Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 1350-1357
doi:10.4028/p-g9s2nr

Submitted: 2021-12-18
Revised: 2022-01-28
Accepted: 2022-02-18
Online: 2022-07-22

Flow Behaviour of Carbon Fibre Sheet Moulding Compound

C.C. Qian[a *], H. Yuan[b], M. Jesri[c], M.A. Khan[d] and K.N. Kendall[e]

Automotive Composites Research Centre, WMG, University of Warwick, Coventry, United Kingdom, CV4 7AL

[a]connie.qian@warwick.ac.uk, [b]hao.yuan@warwick.ac.uk, [c]m.jesri@warwick.ac.uk, [d]m.a.khan@warwick.ac.uk, [e]k.n.kendall@warwick.ac.uk

*Corresponding author

Keywords: SMC, compression moulding, squeeze flow, process simulation

Abstract. The growing popularity of SMC compression moulding in the automotive industry has led to great interests in process simulation model development. Existing process simulation models are commonly adapted from models originally developed for short fibre composites and lacking experimental validation data. A novel material model specifically developed for SMC flow simulation is proposed in this paper, where the experimental material characterisation is performed using the squeeze flow testing method. The model is validated through simulation of the squeeze flow testing and the accuracy of the model is assessed by comparing the predicted compression forces against experimental data collected from the squeeze flow testing. The proposed new model has demonstrated significant improvement in comparison to existing commercial models in term of compression force prediction, but the predicted compressive forces diverted away from the experimental values towards the end of the test. The predicted cavity pressure distribution has also been investigated and compared to observations reported in the literature where good correlation between predicted pressure distribution and the literature have been achieved.

Introduction

Compression moulding of long discontinuous carbon fibre based Sheet Moulding Compound (SMC) has attracted growing interests in the automotive industry for manufacturing high-volume vehicle structures due to a number of advantages such as lower material wastage compared to continuous fibre prepregs and relatively fast processing speed compared to many other composites manufacturing processes [1].

Several commercial process simulation packages have been developed for compression moulding of SMC, such as Moldflow by Autodesk, Moldex3D by CoreTech and 3D TIMON by Toray. The constitutive models employed in these packages are commonly adapted from models originally developed for injection moulding of short fibre composites, but very few validation studies have been done to assess the suitability of such models for SMC compression moulding. The co-authors recently conducted a full assessment of the predictive accuracy for all three commercial packages mentioned above using both a flat plaque geometry and a 3D geometry with ribs and bosses [2]. This study found that all these simulation packages failed to correctly predict the compression forces for both geometries, and furthermore, they also failed to correctly predict the filling patterns in the 3D geometry. Therefore, it was suggested that a dedicated material model will need to be developed for compression moulding of SMC.

The key barrier in reliable SMC compression moulding simulation is the lack of understanding in the flow behaviour and suitable material characterisation techniques. The deformation mechanism of long discontinuous fibre composites (such as SMC) during compression moulding processes is very different from that of short fibre composites during injection moulding processes. Firstly, the physical behaviours of the two types of material are different due to differences in the organisation of the fibres. Short fibre composites, especially those with low fibre content typically experiences suspension flow behaviour [3], where the resin carries the fibres as a suspension and material deformation is dominated by the resin. Long fibre composites (e.g. SMC) on the other hand, contains a network of entangled fibre bundles, and the material deformation is dominated by the interactions between fibre bundles [4]. From a continuum mechanics point of view, the former only requires analysis of viscous stresses, while the later might also require analysis of elastic stresses. Secondly, the loading conditions in compression moulding processes and injection moulding processes are also different. In compression moulding processes, the material flows under large compaction force applied over a large surface area, which means the deformation is dominated by compressive stresses. In injection moulding processes, the material flows under high injection pressure applied at one or a few discrete points known as gate, which means the deformation is dominated by shear stresses.

Conventional rheometers are unsuitable for SMC flow characterisation due to the high pressure required in SMC compression moulding. Alternatively, the squeeze flow testing has been adopted by a few researchers [5-7] due to its simplicity and the similar flow regime to the actual compression moulding. This approach was adopted in the development of a macro-scale plug flow model for compression moulding of SMC by Dumont et al. [8] and Sentis et al. [9] where the flow behaviour of SMC was assumed incompressible and purely viscous. More recently, Hohberg et al. modified this model to take into account the compressibility of SMC [10]. In addition to the shear viscosity based constitutive models adopted in the commercial packages, the models developed in [9] and [10] both consider stress components caused by elongational viscosity. Nevertheless, the elastic stress components are still overlooked in these models and the suitability of the loading cases analysed (shear and elongation) is still questionable based on the discussions in the previous paragraph.

This study aims to develop a new modelling approach to support flow simulation in SMC compression moulding. The squeeze flow testing setup is adopted for investigating the flow behaviour of SMC under the typical compression moulding conditions. The force-displacement history for different compressing speeds is recorded and used for derivation of the correct compressive stress-strain relationship. A new constitutive model is developed based on these data and implemented in ABAQUS/Explicit using in-built plasticity model. The accuracy of the model is assessed in terms of predicted compression forces and pressures.

Experimental Material Characterisation

The material used in this study was a vinylester based carbon fibre SMC with 12.5mm fibre length, and 47% fibre weight fraction. The material is specifically designed for high volume automotive applications. Experimental material characterisation was conducted using a squeeze flow rig attached to a Zwick 250kN servo-hydraulic testing machine. The squeeze flow rig features a pair of heated steel platens coated with silicon release agent resembling the surfaces of typical compression moulding tools (see Fig. 1). During the squeeze flow test, a circular SMC sample is positioned in the centre of the bottom platen using a removable sample locator, and the top platen moves down at a constant speed until the sample is compressed to a target thickness. No preheating was performed in this study, which means the initial sample temperature equals the room temperature. All samples presented in this paper had initial diameter of 50mm and were compressed to a final thickness of 0.2mm (see Fig. 2). The initial sample thickness was found to range between 1.4mm to 1.8mm for the material studied. It should be noted that due to the nature of the compounding process, raw SMC samples typically have highly uneven thickness, creating extra challenges in material characterisations. Squeeze flow tests were performed at three compression speeds (2 mm/s, 5 mm/s and 10 mm/s) and two platen surface temperatures (80°C and 120°C) to understand the rate dependency and temperature dependency of the material.

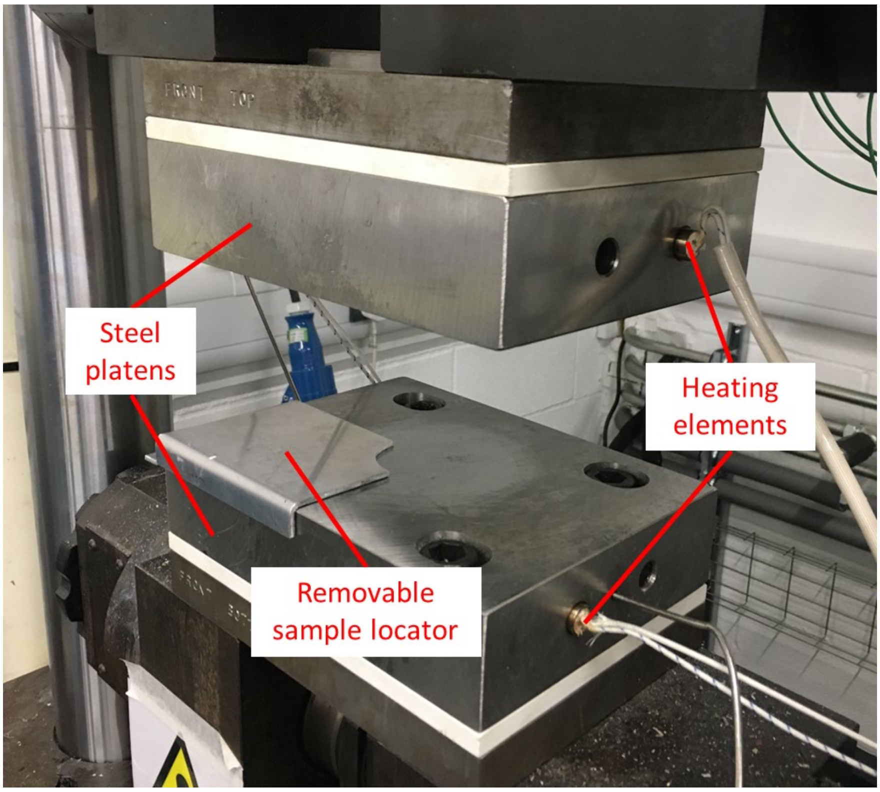

Fig. 1: The squeeze flow testing rig.

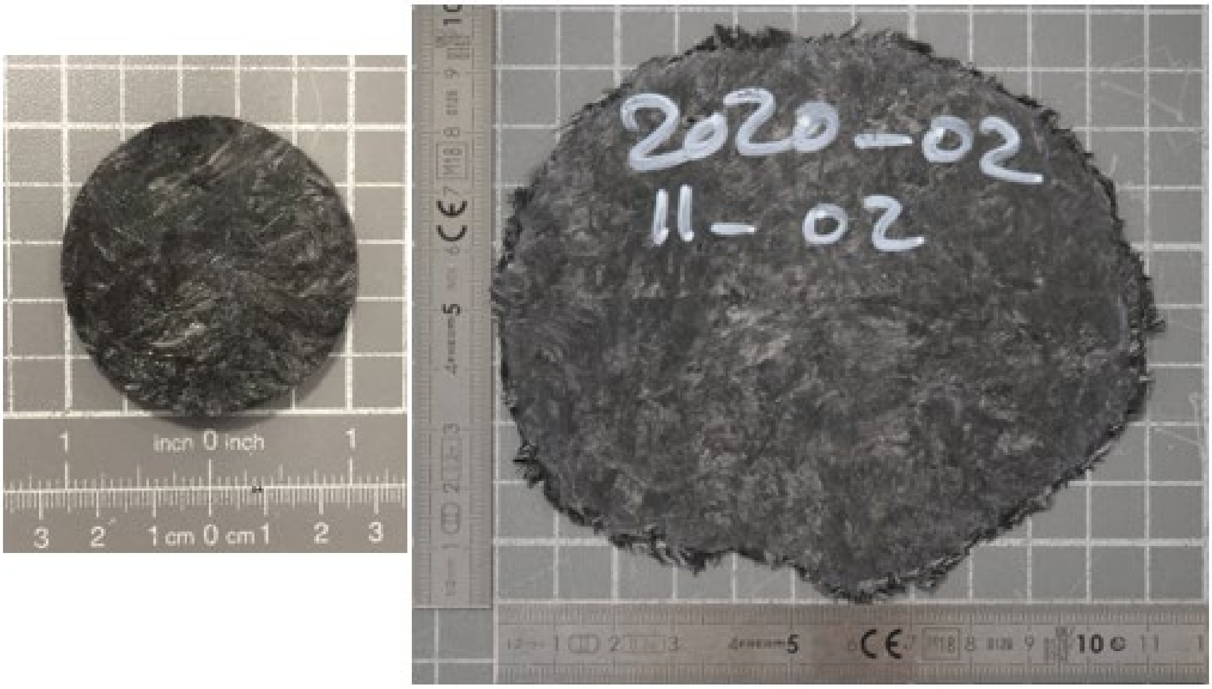

Fig. 2: An example squeeze flow testing sample tested at 80°C and 2mm/s closing speed.
Left: before compression. Right: after compression.

Numerical Simulation Methodology

Constitutive Material Model. The new constitutive material model proposed here describes the flow behaviour of SMC using a compressive stress-strain based relationship. The following assumptions were made at this stage:

1. The material is fully homogeneous, isotropic and incompressible.
2. The material undergoes plastic deformation with a yield strength of virtually zero.

3. The plastic strain in the material is significantly higher than the elastic strain.
4. The thickness is uniform within a sample, so that the sample surfaces were in full contact with the platen surfaces from the beginning of the compression
5. There is no friction at the sample/platen interface (perfect slip)

Based on these assumptions, the true compressive stress in the sample can be written as:

$$\sigma = (F \cdot h)/(A_0 \cdot h_0). \tag{1}$$

where F denotes the compression force, h denotes momentary sample thickness, and A_0 and h_0 denote the initial sample area and thickness.

The total compressive strain in the sample can be expressed as:

$$\varepsilon = \ln (h/h_0). \tag{2}$$

and the plastic strain can be expressed as:

$$\varepsilon^{pl} = \varepsilon - \sigma/E. \tag{3}$$

where E denotes the elastic modulus of the material.

Numerical Implementation. The constitutive model was implemented in ABAQUS using the in-built plasticity model with isotropic hardening. ABAQUS offers the option of defining plasticity behaviour using discrete (tabulated) yield stress vs. plastic strain data. Rate dependency and temperature dependency can also be incorporated using this method. Other material parameters defined in the material model included density of 1500 kg/m^2, elastic modulus of 30GPa and Poisson's ratio of 0.49. Note that it was not possible to physically determine the elastic modulus and Poisson's ratio of the material using the current squeeze flow testing setup, therefore these values were arbitrarily selected based on assumptions 1 and 3 mentioned above.

Model Validation. The proposed material model was validated by simulating the squeeze flow test and comparing the predicted force-displacement curve against the experimental curve. Due to the large deformation in SMC flow, adaptive meshing is required to prevent excessive element distortion. Therefore, the analysis was performed in ABAQUS/explicit utilising the Arbitrary-Lagrangian-Eulerian (ALE) remeshing function.

The SMC sample was modelled as a 3D deformable body and meshed using 8-node linear brick elements with reduced integration (C3D8R). The testing surfaces on the top and bottom platens were modelled as discrete rigid shells and meshed using 4-node rigid elements R3D4. The kinematic contact was applied at the sample-platen interfaces and the contact properties were frictionless in the tangential direction, and "hard contact" in the normal direction. Encastre boundary conditions were applied to the bottom platen and velocity boundary conditions were applied to the top platen. The velocity was increased from 0 to the full magnitude within the first 0.05s using a smooth step profile to minimise the fluctuation in forces caused by the explicit solver. The test was modelled isothermally meaning that temperature dependency was currently not captured in the analysis. The force-displacement curve for the top platen was extracted from the simulation results and compared with the experimental force-displacement curve.

To demonstrate the improved accuracy of the newly proposed model the simulation result was also compared with two commercial packages 3D TIMON and Moldex3D, where shear viscosity based constitutive models are adopted in both packages. Experimental material characterisation and material card for flow simulation in 3D TIMON were provided by Toray Engineering D Solutions. The material card was then converted to Moldex3D material card by the authors as the material models in 3D TIMON were also available in Moldex3D. Due to the reasons of confidentiality the material models used for the commercial packages will not be disclosed in this paper.

Results and Discussions

Squeeze Flow Testing Results. Fig. 3 presents the compressive stress-strain curves from the squeeze flow tests performed at different speeds and temperatures. It should be noted that data recording terminated at lower strain values as the testing speed increased, which was due to a fault with the current data acquisition system rather than the testing machine itself and expected to be fixed in the future. Nevertheless, existing data suggest that all curves seem to experience very similar characteristic shapes. Comparison between the curves also suggests that the material experiences both temperature dependency and rate dependency, such that the compression forces increase with increased speed and decreased temperature.

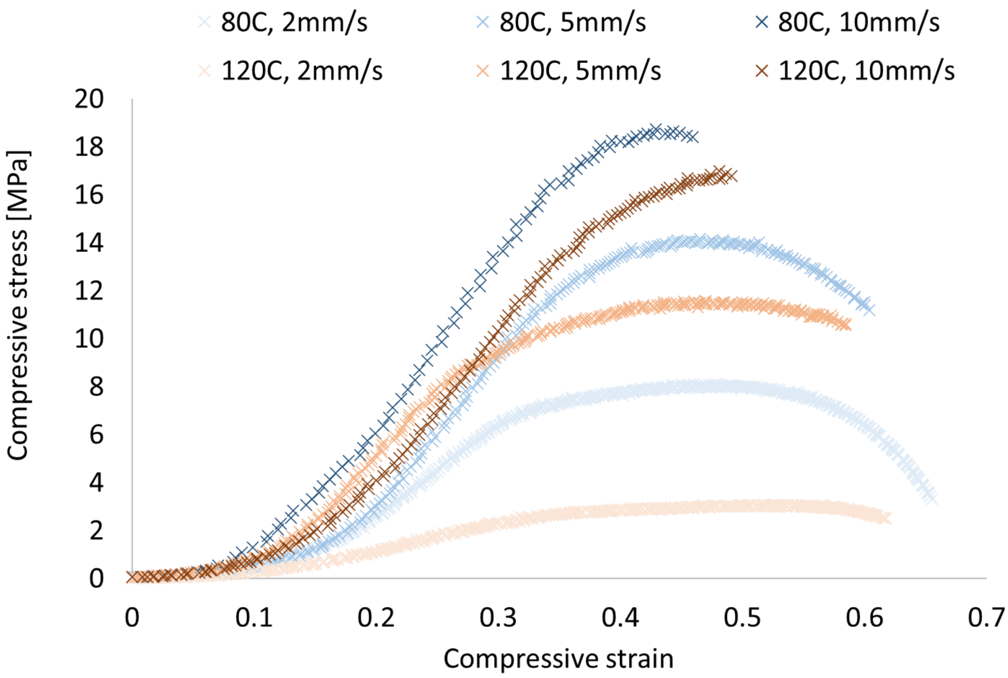

Fig. 3: Compressive stress-strain curves from the SMC squeeze flow tests at various platen temperatures and closing speed.

Numerical Simulation and Model Validation. Numerical simulation for the squeeze flow sample tested at 120°C and 2mm/s is presented in this section as these parameters are closest to the processing conditions recommended in the material supplier's datasheet. Fig. 4 illustrates the procedure of converting the experimental stress-strain data into appropriate ABAQUS input format as described in the previous section of the paper: discrete true stress-strain data points were firstly selected from the experimental curve, at 0.02 strain increment. The discrete point data were then used to generate the plastic strain data using Equation (3), which were directly entered into ABAQUS as tabulated data. It should be noted that the ABAQUS in-built plasticity model cannot capture the final drop in the stress-strain curve after the stress has reached the maximum value. Instead, an approximation is used such that the stress value plateaus after the maximum stress value has been reached, as indicated by the red arrow in Fig. 4.

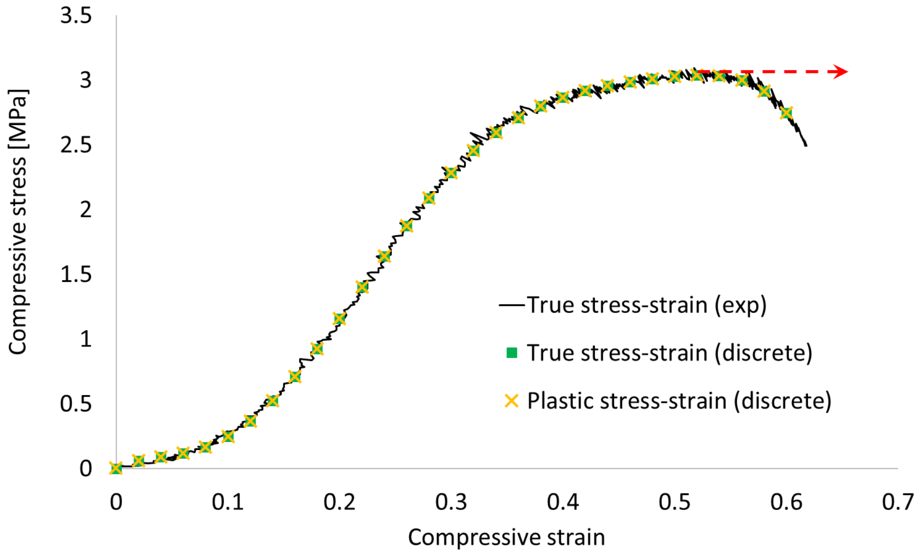

Fig. 4: Comparison of compressive stress-strain data for the simulated squeeze flow sample (120°C, 2mm/s) between experimental true stress-strain data, discrete true stress-strain data points selected from the experimental curve and discrete plastic stress-strain data points used as ABAQUS input data. The red arrow indicates the approximation adopted by the ABAQUS in-built model.

Fig. 5 compares the compression force-displacement curve predicted using the newly proposed model against the experimental data and the curves predicted using commercial process simulation packages. Overall speaking, the predictions from the proposed model show very good agreement with the experimental results until the displacement reaches ~0.8mm, and the discrepancy beyond this point can be explained by the approximation used by ABAQUS's in-built plasticity method as indicated in Fig. 4. The commercial models on the other hand, show poor agreement with the experimental results in terms of both the magnitude of the compression forces and the characteristic shape of the curve. It is also interesting to notice that both commercial models have predicted non-zero compression force at zero displacement, which has also been observed in [2].

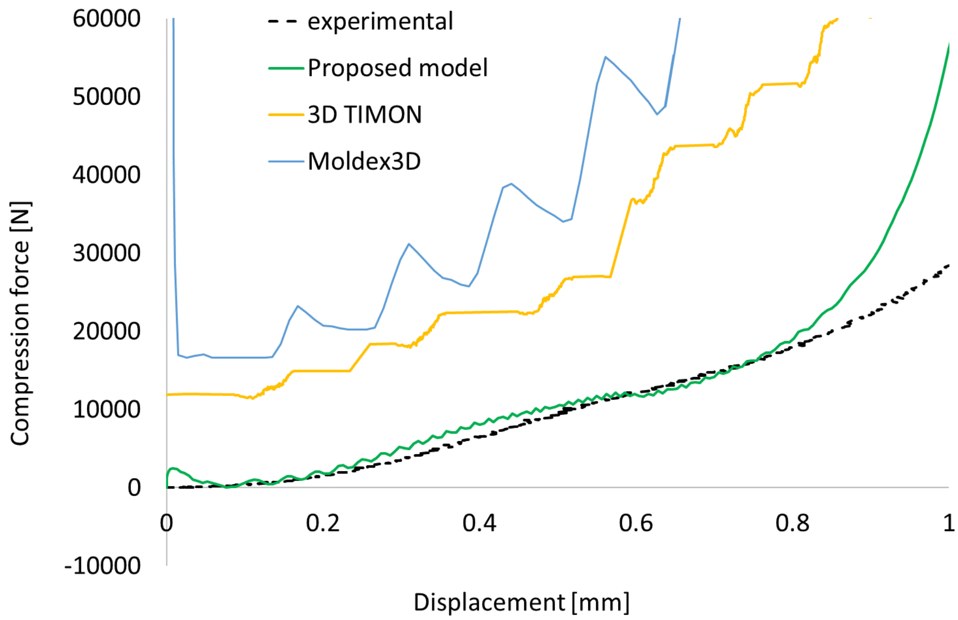

Fig. 5: Comparison of compression force-displacement curves predicted by different models against the experimental curve.

Fig. 6 presents the pressure distribution at the bottom sample-platen interface predicted at displacement of 0.8mm using the proposed new model. Although the current squeeze flow rig is not instrumented for measuring the pressure distributions, the pressure values in Fig. 6 are representative of typical pressure range seen during the flow stage of most compression moulding processes. Fig. 7 shows the pressure distribution along the sample radius extracted from Fig. 6. The characteristic shape of the pressure distribution curve in Fig. 7 is very similar to an illustration of typical pressure distribution curve from a simple compression test (i.e. squeeze flow test) provided in the literature by Guiraud et al. [11].

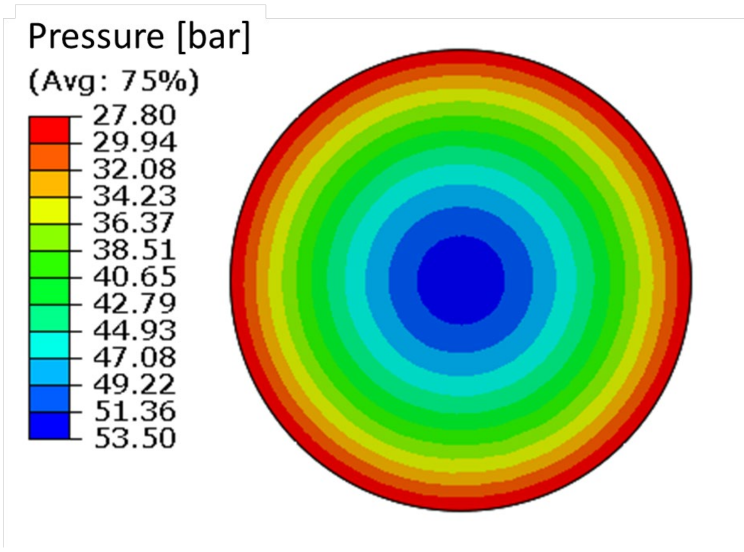

Fig. 6: Pressure distribution at the sample/platen interface at displacement of 0.8mm, predicted using the proposed new model.

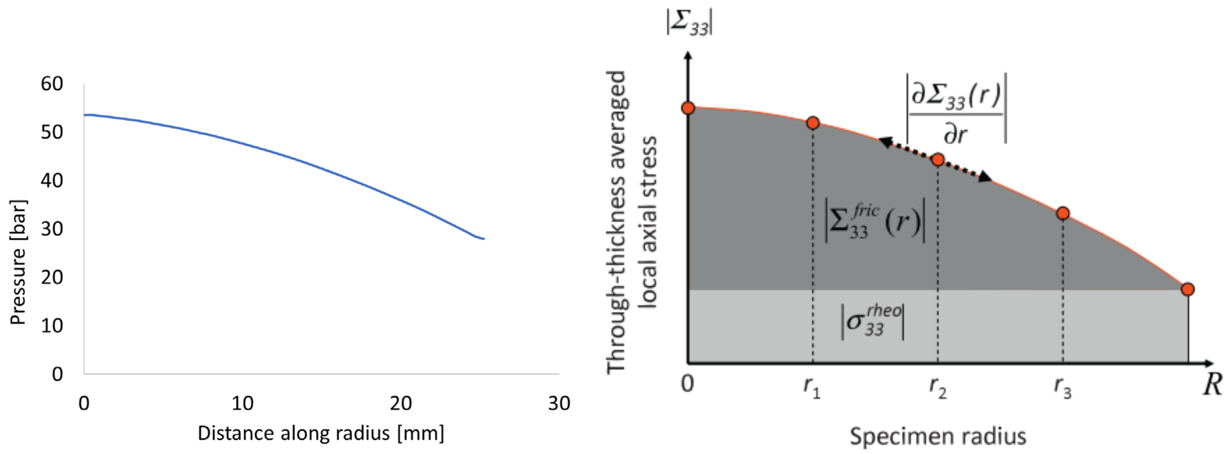

Fig. 7: Left: pressure distribution along the sample radius at displacement of 0.8mm, predicted using the proposed new model vs. Right: typical pressure distribution along the sample radius in a simple compression test (i.e. squeeze flow test) [11].

Conclusions

A dedicated material model has been developed for flow simulation of SMC compression moulding. The model describes the flow behaviour of SMC using a compressive stress-strain relationship and the squeeze flow test has been employed to determine the material input data. The squeeze flow testing results have suggested that the material behaviour is both rate dependent and temperature dependent. The new material model has been implemented in ABAQUS using an in-built plasticity model and validated through simulation of the squeeze flow test. Due to the approximation used in the ABAQUS in-built plasticity model, the predicted compressive forces diverted away from the experimental values towards the end of the test. Nevertheless, the proposed model has demonstrated significant improvement compared to commercial packages. Meanwhile, the predicted pressure distribution within the sample shows good correlation with the observations reported in the literature.

The proposed new modelling technique is simple and accurate and can be implemented in most generic FEA packages. Potential future work will include more comprehensive model validation through instrumentation of the testing rig and more case studies based on real-life compression moulding processes. The limitations identified with the current constitutive model will also be addressed.

Acknowledgement

The authors would like to acknowledge the financial support from the EPSRC Future Composites Manufacturing Hub (grant number EP/P006701/1) and the China Scholarship Council.

References

[1] G. Alnersson, M. W. Tahir, A.-L. Ljung, and T. S. Lundström, Review of the Numerical Modeling of Compression Molding of Sheet Molding Compound, Processes. 8 (2020) 179.

[2] C. Qian, A. Deshpande, M. Jesri, R. Groves, N. Reynolds, K. N. Kendall, A Comprehensive Assessment of Commercial Process Simulation Software for Compression Moulding of Sheet Moulding Compound, the 24th International Conference on Material Forming, Liège, Belgique. (2021).

[3] J. F. Morris, Shear Thickening of Concentrated Suspensions: Recent Developments and Relation to Other Phenomena, Annual Review of Fluid Mechanics. 52 (2020) 121-144.

[4] S. Toll, Packing mechanics of fiber reinforcements, Polymer Engineering and Science. 38 (1998) 1337-1350.

[5] M. R. Barone, D. A. Caulk, A Model for the Flow of a Chopped Fiber Reinforced Polymer Compound in Compression Molding, Journal of Applied Mechanics. 53 (1986) 361-371.

[6] G. Kotsikos, A. G. Gibson, Investigation of the squeeze flow behaviour of Sheet Moulding Compounds (SMC), Composites Part A: Applied Science and Manufacturing. 29 (1998) 1569-1577.

[7] A. G. Gibson, S. Toll, Mechanics of the squeeze flow of planar fibre suspensions, Journal of Non-Newtonian Fluid Mechanics. 82 (1999) 1-24.

[8] P. Dumont, L. Orgéas, D. Favier, P. Pizette, C. Venet, Compression moulding of SMC: In situ experiments, modelling and simulation, Composites Part A: Applied Science and Manufacturing. 38 (2007) 353-368.

[9] D. Ferré Sentis, L. Orgéas, P. J. J. Dumont, S. Rolland du Roscoat, M. Sager, P. Latil, 3D in situ observations of the compressibility and pore transport in Sheet Moulding Compounds during the early stages of compression moulding, Composites Part A: Applied Science and Manufacturing. 92 (2017) 51-61.

[10] M. Hohberg, L. Kärger, F. Henning, A. Hrymak, Rheological measurements and rheological shell model Considering the compressible behavior of long fiber reinforced sheet molding compound (SMC), Composites Part A: Applied Science and Manufacturing. 95 (2017) 110-117.

[11] O. Guiraud, P. J. J. Dumont, L. Orgéas, D. Favier, Rheometry of compression moulded fibre-reinforced polymer composites: Rheology, compressibility, and friction forces with mould surfaces, Composites Part A: Applied Science and Manufacturing. 43 (2012) 2107-2119.