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Modelling compaction-induced defects in overmoulding of thermoplastic composites

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Abstract. This study introduces a computationally efficient numerical tool for the design and manufacturing of thermoplastic overmoulded parts. The tool is set to predict compaction-induced wrinkles in overmoulded continuous fibre organosheets. Using a homogenisation approach, whereby the constitutive behaviour of each organosheet is described by the DefGen Protocol material model, allows to significantly reduce the required computational time in comparison with traditional ply-by-ply methods. Experimental characterisation of the material was performed under various processing conditions to extract model parameters, and results validation was conducted for small coupon tests and full-size industrial panels. The results showed high accuracy in predicting wrinkle geometry, with errors below 5%.

Introduction

Thermoplastic injection overmoulding is widely used for structural applications in the automotive and aerospace industries. Low-cost, fibre-filled polymers are combined with high-stiffness continuous fibre organosheets to simplify manufacturing (see Fig. 1.a). The continuous fibre requires minimal reshaping, while the discontinuous fibre enables complex geometries through injection moulding. However, overmoulded parts face design and manufacturing challenges. Abrupt transitions between inserts and base material create stress concentrations due to stiffness differences, thus, reducing the insert's efficiency. In order to manage this effect careful design of the laminate and geometry is required. Moreover, manufacturing issues like fibre wash and flow-induced alignment also affect bond strength variability.

The need for a robust modelling tool for the overmoulding process arises from the high costs associated with industrial compaction and injection hardware settings, making a traditional trial-and-error approach impractical and too expensive for optimising processing parameters. Currently, overmoulding processes are constrained by tooling choices that do not account for the complexities and nuances of the manufacturing process. Once set up, replacing such tooling is impractical due to high costs. Therefore, the ability to model the overmoulding process in advance allows for precise optimisation of manufacturing parameters prior to hardware deployment, ensuring a more efficient and cost-effective production process. Consequently, a design-for-manufacturing tool is required to drive the virtual simulation of large, industry-scale parts forward. This study introduces a numerical tool designed to support the design and manufacturing of industrial-scale thermoplastic overmoulded components.

Modelling the effects of overmoulding is a challenging task. While understanding the bonding mechanisms between polymers at the interface is essential, overmoulding remains a relatively new field with no standardised approach for characterising interface strength. Injection-molded parts often develop heterogeneous fibre architectures due to flow-induced alignment, which can significantly influence the variability of bond strength in overmolded components [1]. Recent modelling efforts were aimed at the injection flow simulation [2], interface bonding mechanisms [3], [4], the degree of healing based on the degree of melting and the thermo-mechanical history during the forming process [5] of an overmoulded joint.

a **b**

Figure 1 – a) overmoulded organosheet panel; b) organosheet panel with no ribs (no injection)

This work is focused on modelling compaction-induced defects in overmoulded panels caused by the pressure difference between a contact surface and an injection cavity. The injection process starts after the organosheet has undergone compaction. Consequently, under real conditions, the wrinkle has already formed, and the highest surface pressure is reached before the injection begins (see Fig. 1.a). Due to this and the complexity of conducting a coupled thermo-mechanical analysis for a fluid-structure interaction problem, the injection phase was not considered in this work in order to estimate the wrinkle geometry under conditions of maximum pressure difference.

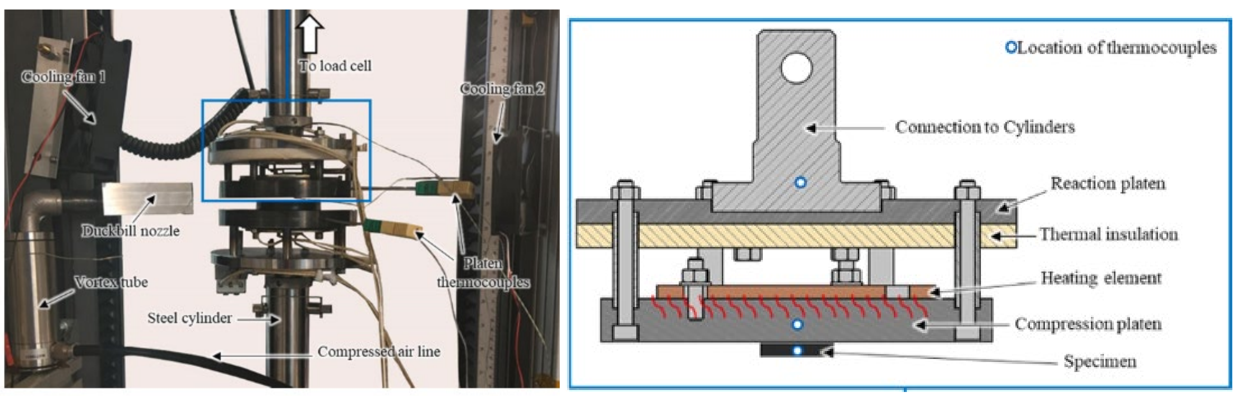
The proposed numerical tool predicts fibre angle deviation in the continuous fibre insert which occurs due to pressure differences during mould closure (see Fig. 1.b). The tool is based on the DefGen ProToCoL material model previously developed at the Bristol Composites Institute. While it was originally developed for thermoset composites, it also applies to thermoplastics [6]. To reduce the high computational cost of traditional ply-by-ply modelling, a homogenisation scheme [7] is used for the analysis.

Modelling approach

A novel framework is presented for modelling structures composed of soft, anisotropic, layered materials, optimised for computational efficiency to facilitate use in early design stages. This approach leverages the DefGen Protocol, a phenomenological material model developed by the Bristol Composites Institute.

The compaction behaviour of composite materials is fully defined by the dominating flow and deformation mechanisms occurring during manufacturing. During consolidation, two flow types are observed: percolation, where fluid is squeezed and bleeds out, and shear flow, where the composite behaves as a viscous fluid reinforced by inextensible fibres. The DefGen model is able to represent the characteristic features of both flows [8]. Recent advancements have transformed previously empirically fitted parameters into a physics-based relation [9]. These analytical expressions connect thickness evolution with temperature and pressure conditions, resin viscosity, and meso- and micro-level geometric properties of the reinforcement (such as volume fraction, fibre radius, ply width, and thickness). The model averages deformation through the ply thickness and incorporates through-thickness compaction and in-plane spreading. A transition criterion between flow modes is derived, assuming fibre convection stops when shear deformation at ply edges reaches a critical threshold. Such development introduces a compaction limit: beyond this point, fibres are tightly packed, and further compaction ceases. Before reaching this limit, squeezing flow is incompressible. Beyond this, the ply becomes fully compressible, with volume loss occurring due to bleeding flow.

The DefGen model has been used to model various manufacturing processes, including thermoset prepreg compaction [10], thermoplastics [6], defect simulation [7], [11], and automated fibre placement [12]. Recently, the model was transferred from a ply-by-ply to a homogenised approach. The laminate is constructed by iterative homogenisation of material blocks, and interfaces are modelled as weak discontinuities, behaving like plies without a dominant fibre direction. This method significantly improves computational efficiency, enabling analysis of large composite structures within reasonable computational time, which traditional ply-by-ply methods often struggle to achieve using standard hardware. To fully define the model for a given material, the parameters a (which governs the material's non-Newtonian response), b (which acts as an energy barrier controlling the resin flow through the fiber network), and k (which controls the permeability of the fibre bed) must be determined to characterise its physical behaviour during compression. A detailed mathematical formulation of the material model can be found in [9]. This set of parameters is to be retrieved from the experimental data for the considered material. The test setup used in this study (Fig. 2) includes compaction heater platens integrated into a compression test machine. A test specimen is put in between the plates and the predefined loading programme is executed to acquire material's compaction response necessary for material characterisation.



a **b**

Figure 2 – a) compression heater platens setup; b) detailed view of the top compression platen with a specimen.

The material used in this study was PA6 glass/nylon consolidated composite laminate (TEPEX Dynalite 102-RG600, fibre volume fraction 47%). Test coupons were laid up in a crucifix shape as shown in Fig. 3 to facilitate unrestricted material flow during compaction. Each coupon consisted of eleven plies connected with polyamide temperature-resistant tape securing the edges together due to the material's lack of tack.

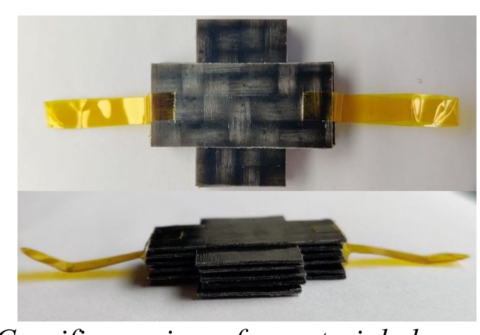


Figure 3 – Crucifix specimen for material characterisation

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In order to collect diverse set of data, four different load schedules were defined for the material characterisation. A two-stage parameter extraction framework previously developed in the Bristol composites institute [10] was employed to retrieve an optimal set of parameters for the DefGen Protocol material model. The resulting model's thickness output along with the experimental compaction response are shown in Fig. 4.

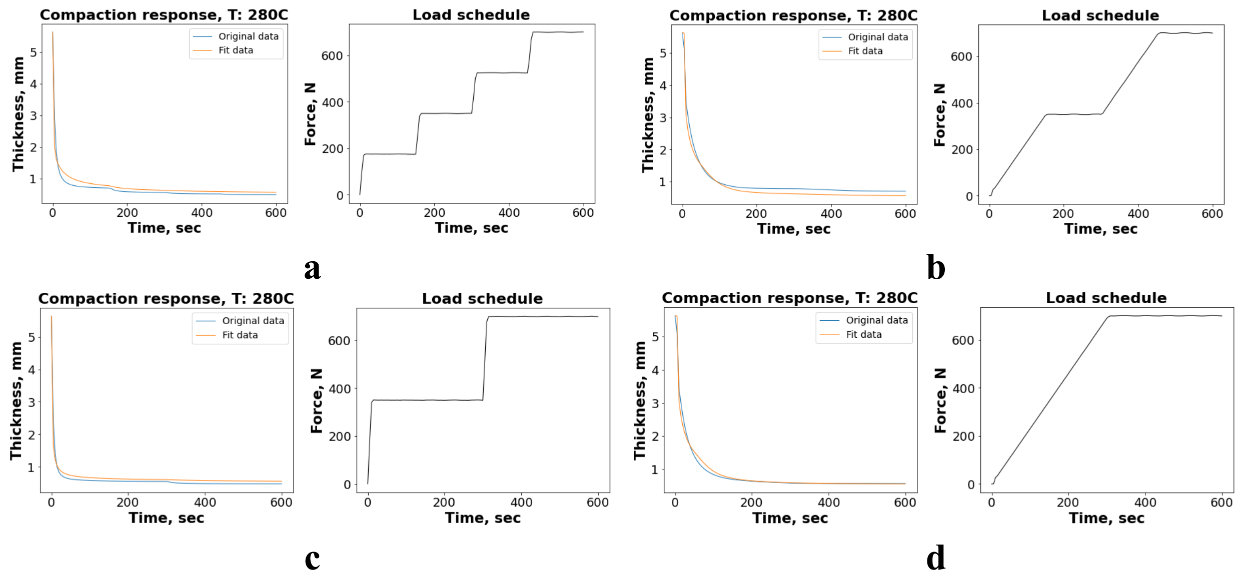


Figure 4 – Compaction response and material model fit. Example for 280C temperature. a)-d) test programmes designed for the material characterisation

The resulting material model parameters are presented in Table 1.

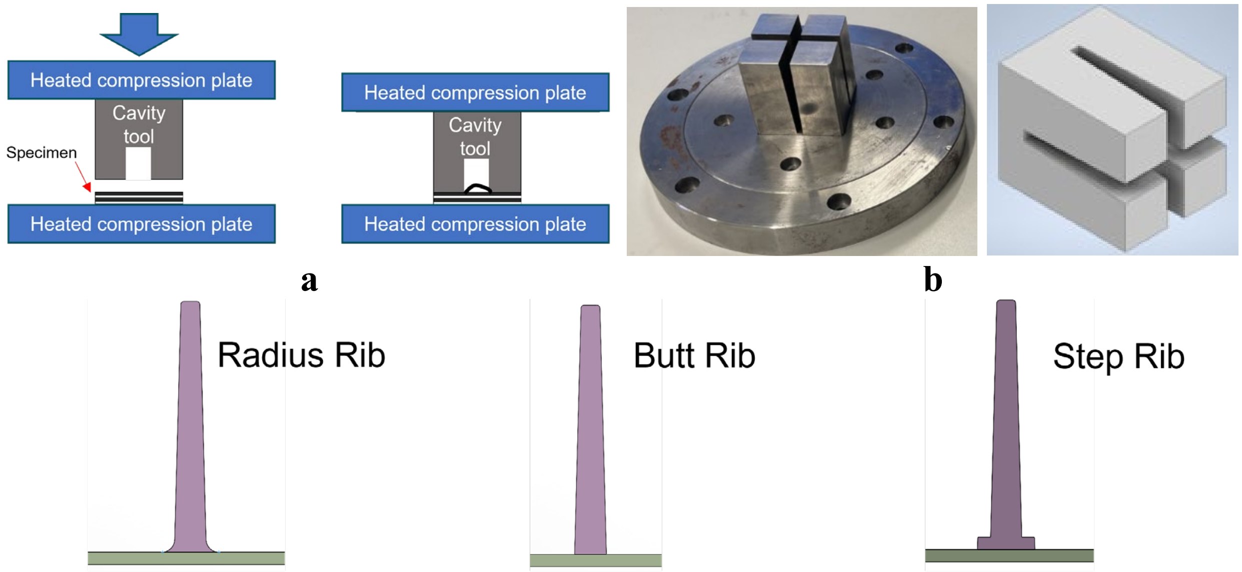
Table 1 – DefGen model parameters.

Temperature, C	Material model parameters		
	a	b	k
280	-0.489	-12.220	0.520
270	-0.549	-12.220	0.520
260	-0.583	-12.220	0.520
250	-0.649	-12.220	0.532
230	-0.745	-12.220	0.534
200	-0.933	-14.647	0.930

To validate the proposed modelling approach, it was applied to two case studies. The first case was to model the compaction and overmoulding effects of a small 25 x 25 mm coupons of the 2 mm-thick organosheet (PA6 glass/nylon). For this exercise, the existing compression test setup displayed in Fig. 2 was modified by attaching a metal cavity tool to the top compression plate as shown in Fig. 5.a. The cavity tool is designed to simulate a cross-shaped 5 mm-wide cavity (see Fig. 5.b). When it comes in contact with the top surface of the specimen, a pressure difference between the contact surface and the cavity occurs, causing a wrinkle to form, as shown in Fig. 5.a. The test was performed at a constant temperature of 230°C with a maximum compaction force of 300 N, corresponding to an average laminate pressure of 0.9 MPa (excluding the cavity from the contact area).

The second case focused on modelling a full-size organosheet panel manufactured in an industrial setting at the National Composites Centre (see Fig. 1.b). The same material was used as in the first case. Three distinct cavity shapes were introduced to observe the effect on the wrinkle formation (see Fig. 5.c): a 5 mm-wide butt joint (smooth contact-cavity transition), a 9 mm-wide radius joint (abrupt contact-cavity transition), and a 9 mm-wide step joint (abrupt contact-cavity transition). The compaction process was conducted at 200°C with a compression force of 5000 kN applied to the tooling.

Both the small coupons and the full panel were modelled using the proposed homogenisation approach, and the resulting geometries were then compared with the experimental data.



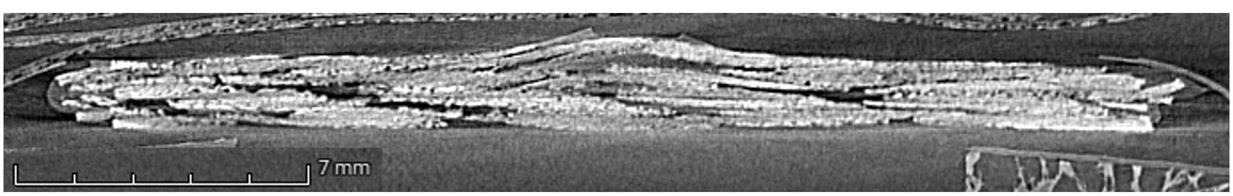
c

Figure 5 – a) schematic representation of the first case study, the specimen is placed inside heater plates with a cavity tool installed on the top plate; b) top heated compression plate with a cavity tool attachment (used for the first case study), close view of the cross-shaped cavity tool; c) explored rib types within the second case study: radius, butt, and step single/cross-shaped ribs

Results and discussion

The results of the first case study, including both experimental and modelling outcomes, are shown in Fig. 6. The measured wrinkle geometry (from the bottom surface of the coupon to the wrinkle's top) of the real coupon and the FE simulation are 2.35 mm and 2.25 mm, respectively, resulting in a total wrinkle height error of 4.3%.

It is important to note that small coupons are prone to resin bleeding during testing, as the experiments were conducted above the melting temperature with the edges of the coupon left unrestricted. Excessive compressive loads applied to such coupons can lead to void formation (visible in CT scans in Fig. 6.a) and dry fibre regions, which are not captured by the homogenised model. Despite these limitations, the proposed approach accurately predicts the wrinkle geometry within a reasonable error margin of less than 5%. Additional coupons are currently being processed for CT scanning to provide more data for further validation of the model.



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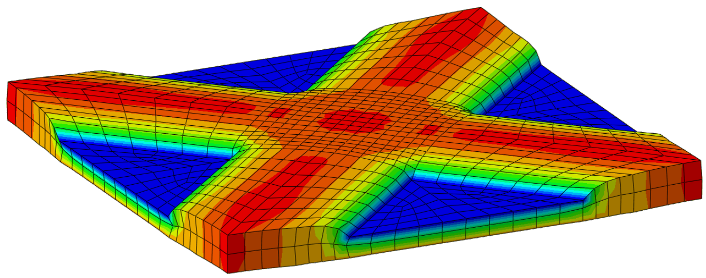
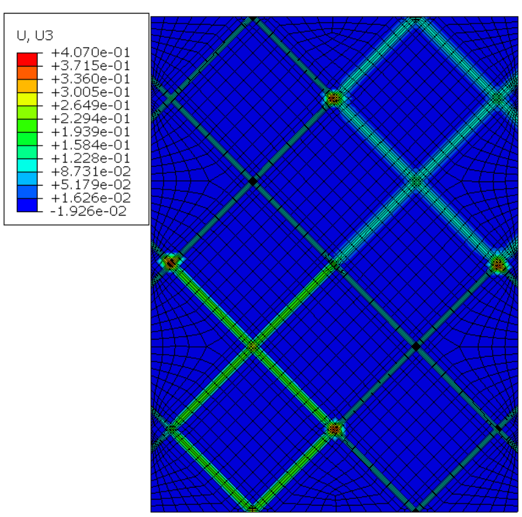


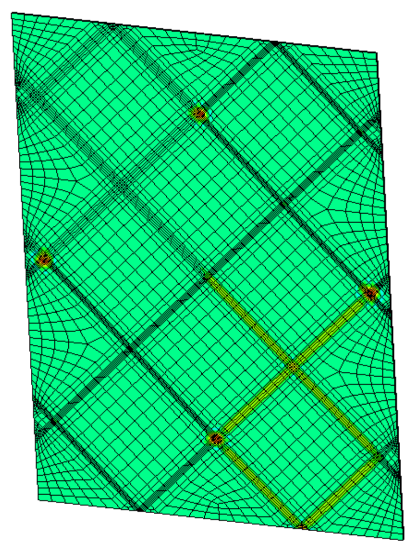
c

Figure 6 – First case study a) CT scan of the compacted specimen, cross section, full thickness of the laminate; b) top view of the compacted specimen; c) modelling results (vertical out-of-plane displacement)

The modelling results (vertical out-of-plane displacement, U3 mm, of the organosheet caused by the surface pressure difference) for the second case study are presented in Fig. 7. It can be clearly seen that the displacement profile varies across the different cavity/overmoulded rib types. The largest displacement was observed in the bottom-left region of the organosheet, corresponding to the 9 mm-wide step joint.



a



b

Figure 7 – Modelling results of the compacted organosheet, out-of-plane displacement (mm) due to the pressure difference between the tool's contact surface and the cavity (zero pressure due to no injection); a) top view (cavity side); b) bottom view

To compare the resulting geometries with the modelling outcomes, a set of cross-sections representing different rib types were cut out from the organosheet, and microscopy images were taken to analyse wrinkle characteristics. The comparison between the modelling and the experimental results is shown in Fig. 8. The registered wrinkle height errors were 3.9%, 3.4%, and 2.6% for the butt, radius, and step joint types, respectively. Notably, the total computational time for this case study was 15 minutes, significantly faster compared to the 5+ hours required for an equivalent ply-by-ply modelling approach.

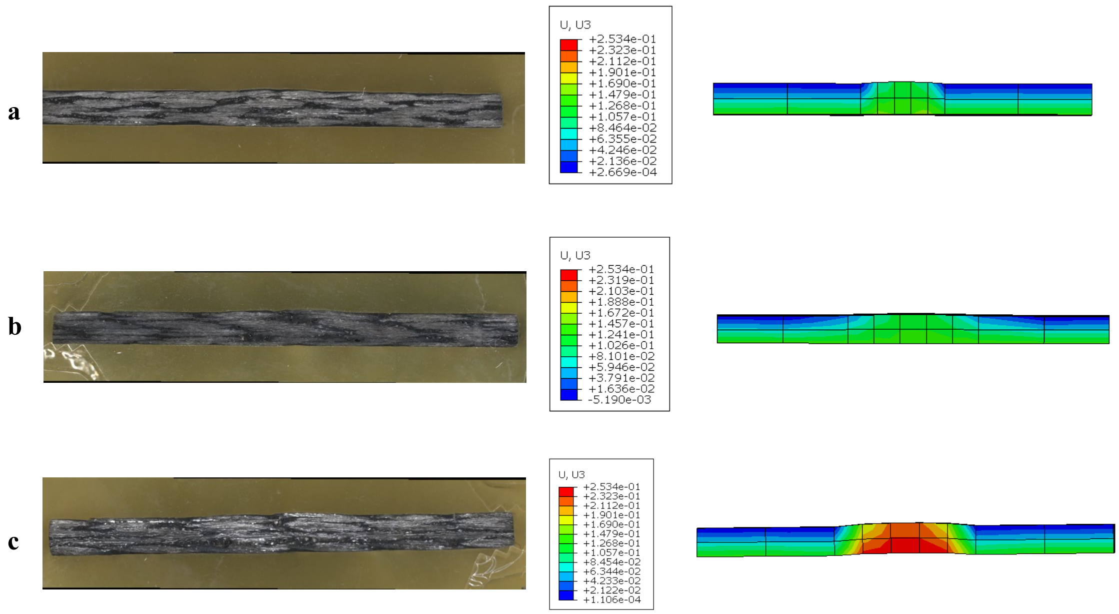


Figure 8 – comparison of the microscopy images of the organosheet's cross-sections (left) and modelling results (right); a) butt joint (5mm wide); b) radius joint (9 mm wide); c) step joint (9 mm wide).

Conclusions

A new computationally efficient design for manufacturing tool was developed that could allow removing some of the physical trials currently used for overmoulded panels in the industry. A series of characterisation tests for thermoplastic material were performed. The proposed model showcased an ability to handle large deformations in both small specimens and large structures within reasonable computational time. Error in wrinkle geometry estimation does not exceed 5%.

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