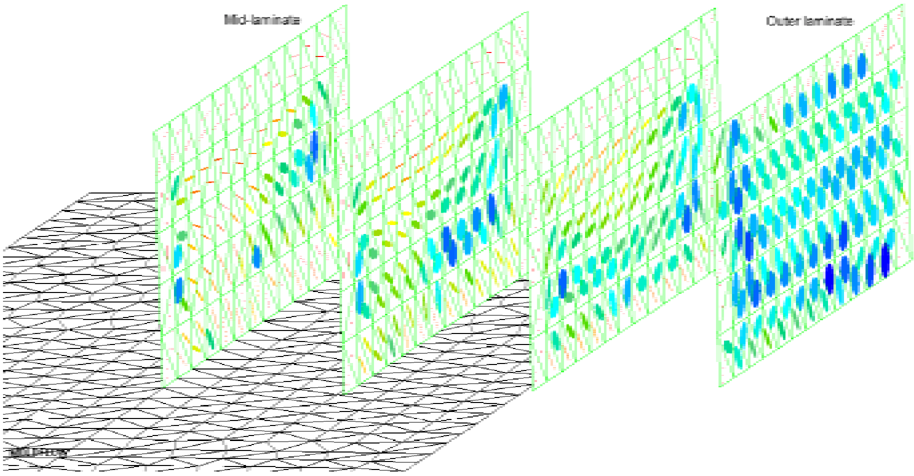


Figure 15 Exploded view of four laminates from midplane to cavity wall. The software predicts high orientation at the central laminate becoming more random towards the wall.

The Moldflow data indicates a medium to high level of orientation in the rib which reflects the measured values well.

The section of the clutch pedal taken for the analysis is illustrated in Figure 2. The sample is 22mm x 20mm x 4.3mm and was chosen for the following reasons:-
1) The section is thicker than average for an injection moulded part, at the limit of accuracy of the generalised Hele Shaw approximations [10], which are adopted in commercial software such as Moldflow, in approximating flow sections as thin and flat.
2) The section contains an intersection with two reinforcing ribs. Some flow of polymer into and out of the plane of the section in this area could therefore be expected. Although it is known that the Hele-Shaw based commercial simulation software does not attempt to model this type of flow accurately, it is of interest to observe how the results from a 2D simulation compare with measured orientation distributions.
3) The section was flat and had a constant thickness. Grinding down the sample allowed a direct comparison of measured data with the predictions produced using Moldflow for various planes (laminates, see Section 2.3) through the section.
A further method of comparing experimental and predicted FODs is shown in Figures 8-12 which display the magnitudes of both the predicted and measured $a_{xx,}$ a_{yy} and a_{zz} tensor components over the area of each laminate, using a colour scale, here converted to grey scale. The experimental results were of a much higher resolution than the elemental values produced by Moldflow (5600 values as opposed to the 220 values gained using the refined Moldflow mesh). To compare results we therefore use a plot over the area of each scan, using grey-scale values corresponding with the degree of orientation mapped onto the refined Moldflow mesh.

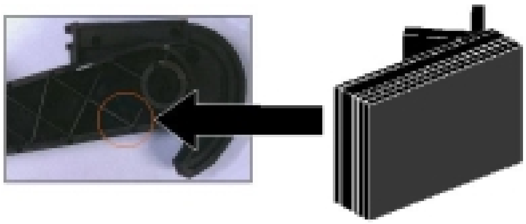


Figure 16 Location of sample cut from the clutch pedal. Orientation measurements were taken for 5 laminates through the sample.

Figure 8 displays orientation data for laminate 1, located at the mould/wall interface, which contains material which formed the skin layer during mould filling. The polishing process removed some of the skin layer material over the surface of this laminate, but the experimental values shown in Table 2 and Figure 13 indicate the presence of the remaining skin layer with a lower level of orientation in the flow direction than the other laminates through the section. The skin layer produced along the free edge at the top of the section can clearly be seen as a sizable out of plane orientation. (Figure 8c).

The software predicted high orientation values in the flow direction along the top edge of the section. This is due to the inclusion of an ‘edge effect’ into the code, which corrects the inability of the Hele-Shaw model to model ‘no-slip’ boundary conditions at the wall and also prevents the rotation of fibres in this region. Consequently, the fibre orientation is constrained to a highly aligned state, parallel to the direction of flow, within the elements along this edge.

Both data sets for laminate 2 (Figure 9) show a high orientation parallel to the flow direction, caused by the high gap-wise shear in this laminate, which lies in the shell region of the section. The edge effect is apparent once more, but it can be seen that the use of a refined mesh improves the result, mainly by reducing the size of the free edge elements containing artificially high orientation values. It is therefore desirable to create elements along free edges which are as small as possible, in order to avoid overestimation of orientation in the direction of flow whilst still gaining the benefits of the edge effect.

Both data sets produced for the third laminate (Figure 10) show a lower degree of orientation than laminate two, which is due to a lower shear rate in the gap-wise direction occurring in this region during moulding. The edge effect produces an over-estimation of orientation across the laminate as a whole, but the results across the lower section of the laminate concur reasonably well.

Laminate 4 (Figure 11) is the mid-plane of the section, which is where the core region of the fibre orientation is expected to occur. This laminate contains minimal gap-wise shear and a correspondingly low degree of orientation in the flow direction can be seen in both sets of data. The predicted and experimental results do not concur because the experimental data indicates a predominant orientation in the flow direction whereas the software simulation suggests an orientation perpendicular to the direction of flow. The experimental data suggests that the core region is not continuous in the central region, as shown in Figure 13, and the influence of the core on the overall level of orientation is low. It is also noted that our experimental results suggest that the fibre orientation distribution is approximately symmetric perpendicular to the flow direction.

Zero gap-wise shear in the Moldflow mid-laminate results in minimal flow induced alignment and the orientation state is convected down the flow. The predicted orientation state is the result of a divergent

flow in another region of the pedal which was transported into the section of interest, as the mould filled. This result underlines the importance of history of flow in fibre filled polymer moulding.

The Moldflow simulation results for laminate 5 (Figure 12) were very similar to the results for laminate 2. These laminates are equidistant from the mid-plane of the section and will contain an equal amount of gap-wise shear, resulting in similar orientation distributions. As noted previously, the experimental data for the laminate displayed lower levels of orientation than that measured within laminate 2, which was due to the flow of material into the adjoining ribs causing a increase in both out-of-plane and *x* directions. The software is unable to model an out of plane flow, and hence this result could not be calculated.

Mechanical testing

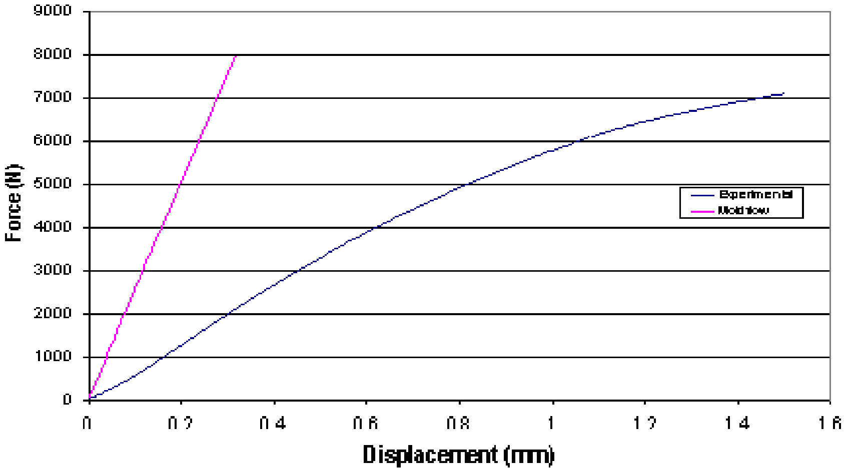
Modulii were calculated in three different ways for the tensile bar; from the extensometer tests, from the MFStress analysis and using the Tandon Weng composite model with the measured orientation data. These three results are shown in Table 1

Measurement	**Tensile Modulus** $\mathbf{E_{yy}}$ **/ GPa**	**Poisson's Ratio** ν_{xy}
Extensometer Measurement	12.7 ±0.5	0.39 ± 0.07
Tandon-Weng / Ward Models	11.83	0.321
Moldflow MF-Stress simulation	11.92	N/A

All three values for the modulus of the bar agree closely.

The force/displacement curves for the transverse ribbed plaque are shown in Figure . It clearly shows that the software overestimates the modulus of the composite in the strain direction. The same result appears for the longitudinal plaque - the modulus appears to be overestimated by a factor of four. There are a number of possible explanations for this result. One reason for the inaccuracy in the longitudinal ribbed plaque result is that the cross section of the part as moulded in Moldflow is larger than the actual cross section of the part. This is because it is impossible to model the geometry fully using two dimensional planes as illustrated in Figure . The discrepancy in this case is 2.5% which. Another explanation for the overestimation of the modulus may be down to the material itself. Nylon 6 is notoriously hydroscopic and must be dried well before processing. However, once moulded, the parts will continue to absorb moisture causing a reduction in modulus and an increase in ductility. All three Nylon 6 components were left in a standard atmosphere at room temperature for over three months to allow them to reach an equilibrium, but if the mechanical data in the Moldflow database was gained under different conditions, then different modulus values may result. One final explanation for the mechanical test results may be whether the two dimensional mesh is suitable for solid deformation anaylsis. A more accurate result could probably be gained by importing the modulus data for each element

Figure 17 Force vs Displacement for test on transverse ribbed plaque.



1)

Figure 18 Force vs Displacement for test on longitudinal ribbed plaque.

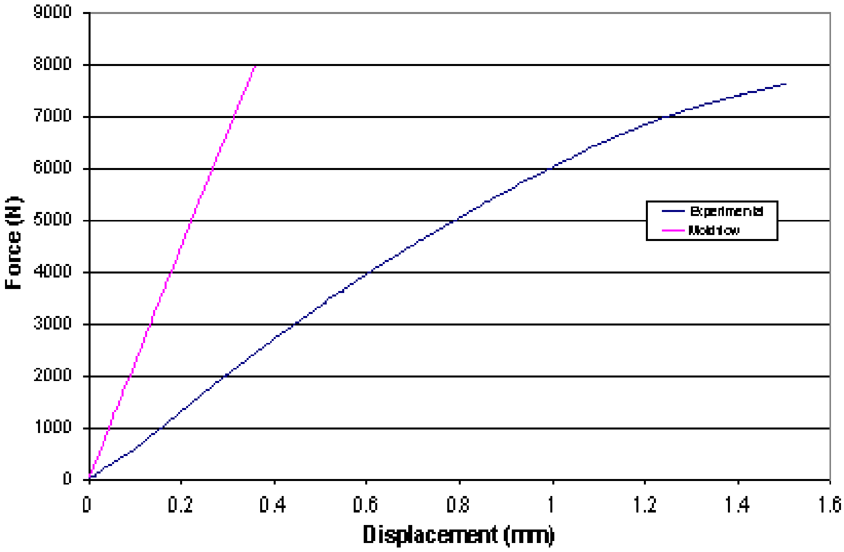


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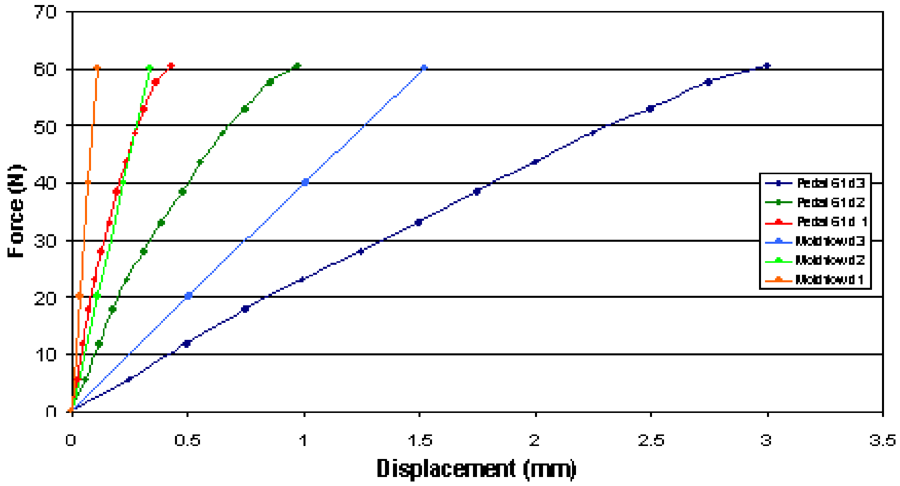
Figure 19 Force vs Displacement for clutch pedal test.



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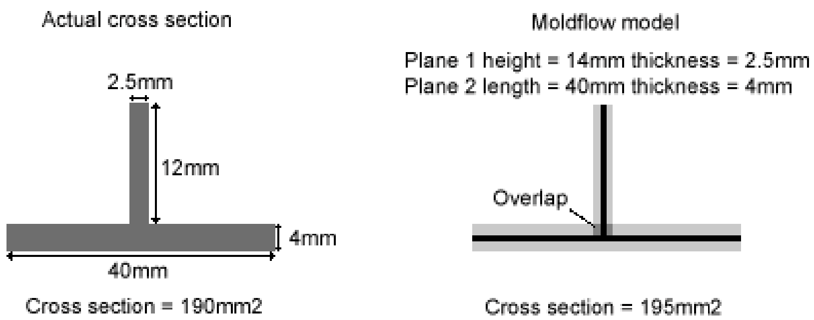
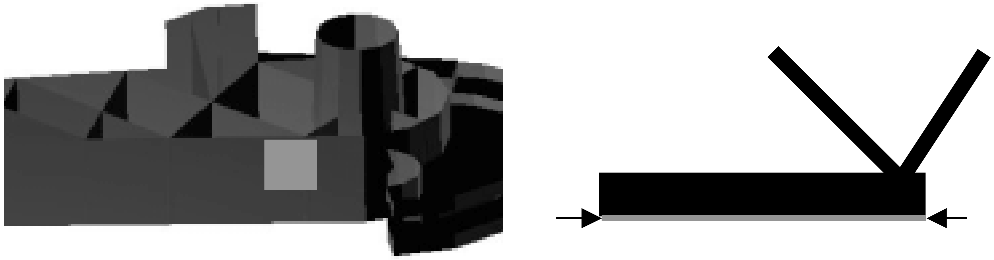


Figure 20 Illustration of inaccuracies present using the 2.5D modelling method required by Hele-Shaw based melt flow simulations.

Concluding Comments



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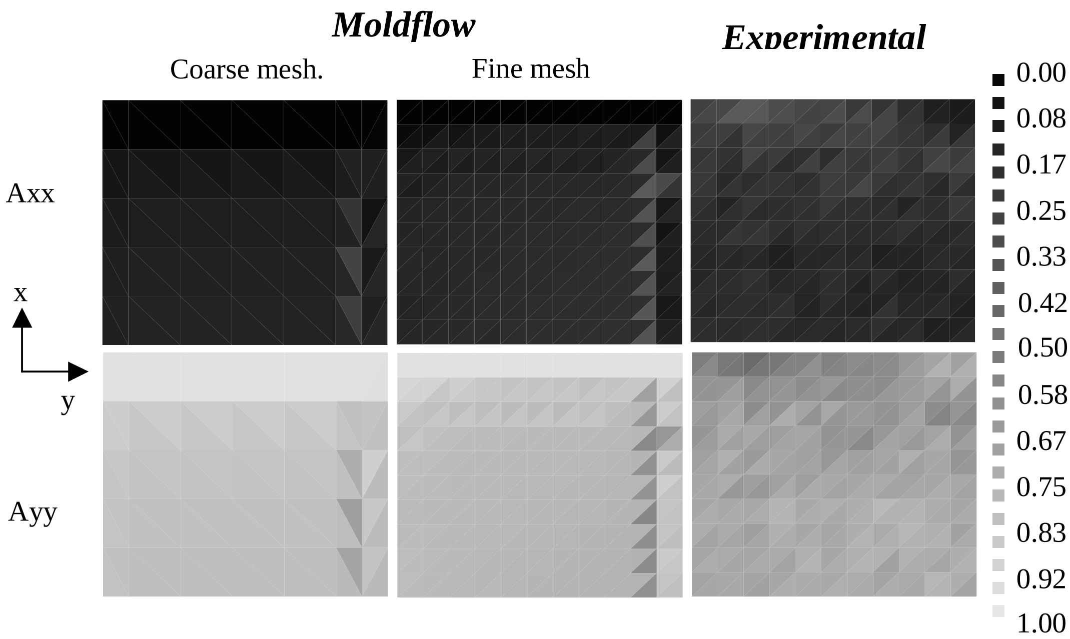

Moldflow
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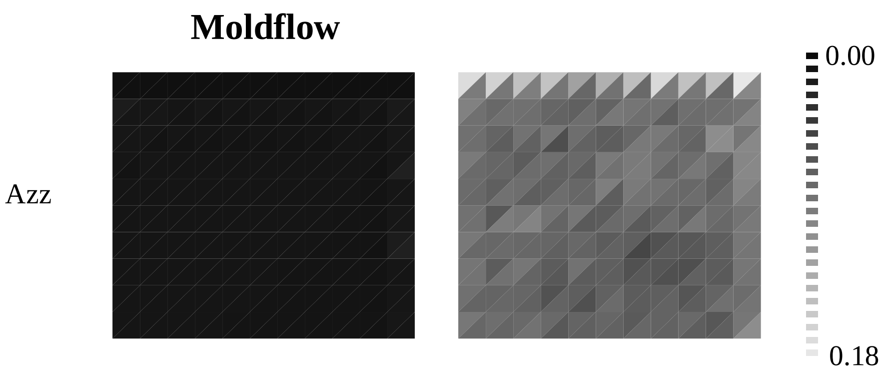

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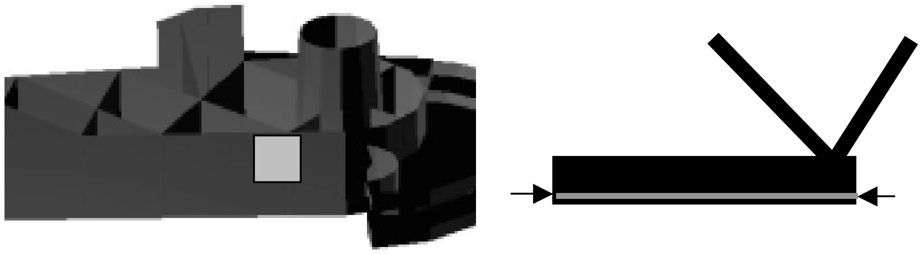

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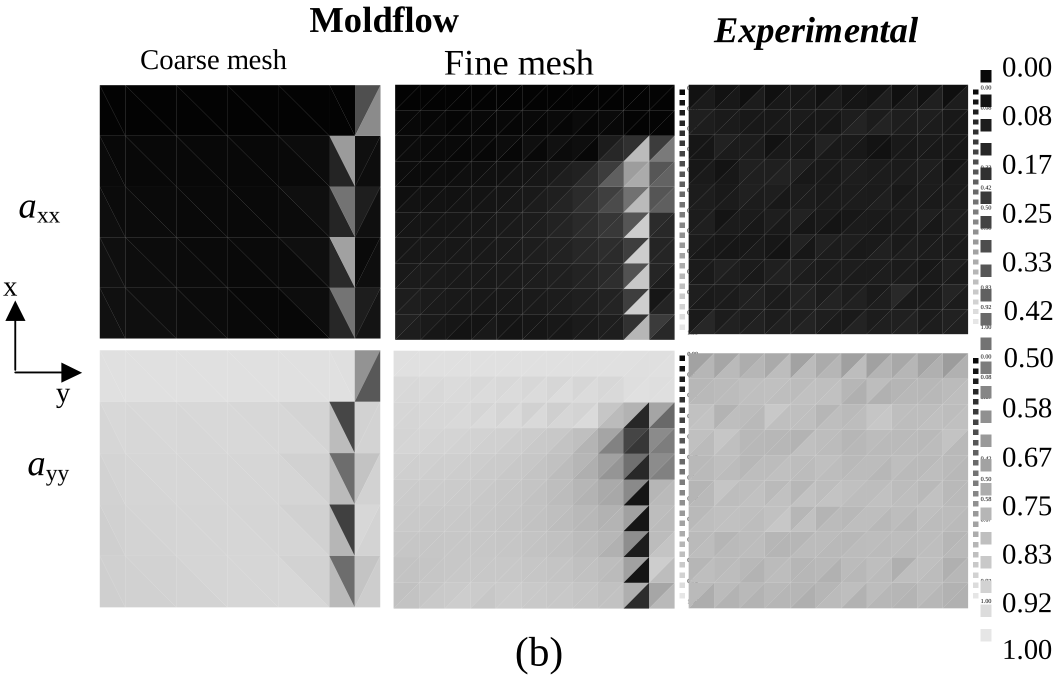
Moldflow
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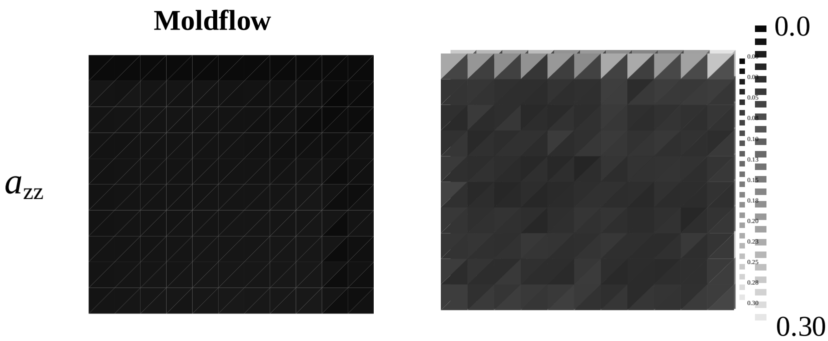
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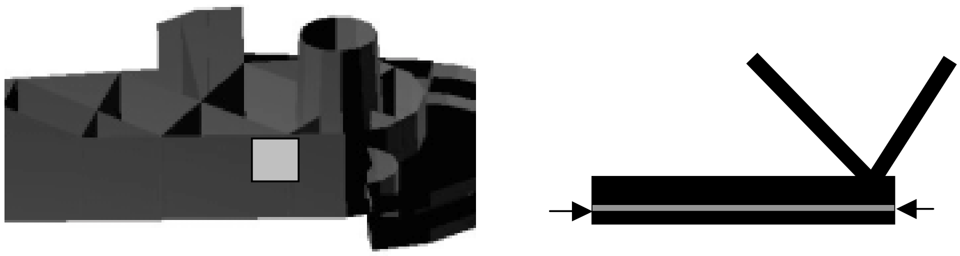

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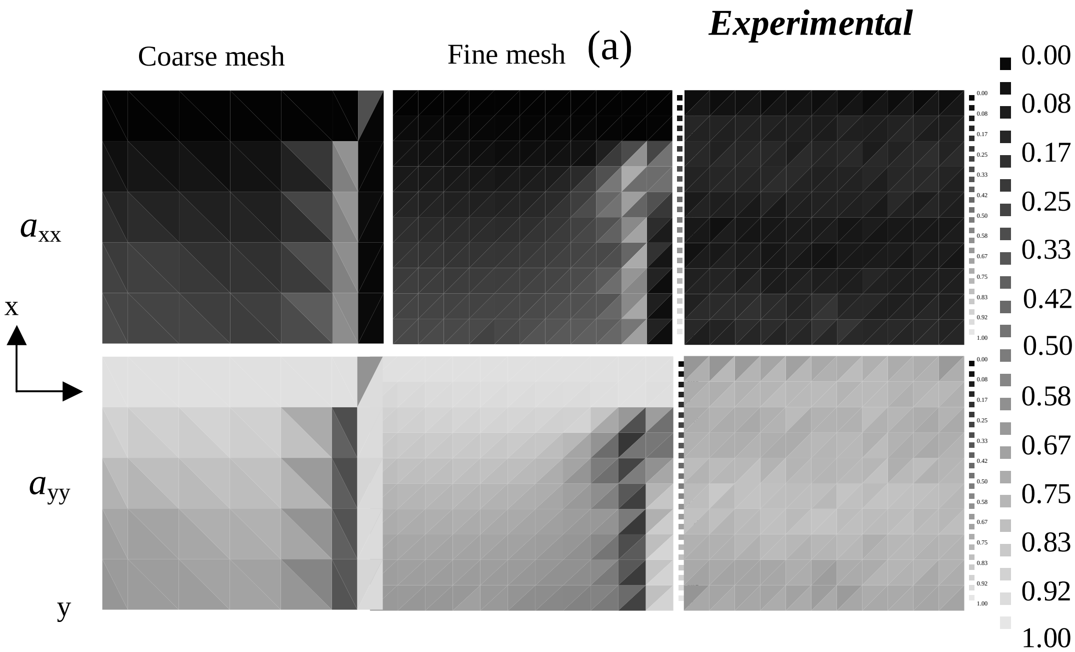

Experimental
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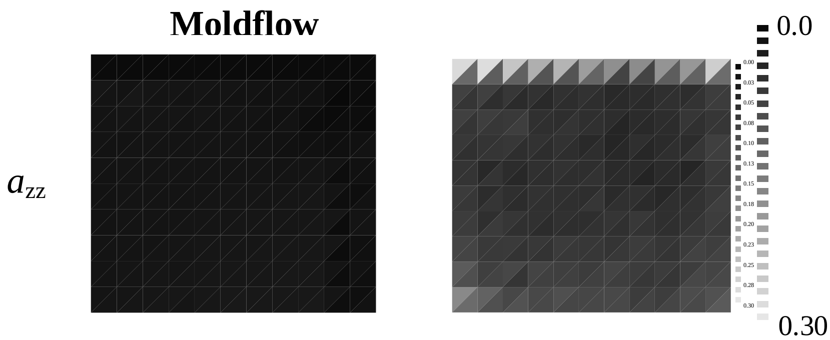

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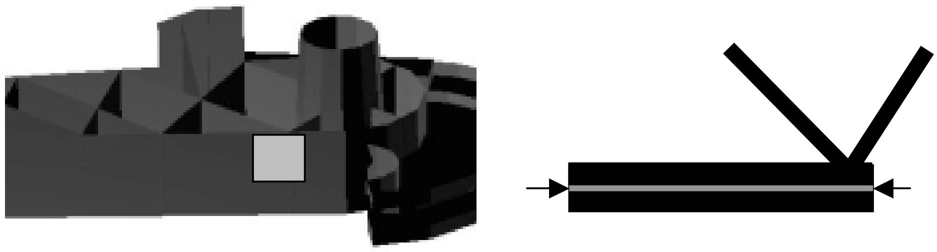

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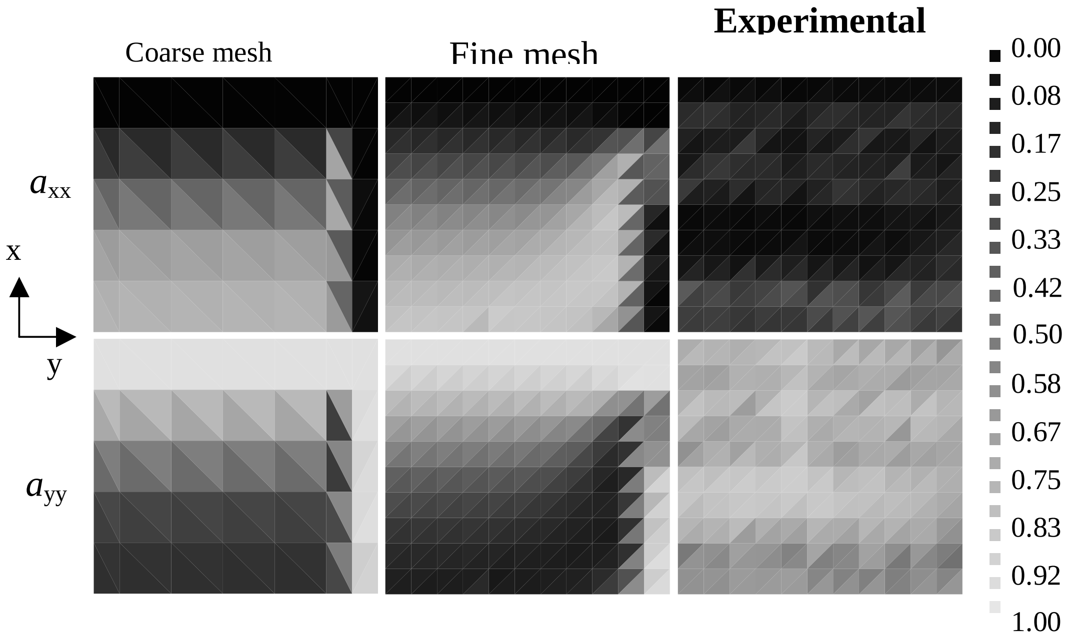
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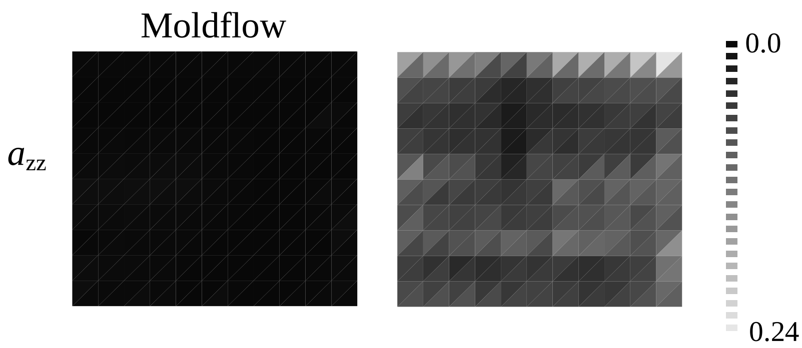
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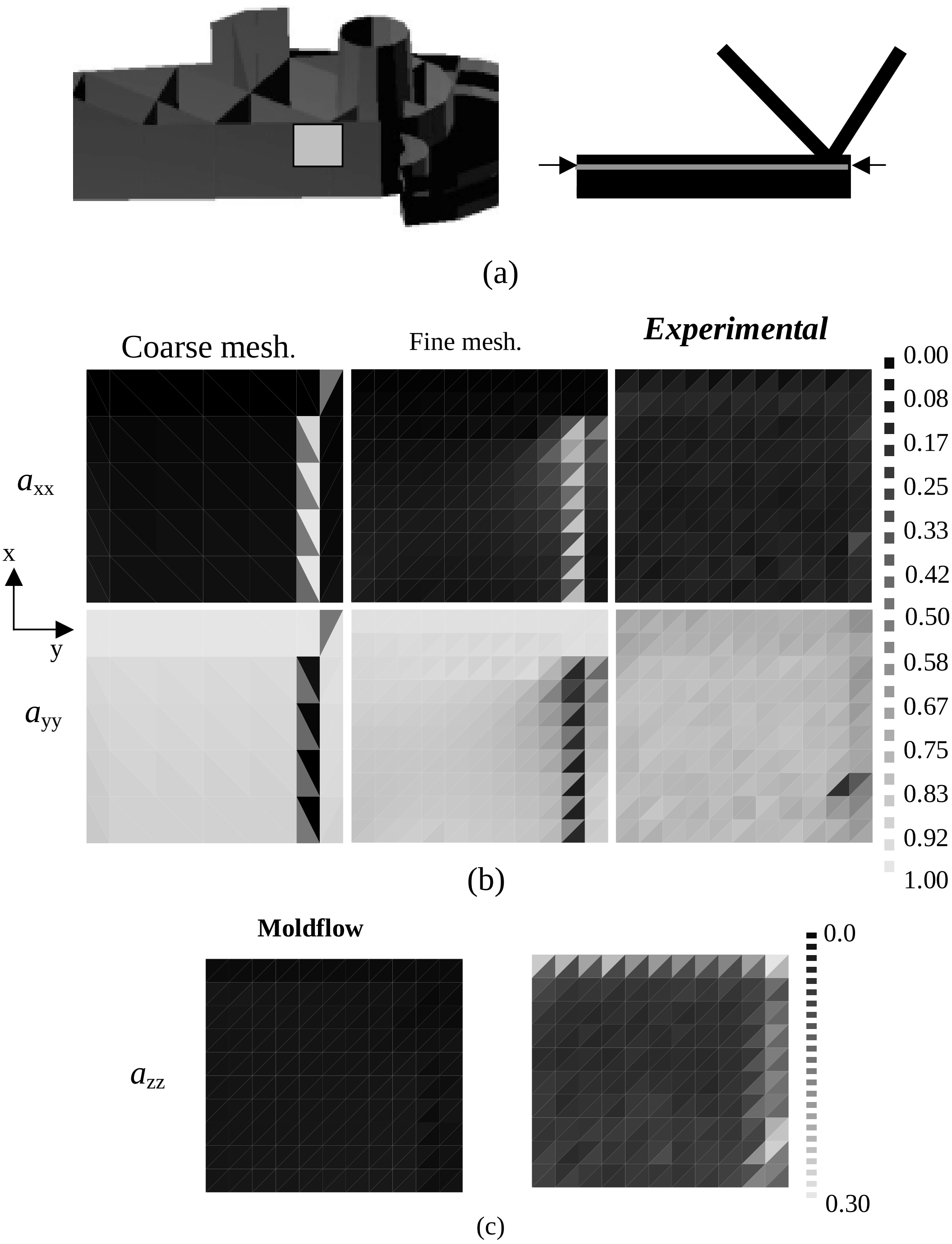
(a)
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Moldflow
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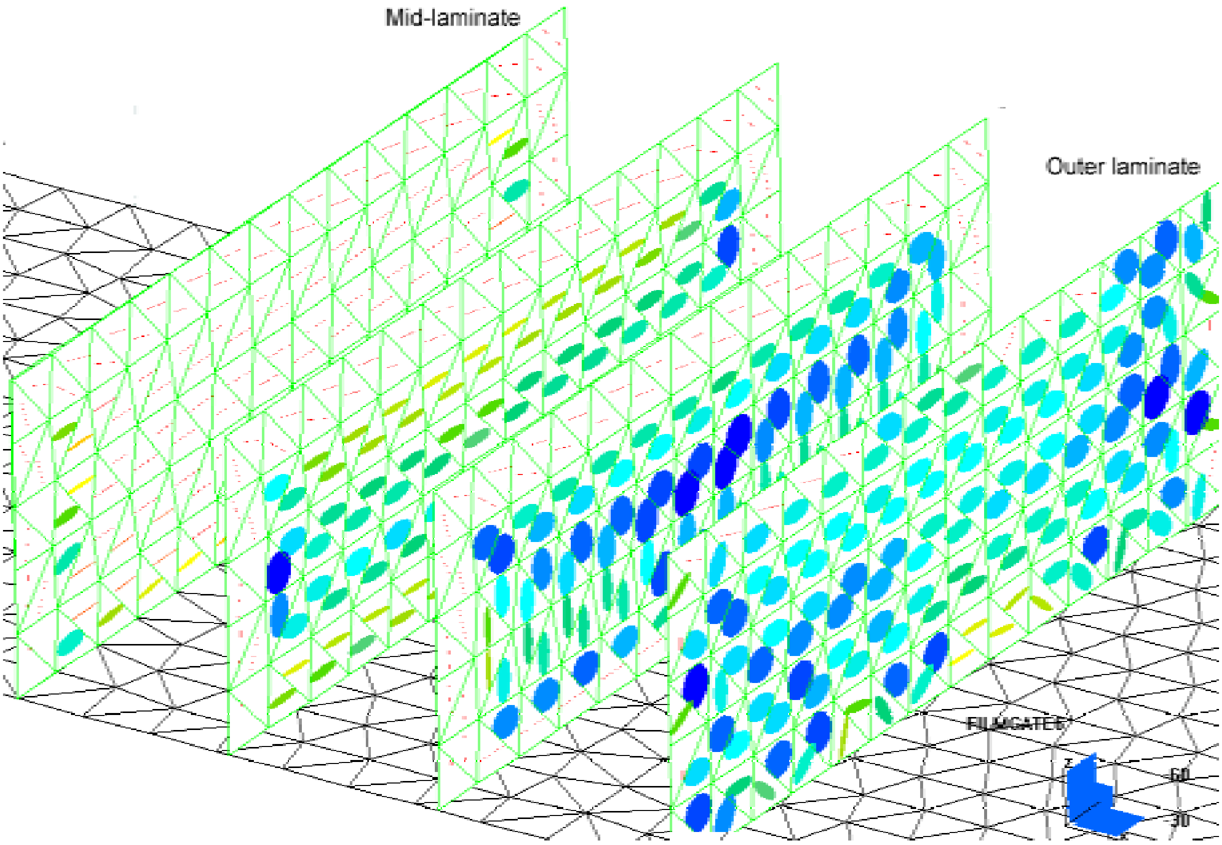
0.30
(c)


Mid-laminate
Outer laminate