3D FIBRE ARCHITECTURE CHARACTERISATION FOR DISCONTINUOUS CARBON FIBRE COMPOSITE STRUCTURES USING COMPUTED TOMOGRAPHY TECHNIQUE

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ABSTRACT

Compression moulding of high fibre content, long discontinuous carbon fibre based Sheet Moulding Compound (SMC) is an attractive solution for high-performance composite structures because the material can flow into complicated cavity geometry. Such process can also incorporate continuous fibre prepreg for manufacturing of hybrid architecture composites, allowing the superior mechanical properties of continuous fibre reinforcements and the superior foamability of SMC to be integrated in a single part. One of the main design challenges with SMC is that in-cavity flow during compression moulding increases the level of heterogeneity of the material, particularly in terms of fibre content and fibre orientation. This has also become a challenge in the development of process simulation models because there is insufficient data to support the fibre prediction model development and the model validation.
This paper aims to address the current challenges identified through the development of a CT based characterisation method for fibre orientation distributions in compression moulded carbon SMC and hybrid architecture composites. The proposed new method will be demonstrated using two different types of sample, including a series of flat SMC-only samples, and one 3D hybrid architecture sample. The data collected form the flat SMC-only samples will also be used to validate an existing fibre prediction process simulation model.

1 INTRODUCTION

Compression moulding of high fibre content, long discontinuous carbon fibre based Sheet Moulding Compound (SMC) is an attractive solution for high-rate manufacturing of high-performance composite structures. SMC flows under compression force to fill the mould cavity, allowing complicated geometry (e.g. ribs and bosses) to be manufactured. The process can also incorporate continuous fibre prepreg to manufacture hybrid architecture composites, allowing the superior mechanical properties of continuous fibre reinforcements and the superior foamability of SMC to be integrated in a single part. One of the main design challenges with SMC is that in-cavity flow during compression moulding increases the level of heterogeneity of the material, particularly in term of fibre orientation, which can significantly affect the mechanical properties of the part. Furthermore, in case of combining SMC and prepreg in a single-stage compression moulding process, the SMC flow can induce large distortion in the continuous fibre phase [1, 2], meaning that the mechanical properties of the continuous fibre reinforcements will also be affected.

Understanding the fibre behaviour during the manufacturing process is the key to improve part quality, and to better predict the structural performance of the part. The level of heterogeneity and complicated fibre architecture in SMC and hybrid architecture composites requires 3D analysis of the material's internal meso-scale structure. There are two commonly used approaches for quantifying the fibre orientation distribution in composite parts: experimental methods and numerical methods. The former involves using experimental techniques to physically determine the fibre orientation in post-manufactured parts, and the latter involves using process simulation techniques to predict the fibre orientation without manufacturing the physical part. In terms of experimental methods, radiology-based techniques such as ultrasonic scanning [3] and X-ray Computed Tomography (referred to as CT in the rest of the paper) scanning [4] have been adopted for fibre orientation analysis in glass fibre SMC. However, application of radiological techniques for carbon SMC is particularly challenging due to the low contrast between the densities of carbon fibre and polymer matrix, and a very high scanning resolution must be used to clearly distinguish the fibre and the polymer. Consequently, only very small sample sizes (micro-scale) can be scanned using conventional CT scanners and the fibre architecture can only be studied at filament level.

In terms of numerical methods, several commercial flow simulation software offer the capability of SMC-only compression moulding simulation, where commonly used fibre prediction models include phenomenological models and meso-scale models. Phenomenological models (e.g. the Folgar-Tucker model[5]) use fibre orientation tensors to represent the fibre orientation, usually on an element-by-element basis, where each fibre orientation tensor indicates the probability of the fibres aligned in each direction. Meso-scale models on the other hand, predict the orientation of individual fibres by modelling the physical movement of each fibre (e.g. [6]). When applied in conjunction with flow simulation model, the physical fibre architecture of the manufactured part can be predicted using a meso-scale model, which can then be subsequently converted into fibre orientation tensors if needed. Although meso-scale models often require significantly higher computational power than phenomenological models, they are still considered as powerful numerical simulation methods as meso-scale fibre architecture information is critical for failure prediction for discontinuous fibre composites. Nevertheless, because of the lack of experimental methods for quantifying fibre orientation in carbon fibre composites, very limited validation data are available for either type of models, and the confidence in applying these numerical models to carbon fibre SMC remains low.

This paper presents a joint experimental and numerical study for characterising fibre orientation distributions in compression moulded carbon fibre SMC and hybrid architecture composites. A novel and robust experimental method utilising CT scanning and image analysis techniques were adopted for physically determining the fibre orientation distributions. The new experimental method were demonstrated using a series of SMC only samples as well as a hybrid architecture sample. The numerical study for fibre orientation prediction focused on SMC-only samples where a meso-scale model available through a commercial compression moulding simulation software was investigated. The fibre architecture predicted by the numerical study was compared against the results from the experimental study to assess the predictive validity of the fibre prediction model. It should be noted that the focus of this research is on assessing and comparing the results generated using different analysis methods, rather than the development of each analysis method.

2 EXPERIMENTAL METHODOLOGIES

2.1 Sample manufacture

Two sets of samples were investigated experimentally including a series of SMC-only samples from a flat plaque, and a hybrid architecture sample from a more complicated, 3D geometry. All samples were manufactured using compression moulding processes performed on an Engel V-Duo 1700 tonne press.

For the SMC-only samples, the material used was a vinyl ester based carbon fibre SMC with 12.7mm fibre length and 57% fibre weight fraction. A simple flat plaque geometry of 550mm x 550mm x 2mm was selected in this study, and an initial charge of 30% coverage was positioned in the centre to encourage a 1D flow regime (Figure 1). The compression moulding process was initially under speed control with 3mm/s closing speed and changed to force control at a switch-over force of 500kN. The holding force was 4500kN. Four long strip samples were cut from the top-right region of the moulded plaque, as indicated in Figure 1. The samples widths were 100mm, 75mm, 50mm and 25mm from top to bottom as shown in Figure 1. Different sample widths were chosen in this study to understand the sample size effects on the quality of CT scan and the measured fibre orientation results.

For the hybrid architecture sample, three different materials were co-moulded together including a woven prepreg with 30K 2x2 twill weave, 660gsm areal mass and 55% fibre volume fraction; a UD prepreg with 186gsm areal mass and 51% fibre volume fraction; and an SMC material made from the chopped UD prepreg with a fibre lengths range between 27mm and54 mm, 1048 gsm areal mass and 53% fibre volume fraction. All materials used in the hybrid architecture part consisted of carbon fibre and the same epoxy resin specially designed for high-volume processing with a 2-minute cure time at 150°C. A ribbed C-channel geometry with overall dimensions of 600m x 84mm x 45mm (see Figure 2) was compression moulded using a combination of all three materials. The prepreg materials was laminated in a [0/90, ±45, (0)7, ±45, 0/90] layup arrangement (i.e. 7 plies od UD sandwiched between 4 plies of woven, total 11 plies) and preformed into the main body of the C-channel (see Figure 2). The SMC phase consisted a single ply of initial charge rolled in to a sausage shape and located in the middle of the C-channel. The compression moulding process was initially under speed control with 3mm/s closing speed and changed to force control at a switch-over force of 500kN. The holding force was 3500kN. The sample used for CT analysis was indicated by the cut lines in Figure 2.

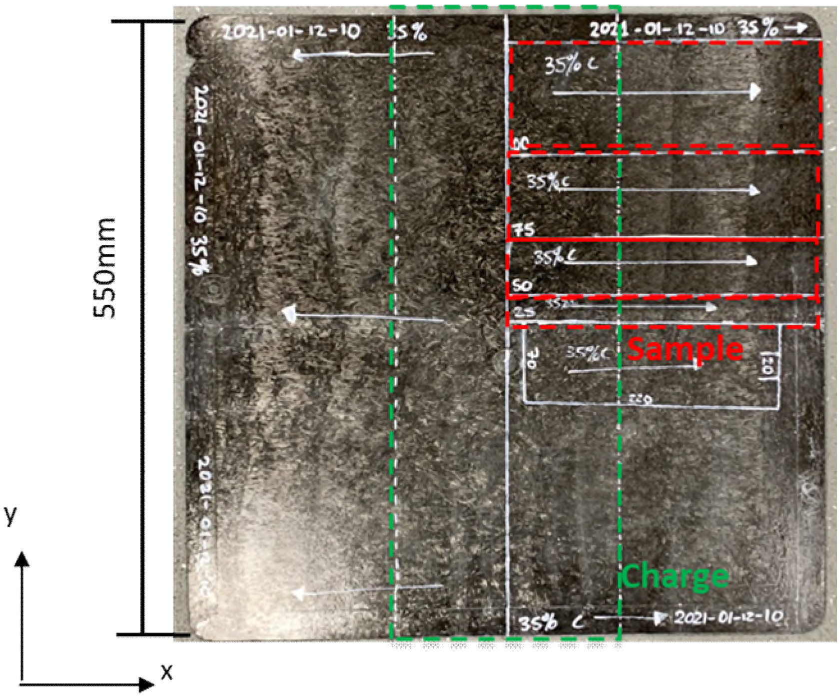


Figure 1: The flat plaque geometry with 550mm edge length and 2mm thickness. The green box indicates the initial charge location (approximately 30% centrally located), and the red boxes indicate the location of the CT samples (sample width 100mm, 75mm, 50mm and 25mm)

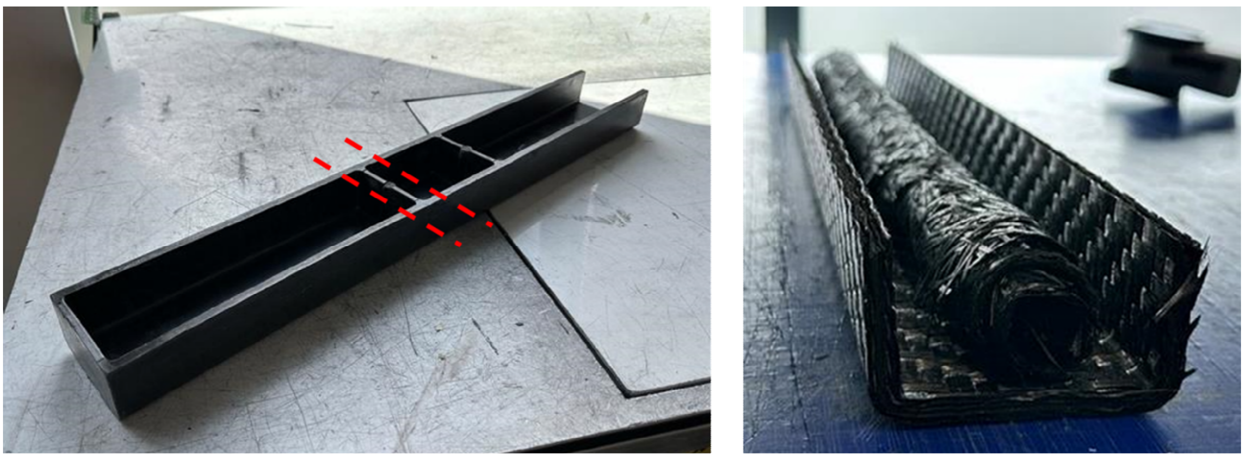


Figure 2: Left: C-channel geometry with ribs moulded using hybrid architecture material. Right: Initial material layout. The prepreg laminate was preformed into the main body of the C-channel and the SMC

phase consisted of one single sheet of material rolled into a sausage shape. The red dashed lines indicate the cut lines for the CT sample.

2.2 Experimental fibre orientation characterisation

Experimental characterisation of fibre orientation distribution within each sample was performed using CT scanning technique. All samples were scanned using a TESCAN UniTOM XL CT scanner. A preliminary study had been conducted to determine the optimum scanning parameters for different sample sizes to achieve the best image quality [7].

The four SMC-only samples studied in this paper were scanned at different resolutions depending on the sample size, where the 25mm sample was scanned at 15µm resolution, the 50mm sample was scanned at 30µm resolution, the 75mm sample was scanned at 42µm resolution, and the 100mm sample was scanned at 55µm resolution. It should be noted that during each scan, the sample was held by a fixture on the initial charge's side (i.e. left hand side in Figure 1), therefore a section of approximately 30mm long was not scanned. VGStudio was employed to reconstruct and analyse the CT scans. The hybrid architecture samples was scanned at 40 µm resolution.

3 NUMERICAL SIMULATION METHODOLOGY

Compression moulding process simulation was performed using 3D TIMON's Composites PRESS by Toray Engineering D solutions. 3D TIMON has a unique in-built Direct Fibre Simulation (DFS) model [6], which models individual fibre tows and their movement caused by the flow. Therefore, the DFS model can predict the physical fibre architecture formed by the flow process. Compression moulding process simulation in 3D TIMON was setup in the same manner as described in [8]. The model was meshed using global element size was 2mm x 2mm x 0.5mm, which was identical to the grid size used in the CT scan analysis. Experimental material characterisation and the material card for 3D TIMON was provided by Toray Engineering D solutions. Due to the reasons of confidentially the detailed material data will not be disclosed in this paper.

4 RESULTS AND DISCUSSIONS

4.1 Experimental results for SMC-only samples

Figure 3 compares the grey-scale images from the CT scans of all four SMC-only samples. There is a clear trend of reduced image quality as the sample width increases. The image becomes more blurred for wider samples, and the brightness becomes less uniform such that the regions around the top and bottom edges of the sample are darker than the centre of the sample. Zoomed-in views of a section of the sample are also provided for the 25mm sample and the 100mm sample in Figure 3, where in the zoomed-in view of the 25mm wide sample the fibre tows can be clearly identified, but in the zoomed-in view of the 100mm wide sample it is very difficult to distinguish the fibre and the matrix. Furthermore, vertical marks can be seen in the images of larger (e.g. 100mm) samples due to streaking artefacts effects, which can significantly affect the quality of the downstream fibre orientation analysis.

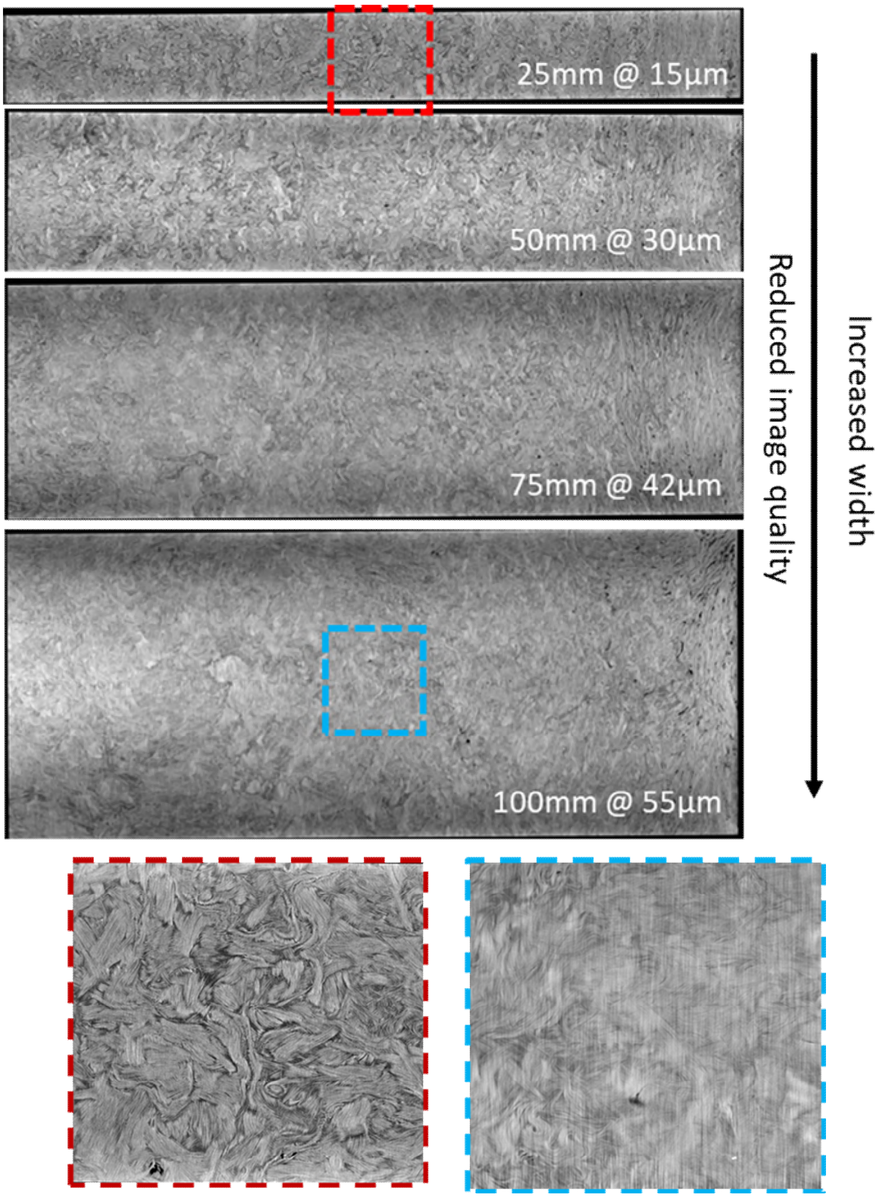


Figure 3: Comparison of grey-scale images from the CT scans for different sample widths. The red box and the blue box indicate the zoomed-in view of a 25mm x 25mm area from the 25mm sample and the 100mm sample respectively.

Figure 4 presents the fibre orientation distribution results from the CT scan analysis for all SMC-only samples. The colours in Figure 4 represent the fibre orientation tensor Axx where blue represents Axx>0.66 (i.e. fibres aligned in the horizontal/flow direction), red represents Axx<33 (i.e. fibre aligned in the vertical/cross flow direction) and green represents values in between (i.e. random fibre orientation). Figure 4 suggests that there is a higher level of fibre alignment in the cross-flow direction for wider samples, although it would be usually expected that more fibres should be aligned in the flow direction. The main cause of this discrepancy is that the highly blurred images for larger samples make it harder for the fibre analysis software to correctly identify the fibre tows, and artificial marks caused by the streaking artefacts effects trick the software to interpret them as vertical/cross-flow fibres. Furthermore, this phenomenon becomes more dominant around the centreline of the sample where the streaking artefacts effects and the brightness are both the highest. It is observed that with the current scanning settings reliable fibre analysis results could only be achieved for the 25mm sample, where no unrealistic fibre orientation results were seen along the centreline of the sample.

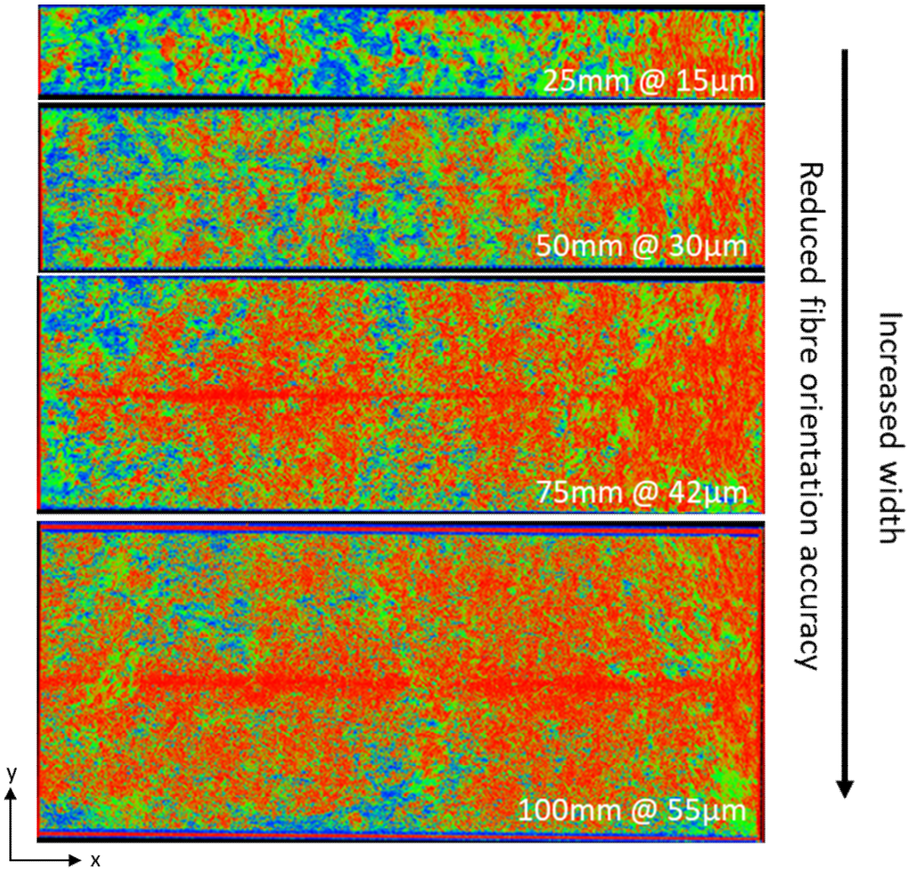


Figure 4: Comparison of fibre orientation distributions from the CT scan analysis for different sample widths. The colours indicate the fibre orientation tensor where blue represents Axx>0.66, red represents Axx<0.33 and green represents the values in between.

Despite the fibre analysis results for the 25mm wide sample has achieved good confidence thanks to the great image quality, there are still regions associated with high level of cross-flow fibres observed with this sample. Figure 5 illustrates the reasons for these apparent cross-flow fibres by comparing the image of the sample surface, the grey-scale image of the fibre architecture obtained from the CT scan and the fibre orientation tensor from the CT scan analysis (Figure 5a-c). The first region with high level of cross-flow fibres can be found on the left half of the sample, as indicated by the black box across Figure 5a-c. The image of the sample surface in Figure 5a suggests that this region contains the edge of an SMC ply, which can also be identified from the grey-scale CT scan image in Figure 5b. The morphology of the ply edge shows similar characteristic as a weldline in the grey-scale image, therefore is interpreted as cross-flow fibres by the fibre analysis software (referred to as ply edge effects). Another region associated with high level of cross-low fibres is at the right hand side of the sample, as indicated by the red box in Figure 5c. Closed-up views of this region in Figure 5d and Figure 5e suggest that this is caused by the wrinkles in the fibres formed in the cross-flow direction as the material crushed into the side-walls inside the mould cavity (referred to as part edge effects).

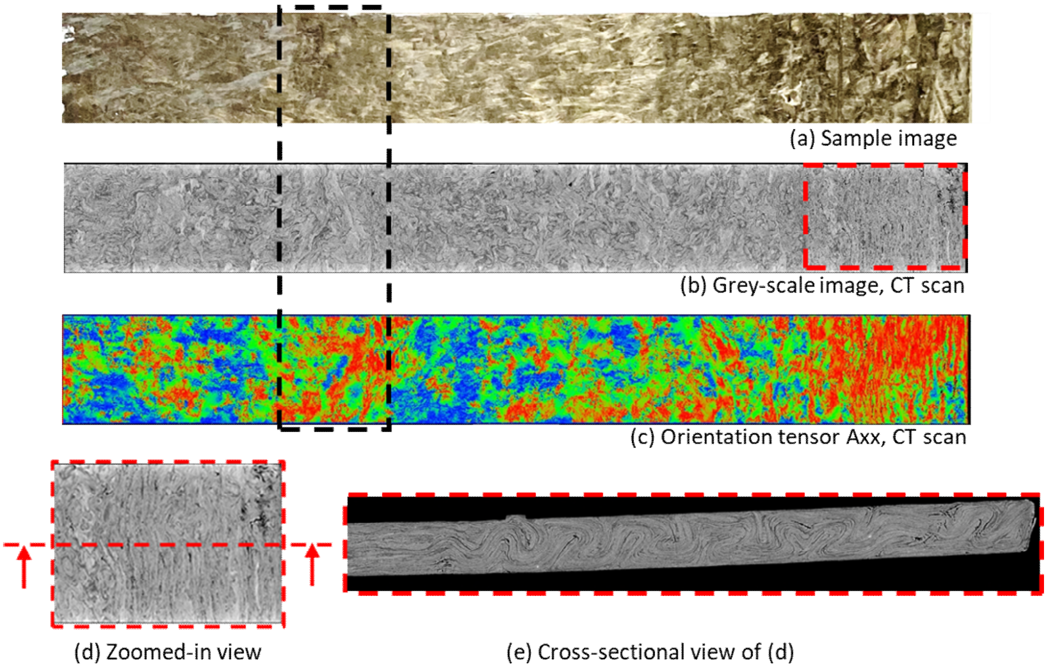


Figure 5: Comparison between (a) the image of the sample surface, (b) the grey-scale image and (c) the orientation tensor Axx from the CT scan analysis for the 25mm wide sample. The black box highlights the edge of an SMC ply observed in all three images a-c. The red box indicates the edge of the plaque with (f) a zoomed-in view of the in-plane fibre architecture and (e) a cross sectional view of the out-of-plane fibre architecture.

4.2 Numerical simulation results for SMC-only samples

Figure 6 presents the fibre architecture of the 25mm sample predicted using the DFS model in 3D TIMON. The fibre architecture of the whole sample is shown in Figure 6a, where the fibre orientation vector X is plotted on each fibre. The volume-averaged fibre orientation tensor Axx distribution for the sample is presented in Figure 6b. It should be noted that very high level of fibre alignment is observed in Figure 6b near the right edge of the sample , which cannot be clearly identified in Figure 6a, which might suggest that there is higher level of fibre alignment in the core region compared to the skin of the part.

Figure 6c shows the zoomed-in view of the fibre architecture near the right edge of the sample, as indicated by the red box in Figure 6a. It can be observed from Figure 6c that there is a gap between the edge of the part and the edge of the fibre network, and the fibres at the edge of the fibre network are primarily aligned in the cross-flow direction. This is due to the constraints applied to the fibres during the DFS analysis: the fibre are not allowed to travel ahead of the flow front, and any fibre nodes that are about to violate the constraint will be shifted back. Therefore, the edge of the fibre network is always slightly behind the flow front, and the fibres at the edge of the fibre network are rotated to the direction tangential to the flow front.

Furthermore, the cross-sectional view of the fibre architecture in Figure 6 shows that the fibres at the part edge do not wrinkle as seen in the actual sample in Figure 5e. Instead the fibres generally have much lower curvatures in Figure 6, and some fibres even penetrate through the boundaries of the part. This is because the DFS model considers the fibres as linked beams with much higher bending stiffness compared to the actual bending stiffness of carbon fibre. The disturbance to the fibre architecture caused by the edge of the mould cavity is much lower in the simulation in Figure 6d compared to in the experimental sample in Figure 5e, which is because the DFS model does not consider the interactions between fibres, so that the stresses caused by the fibre crushing onto the side of the cavity will not be transferred through the fibre network as in an actual SMC material.

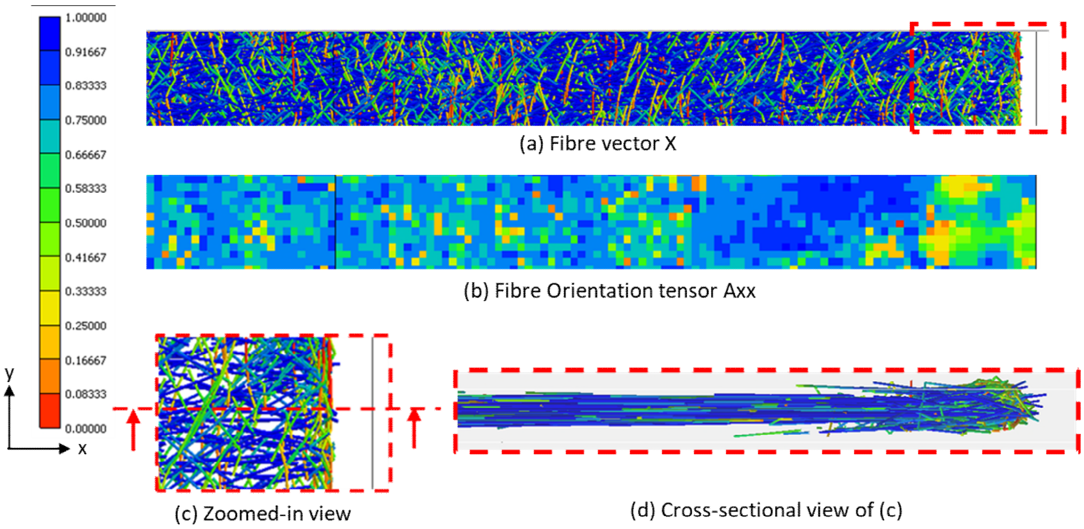


Figure 6: Fibre architecture and orientation distribution predicted for the 25mm wide sample using the DFS model in 3D TIMON. (a) Fibre vector X displayed on fibres. (b) Fibre orientation tensor Axx distribution. (c) Zoomed-in view of the fibre architecture for the region indicated by the red box in (a). (d) Cross-sectional view of (c).

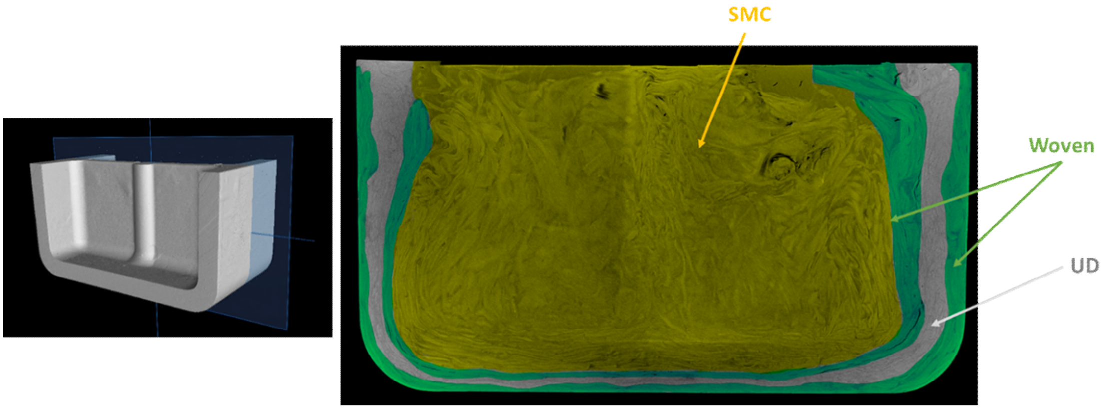
4.3 Experimental results for hybrid architecture sample

Figure 7 presented the fibre architecture of the hybrid architecture sample from three selected planes as indicated by the small images on the left. Fibre orientation analysis was not performed at this stage as it was considered more critical to establish a method for segmenting individual material phase in a hybrid architecture composite. The images in Figure 7 were manually segmented where the three material phases were indicated using three different colours.

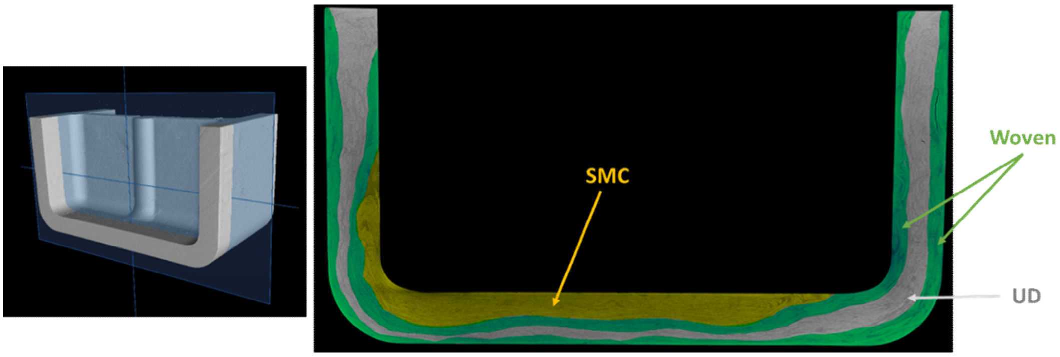
In Figure 7a, resin rich areas can be clearly seen in the SMC phase, near the top edge of the image, especially in the right half of the rib. This indicates fibre-matrix segregation which commonly occurs in tall and narrow ribs filled with SMC as fibres are likely to become congested at the entrance of the rib, which can also be observed in Figure 7a along the bottom of the rib where the SMC phase shows a more compacted fibre architecture.

Furthermore, the images in Figure 7 show an offset in material distribution, such that there is insufficient length of woven material to fill the left hand side wall in Figure 7a, with excessive woven material in the right hand side wall such that the woven material has been pushed into the rib. This is likely to be caused by the inaccurate positioning of the raw material which was performed manually. The positional offset in the woven material has also affected the distribution of SMC, as SMC's ability to flow will fill in any vacancy in the mould cavity. Consequently there is a small amount of SMC in the left hand wall in Figure 7a where there is insufficient woven material to fully fill the cavity, and at the right hand side of the rib there is no SMC in the area that has ben occupies by the excessive woven material. This material offset can also be observed from Figure 7b and Figure 7c. Figure 7b shows a plane slightly away from the rib, which provides a better visualisation of the level of material offset compared to Figure 7a. The SMC has covered most area in the bottom of the channel, and the bottom half of the left hand wall. It is also interesting to notice from Figure 7b that the SMC flow has caused higher level of thickness variation in the UD compared to the woven. This is because the woven material has a more stable fibre architecture due to the interaction between the warp and weft tows, where the UD material has little resistance to deformation in the transverse direction. Therefore the squeeze flow in SMC pushed away the UD fibres underneath, and shifted them in to the other part of the cavity where there was no SMC flowing over the continuous fibres.

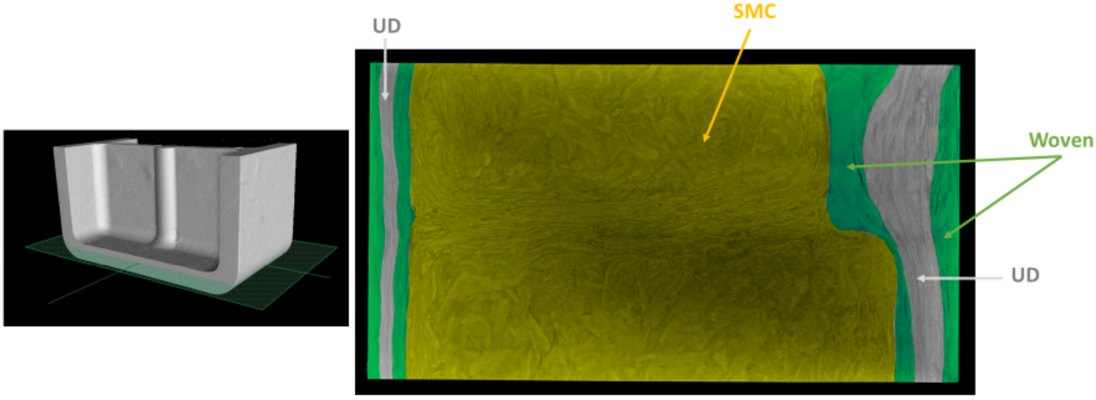
Figure 7c shows the planer view of the fibre architecture taken from the bottom of the channel. It is interesting to notice that the level off material offset varies along the length of the part, where there is a higher level of offset on one side of the rib compared to the other side of the rib. It is hard to determine how the rib affected the local fibre architecture in the part in this case, because the scanned sample has a nearby rib as shown in Figure 2 which was not examined in this paper. Nevertheless, the results presented in Figure 7 highlight the complicity of hybrid architecture composites, and the importance of developing experimental method for investigating the internal fibre architecture. Future work around investigation of hybrid architecture composites will focus on developing automatic segmentation method, and use the collected fibre architecture data to inform the development of hybrid compression moulding process simulation models.



(a)



(b)



(c)

Figure 7: CT scan images for the hybrid architecture sample taken from three planes as indicated by the images on the left. The images were manually segmented to distinguish the three material phased as indicated by different colours.

5 CONCLUSIONS

Experimental and numerical characterisation has been performed to understand fibre orientation distributions in compression moulded carbon fibre SMC-only samples. A flat plaque geometry with 1D flow regime has been selected in this study and samples along the flow direction with different widths have been studied. A CT scanning based fibre analysis technique has been adopted for the experimental study. While this method is capable of inspecting fibre architecture at meso-scale, good image quality and reliable fibre analysis can only be achieved from the narrowest sample (25mm). Commercial compression moulding simulation software 3D TIMON have been used for the numerical simulation study utilising the inbuilt DFS solver for fibre orientation analysis. Comparison between the DFS results and the experimental results has demonstrated differences in the fibre behaviour in some critical regions, such as the ply edge and the part edge, which highlights the limitations of the existing DFS model.

CT scanning has also been performed on a 3D hybrid architecture sample consisting of SMC, UD and woven fibres. Manual segmentation has been performed to distinguish the three material phases. Investigation of the CT images has revealed that there is material offset in the sample, along with fibre-matrix segmentation in the SMC phase in the rib. The SMC flow has also caused distortion in the UD and woven fibres, but the UD material has experiences significantly higher distortion due to the lack of constraint in the transverse direction. Future development in hybrid architecture characterisation will focus on developing automatic segmentation method, and use the fibre architecture data to inform the development of process simulation models.

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