FLOW-INDUCED FIBRE COMPACTION IN A RESIN-INJECTION PULTRUSION PROCESS

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ABSTRACT

Resin-injection pultrusion (RIP) processes rely on high resin pressure for efficient impregnation. This study investigates the effects of flow-induced fiber compaction in RIP, considering temperature measurements and material characterization. Governing equations are derived, and a novel numerical framework is presented. The analysis reveals that fiber compaction reduces flow resistance, facilitating resin impregnation. In the case study, fiber compaction near the inlet resulted in upstream movement of the flow front and increased exit pressure. Furthermore, impregnation occurred over a longer distance due to increased fiber volume fraction at the profile center. The compaction response of the fiber material remained largely independent of injection pressure magnitude. This research contributes to understanding material behavior and improving RIP processes.

1 INTRODUCTION

Pultrusion is a continuous and cost-effective process used for manufacturing fibre-reinforced polymer (FRP) composite profiles with a constant cross-section. The term "pultrusion" is derived from the words "pull" and "extrusion," emphasizing its continuous nature. Unlike other techniques, pultrusion is the only truly continuous processing method for moulding fibre-reinforced plastics. It has gained popularity in the industry due to its high output and relatively low cost compared to other FRP manufacturing technologies. The production output of pultruded products has experienced significant growth, especially in the European FRP market.

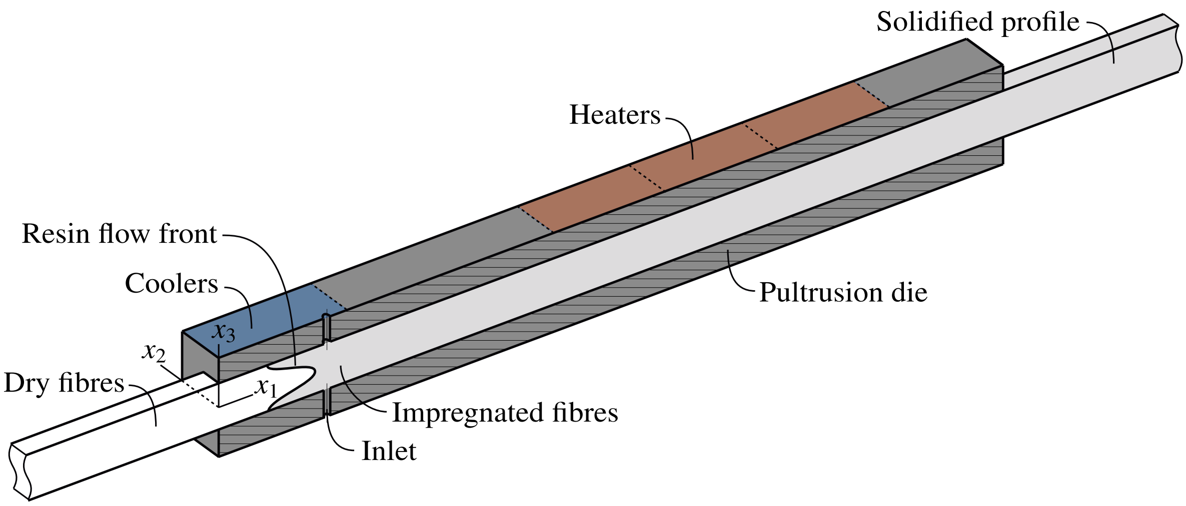

Figure 1: A schematic of a resin-injection pultrusion die. In the figure the material flows from left to right. This figure was taken from [1]

In the resin-injection pultrusion (RIP) process, the fibre material is pulled through an impregnation chamber, followed by a heating die. During the impregnation stage, the resin system saturates the fibre reinforcement, and heating is applied to accelerate polymerization during the curing process. To achieve high production output, the resin system is typically injected at a high pressure. Unidirectional and textured glass fibre rovings are commonly used as fibre reinforcements in RIP processes.

Studies on material characterization have shown that the fibre volume fraction can vary by approximately 20% within the compaction pressure range typically applied in RIP processes [2]. The fibre volume fraction plays a crucial role in determining the product's performance and material flow in composite manufacturing. It influences factors such as permeability, thermal conductivity, process-induced stress and deformation, as well as the elastic properties of the pultruded part after complete curing. Hence, the hypothesis of this work is that flow-induced fibre compaction affects the material flow in RIP.

Numerical modelling has become an integral part of modern manufacturing engineering, enabling the analysis and prediction of various processing steps. The pultrusion process has been the subject of extensive research in numerical modelling for over three decades. For example, researchers have developed coupled thermo-chemical numerical models to predict temperature build-up and cure degree in pultrusion [3,4]. These models have considered different types of thermosets and thermoplastics resin systems, as well as natural reinforcements and non-oil based resin alternatives [5].

Fibre compaction and its effects on material flow have been extensively studied in various composite manufacturing technologies. The compliance of fibrous materials and fibre beds has been shown to exhibit nonlinear, inelastic, and time-dependent behavior. Compaction tests have demonstrated irreversible deformation, viscoelastic effects, inter-ply friction, and cyclic softening in fibre beds. Moreover, when the fibre bed is saturated with a fluid, such as a silicone oil, its compliance increases due to lubrication [6]. Flow-induced fibre compaction is often described using Terzaghi's principle, which is adopted from soil mechanics. This principle accounts for the viscous drag of a fluid flowing through a porous medium. The objective of this study is to investigate flow-induced fibre compaction in an industrial RIP process and evaluate its impact on resin flow, heat transfer, and curing. In this research, we aim to develop and solve the governing equations specifically for flow-induced fibre compaction in RIP.

2 METHOD

Darcy's law (Equation 1) describes the relationship between resin velocity ($\boldsymbol{v_r}$) and fibre velocity ($\boldsymbol{v_f}$) in the flow of a single-phase fluid through a compliant porous medium. This follows the relationship in the studies by Hubert et al. [7] and Michaud and Månson [8]:

$$\boldsymbol{v_r} - \boldsymbol{v_f} = \frac{\boldsymbol{K}}{\mu(1 - V_f)} \boldsymbol{\nabla} p \tag{1}$$

where $\boldsymbol{K}$ is the permeability tensor, μ resin viscosity, V_f is the fibre volume fraction, and p is the resin pressure.

To ensure mass conservation of fibres and resin, the divergence of the velocity field should be balanced with the variations in fibre volume fraction and porosity. In fluid mechanics, which often involves significant bulk motion, Eulerian approaches are commonly used to relate the rate of change to a fixed point in space. By employing the material derivative and transforming the equations, we can simplify them into a single conservation equation [9]:

$$\boldsymbol{\nabla} \cdot \left(V_f \boldsymbol{v_f}\right) + \boldsymbol{\nabla} \cdot \left(\left(1 - V_f\right)\boldsymbol{v_r}\right) = 0 \tag{2}$$

In order to establish stress equilibrium in a fibre material saturated with unsolidified resin, the total stress ($\boldsymbol{\sigma}$, sometimes referred to as the effective stress) of the system was divided into the fibre stress ($\boldsymbol{\sigma_f}$) and the resin pressure, in accordance with Terzaghi's principle [10].

$$\boldsymbol{\sigma} = \boldsymbol{\sigma_f} - p\boldsymbol{I} \tag{3}$$

where $\boldsymbol{I}$ is the identity matrix.

A constitutive relation was employed to establish the relationship between the stress state and the strain state of the fibre bed.

$$\boldsymbol{\sigma_f} = \boldsymbol{C}\boldsymbol{\epsilon_f} + \boldsymbol{\sigma_{f0}} \tag{4}$$

where $\boldsymbol{C}$ is a matrix that holds the constitutive relation and $\boldsymbol{\epsilon_f}$ is the strain state of the fibre material.

Hooke's law was employed to model the constitutive relation following a small-strain approximation of the deformation state of the fiber material. To establish this approximation, the deformation behaviour of the fibre material was linearised using a first-order Taylor approximation based on the stress and strain state of the fibre bed upon entering the die [2,9].

The finite element method in COMSOL Multiphysics software was used for solving and discretizing the governing equations. Second-order elements were used for the resin pressure and fibre deformation. Stabilization techniques, the streamline and crosswind diffusion schemes, were applied to handle convective terms. The mesh size ranged from 5.25 mm to 100 mm, without performing mesh sensitivity analyses. Computational times on a workstation PC with 6-core i7-8300K @3.7 GHz and 64 GB RAM were approximately 15-25 minutes when using a mesh containing around 250K degrees-of-freedom. Material and process parameters are given in [9]. The material properties were based on our characterisation studies in [2,11].

3 RESULTS AND DISCUSSIONS

Figure 2 illustrates the stationary resin pressure, while Figure 3 shows the development of fibre stress (the 33-component of σ_f, i.e., the through-thickness direction of the profile) and fibre volume fraction at the profile's center and edges. Figure 4 (cf. "10 bar") provides a 2D representation of these variables near the resin inlet, along with the resulting permeability (the 33-component of $\boldsymbol{K}$).

As the resin pressure increased towards the inlet (with a positive gradient), the fibre stress increased as well. Consequently, the fibre volume fraction decreased near the resin inlet but increased at the center of the profile, following the pattern of fibre stress. A decrease in the fibre volume fraction near the inlet lead to increased permeability in that region, approximately by 30% as seen in Figure 3 (cf. "10 bar"). This decrease in resistance enables easier resin injection. Hence, we can conclude that fibre compaction facilitates resin impregnation, and disregarding it underestimates the impregnation flow. This is further supported by the downstream shift of the flow front by approximately 3 cm (at the center, cf. "10 bar" in Fig. 3) and the decrease in resin pressure towards the die-exit by approximately 24% (from 6.3 to 4.8 bar, cf. Fig. 3) when fibre compaction is neglected.

We also considered the possibility of fibre detachment from the die-walls, which has been previously suggested in related studies [12]. Such detachment creates an open channel, known as a "race track," between the fibre material and die-wall. This race track offers a low-resistance path for resin flow and significantly impacts resin flow and the position of the flow front, as demonstrated by Bickerton and Advani [13] and others.

Figure 4 illustrates that increasing the injection pressure has limited effects on fibre stress, fibre volume fraction, and permeability. Although the increased pressure causes the flow front to move upstream, affecting a larger zone, the extremes of fibre volume fraction (smallest and largest observed values) remain largely unaffected.

The limited impact of resin pressure on fibre stress and fibre volume fraction may seem surprising at first. Intuitively, one might expect that increasing the injection pressure would lead to more fibre compaction due to the higher applied force. However, this response can be explained by considering the overall conservation of fibre material and resin entering and exiting the pultrusion die. As long as there is no resin overflow and the profile is fully saturated, the injection pressure does not affect the amount of fibre material and resin entering and exiting the die. Only the fibre volume fraction and the profile-advancing pulling speed can alter this balance, while the influx of resin remains unchanged. According to Darcy's law and our derivation from stress equilibrium and Terzaghi's principle, the pressure gradient governs the transfer of load between the resin system and fibre material. Thus, the limited effects on fibre compaction in relation to injection pressure can be attributed to the consistent influx of resin.

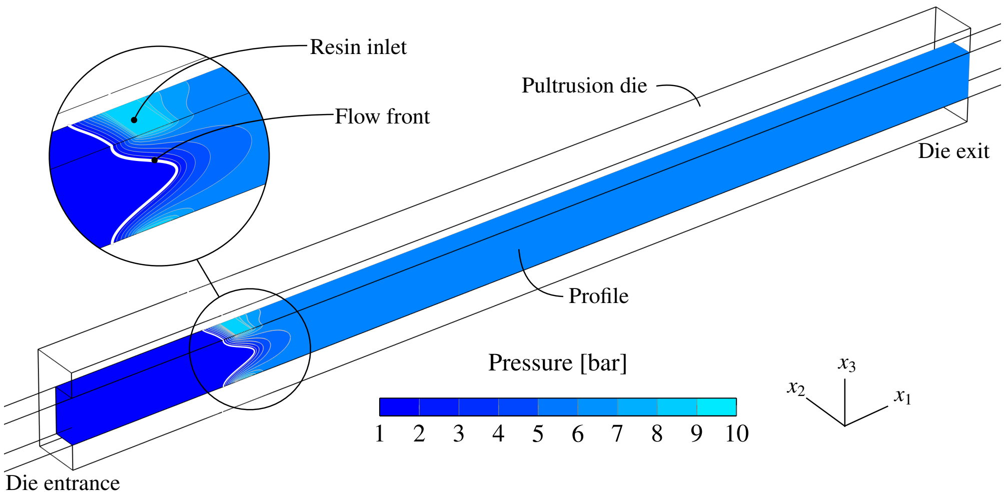

Figure 2: The stationary resin pressure field, incl. location of the flow front.

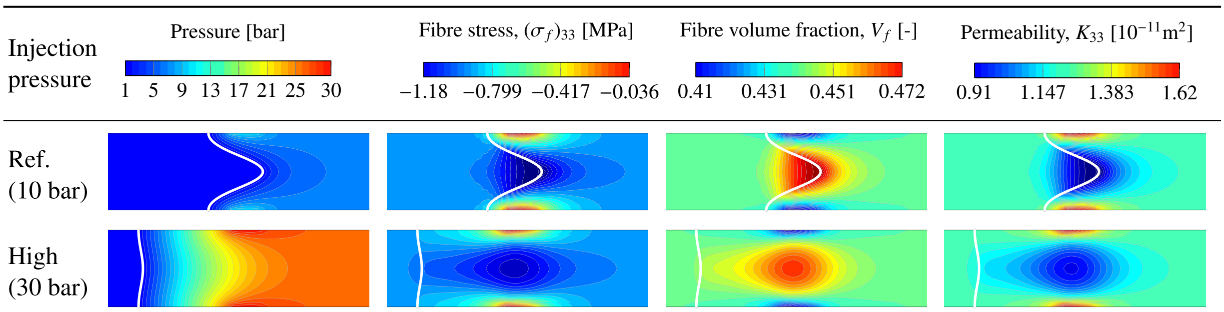

Figure 3: The stationary solution for resin pressure, fibre stress, fibre volume fraction, and permeability for a low (10 bar) and high injection pressure (30 bar)

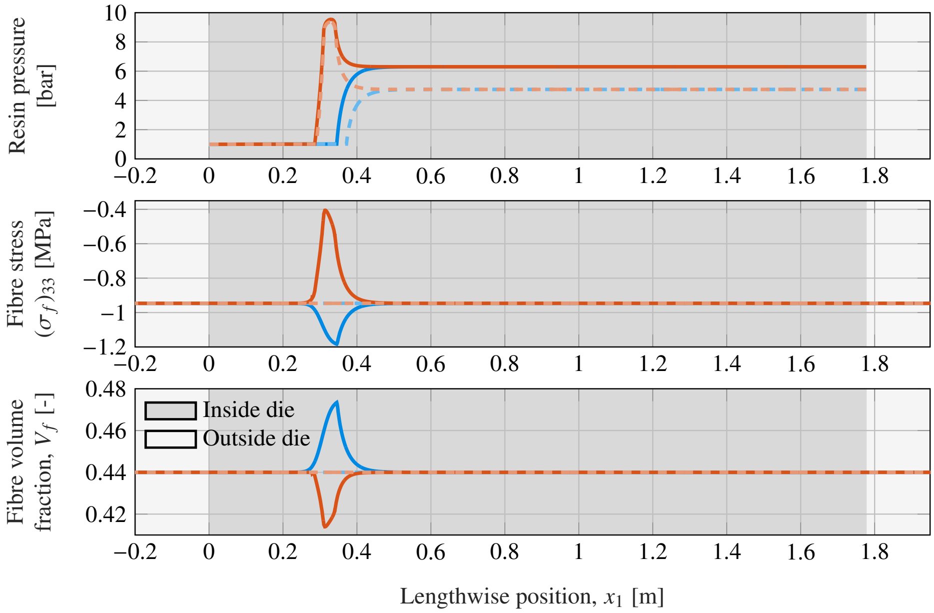

Figure 4: The stationary solution for resin pressure, fibre stress, and fiber volume fraction at the profile centre (blue) and edge (orange). The full lines denote results with compaction and the dashed lines without.

4 CONLCUSION

In this study, we introduced a numerical framework to analyse flow-induced fibre compaction in resin-injection pultrusion (RIP) processes. The key findings and conclusions from the parameter studies conducted using this framework are as follows:

- Flow-induced fibre compaction led to a decrease in the fibre volume fraction near the resin inlet, while an increase was observed at the centre of the profile;
- Incorporating fibre compaction facilitated resin flow by increasing permeability near the injection points, resulting in a deeper flow front; and
- The magnitude of the injection pressure had minimal effect on fibre stress and the associated fibre volume fraction, as long as the profile remained fully saturated and there was no resin overflow.

Considering that this study employed a simple linear elastic model to characterize the constitutive behavior of the fibre material, future research could explore the use of more advanced constitutive laws that account for irreversibility, resin saturation, and time-dependency. Additionally, conducting further parametric studies on resin viscosity, fibre volume fraction, and profile-advancing pulling speed would enhance the understanding of flow-induced fibre compaction in RIP.

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