MODELLING THE EFFECT OF NON-UNIFORM FIBRE DISTRIBUTION ON THE CURING BEHAVIOUR IN RESIN INJECTION PULTRUSION

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Abstract

In the present study, numerical modelling has been used to assess the influence of non-uniform fibre distribution on the temperature and degree of cure field in Resin Injection Pultrusion. The fibre distribution of an industrial glass-fibre/polyutherene profile with a square cross-section was investigated using the burn-out process and light optical microscopy. Both characterization techniques showed non-uniform fibre distributions. The characterized fibre distribution trends were implemented in a numerical model and compared with the corresponding uniform case. The results show a significant change in the cure behavior from solely outside-in curing in case with a uniform fibre distribution to inside-out curing for the center part of the profiles with non-uniform fibre distribution.

1. Introduction

Composite materials, in the form of Fiber-Reinforced Polymers (FRP), are known for their high strength-to-weight ratio and orthotropic material properties. The production of FRPs comprises very complex interactions between part design, performance and the manufacturing process, hence being historically accompanied by inexpedient high production cost. However, the technological development within composites manufacturing has decreased this cost and thus increased the usage of FRPs. A classical example of composites manufacturing is the Resin Injection Pultrusion (RIP) process. Fig. 1 illustrates the RIP process, which is a continuous, automated process for production of profiles with constant cross-section.

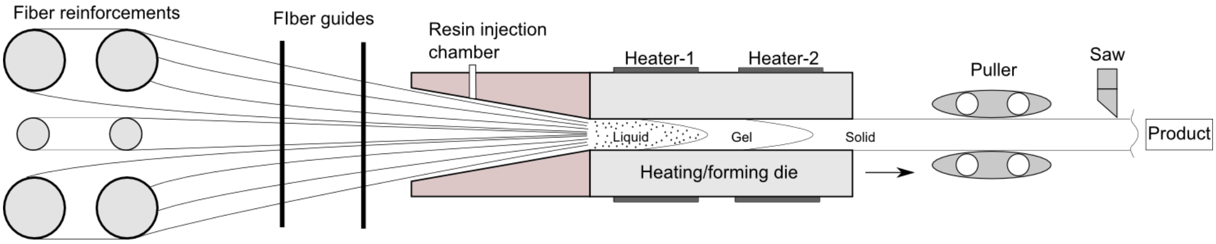

Figure 1. Schematic representation of the Resin Injection Pultrusion process.

Several studies of the RIP process are found in literature, e.g. investigating the temperature and Degree of Cure (DoC) field inside the laminate [1-3] or the resin injection impregnation [4,5], all of which are important aspects, considering high quality pultruded products. In the study by Carlsson et al. [6], an experimental investigation of the pultrusion process showed a trend of enhanced non-uniform fibre distribution with increasing pultrusion speed. However, the effects of such non-uniform fibre distribution during production is not included in the numerical studies found in literature. Hence, the present study will focus on characterizing the actual fibre distribution in a pultruded profile and subsequently investigate the effects of non-uniform fibre distribution on the temperature field and DoC field inside the heating/forming die during pultrusion (cf. Fig. 1).

2. Methodology

The effects of non-uniform fibre distribution on the pultrusion process are investigated by numerical modelling. The cross-sectional fibre distribution is characterized using burn-out tests and Light Optical Microscopy (LOM). The following two subsections will introduce the fibre distribution characterization and numerical implementation, respectively.

2.1 Fibre Distribution Characterization

The fibre distribution characterization by the burn-out process was carried out following the work by Abdalla et al. [7]. The burn-out tests were conducted using two different sectioning patterns as schematically illustrated in Fig. 2a and 2b.

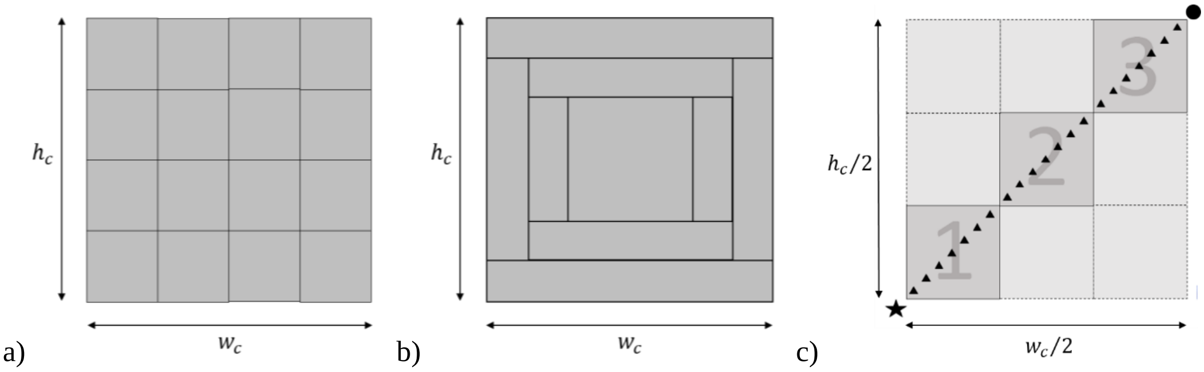

Figure 2. Schematic illustration of the discrete cross-sections for fibre distribution characterization. a) and b) Sectioning for burn-out tests, c) LOM imaging along diagonal. Where $w_c = h_c$ are the width and the height of the composite profile, respectively.

For the LOM investigations, three samples along the diagonal (see Fig. 2c) were mounted and prepared by SiC paper polishing down to grit 4000 followed by 3µm diamonds on DAC cloth by Struers. Seven micrographs for each of the three samples were obtained (see Fig. 2c) using x5 magnification on an Olympus GX41 microscope with a mounted Leica DFC450 camera. The subsequent image analysis was conducted in Matlab following previous work by Klingaa [8]. Both characterization studies are to be considered preliminary and the average fibre volume fraction was therefore normalized and the trends observed were simplified.

2.2 Numerical Method

The pultrusion domain used for modelling is illustrated in Fig. 3 and comprises one quarter of the heating/forming die and the composite profile.

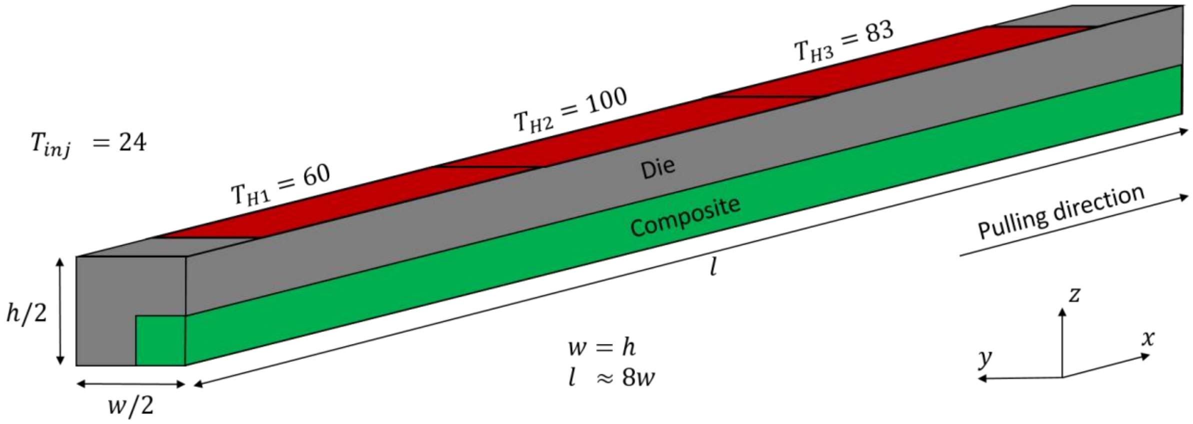

Figure 3. A quarter of the heating/forming die (cf. fig. 1) with normalized process temperatures and relative geometry ($w = 2w_c$; cf. Fig. 2).

The governing equation for the numerical model is the energy equation in three dimensions assuming constant material properties and advection solely in the pulling direction (cf. Fig. 3). Hence, the energy equation becomes

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + S \tag{1}$$

where t is the time in $[s]$; T is the temperature in $[°C]$; ρ is the effective density in $\left[\frac{kg}{m^3}\right]$; c_p is the effective specific heat in $\left[\frac{J}{kg \cdot K}\right]$; k is the effective thermal conductivity in the spatial directions (x, y, z) in $\left[\frac{W}{m \cdot K}\right]$ and $[m]$, respectively; and S is a volumetric source term in $\left[\frac{W}{m^3}\right]$ used for including the exothermic heat released due to curing [2,9]. The source term is governed by the cure kinetic model described in [8]. The domain illustrated in Fig. 3 is discretized using the finite volume method, coupling neighboring control volumes using thermal resistances [10]. The convective terms are discretized using a 3-point central difference scheme while the advective term is discretized using a 2-point upwind scheme; hence ensuring stability [2,8]. Initially at $t = 0$, all control volumes are set to ambient conditions. At $t > 0$, a Dirichlet boundary condition is imposed at the inlet where the DoC is set to 0 (uncured resin), assuming complete wet-out of the fibre preform. The system of equations are solved using the Alternate Direction Implicit method, modified by Douglas and Gunn (ADI-DG) [9,11].

3. Results and Discussion

The characterization trends observed are presented together with the numerical predictions of cure behavior in section 3.1. The changes in cure behavior as a function of fibre distribution are then discussed in section 3.2.

3.1 Results

Examples of micrographs from LOM showing the lowest and highest fibre fraction observed are given in Fig. 4.

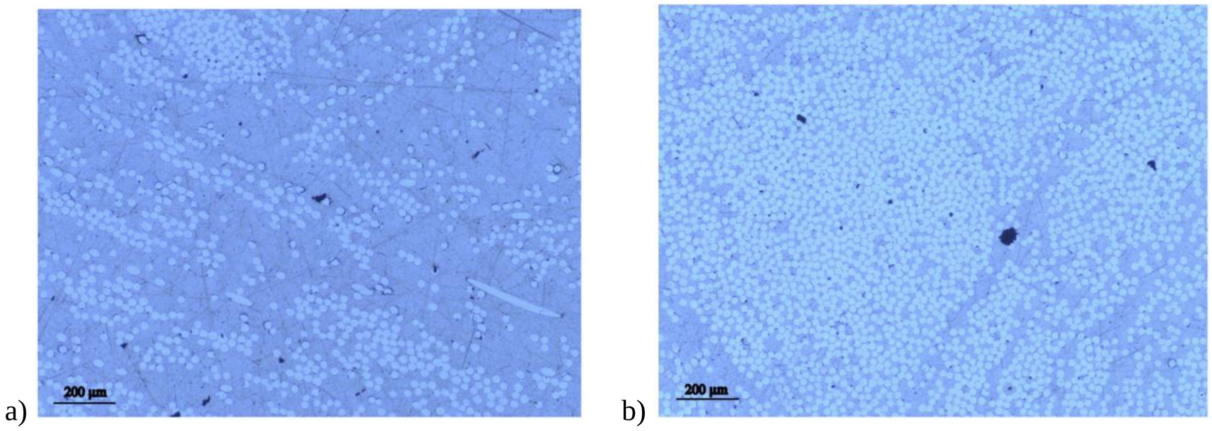

Figure 4. Micrographs from LOM investigations showing: a) Low fibre volume fraction. b) High fibre volume fraction. $(V_f^b \approx 2 \cdot V_f^a)$.

From Fig. 4 it should be noticed how the local fibre volume fraction can vary by up to a factor of 2 between lowest and highest fibre volume fraction. Considering the burn-out tests (cf. Fig. 2a and 2b) an increasing fibre volume fraction from the center and outwards was observed, while the LOM investigations (cf. Fig. 2c) indicated a more fluctuating fibre distribution. The characterized distributions were simplified as described in section 2.1. The resulting fibre distributions are depicted in Fig. 5.

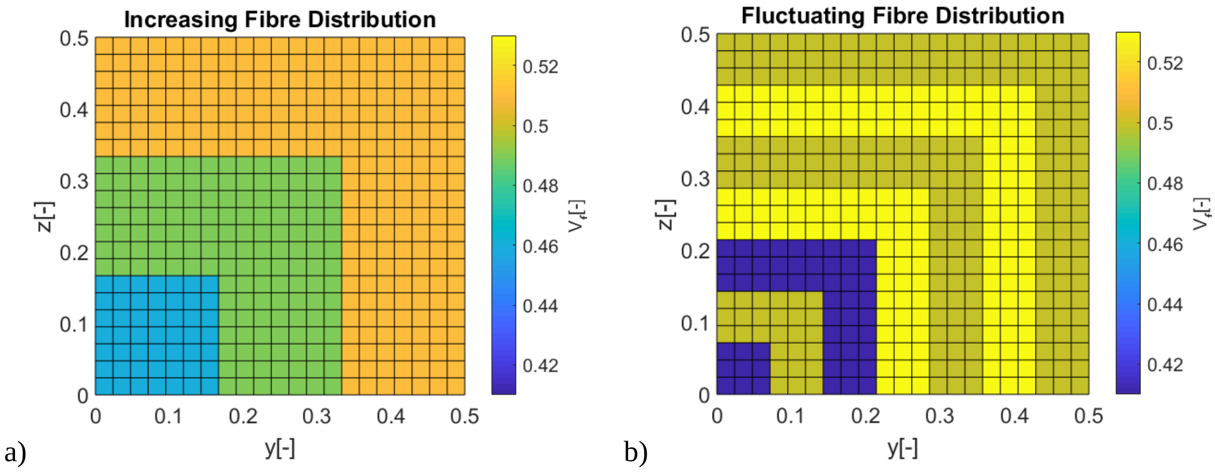

Figure 5. Normalized fibre distributions inspired by experimental investigations (one quarter of the profile with center in origo): a) Trend from burn-out tests, b) Trend from LOM.

The fibre distributions illustrated in Fig. 5 both have a mean fibre volume fraction of 0.5 and the three separate areas in Fig. 5a have the same fibre volume fractions as the average over the corresponding areas in Fig. 5b. This ensures comparability of the simulation results for the 3 case studies: 1) A uniform fibre volume fraction of 0.5, 2) An increasing fibre distribution (cf. Fig. 5a), and 3) A fluctuating fibre distribution (cf. Fig. 5b).

The steady state numerical predictions of temperature and DoC for the three fibre distribution cases introduced above are illustrated in Fig. 6 and Fig. 7, respectively. From Fig. 6, it should be noticed how the pultruding nature of the RIP process imposes an advected temperature field in the pulling direction. Fig. 7 illustrates the DoC field along the middle of the tool (x = 0.25-0.65), which is where most of the curing is taking place. The curvature of the DoC contours follow the same trends as the corresponding temperature contours (compare Fig. 6 and Fig. 7). This is not surprising since the temperature and DoC are strongly coupled via the cure rate and heat generation as described by the authors in [2,9].

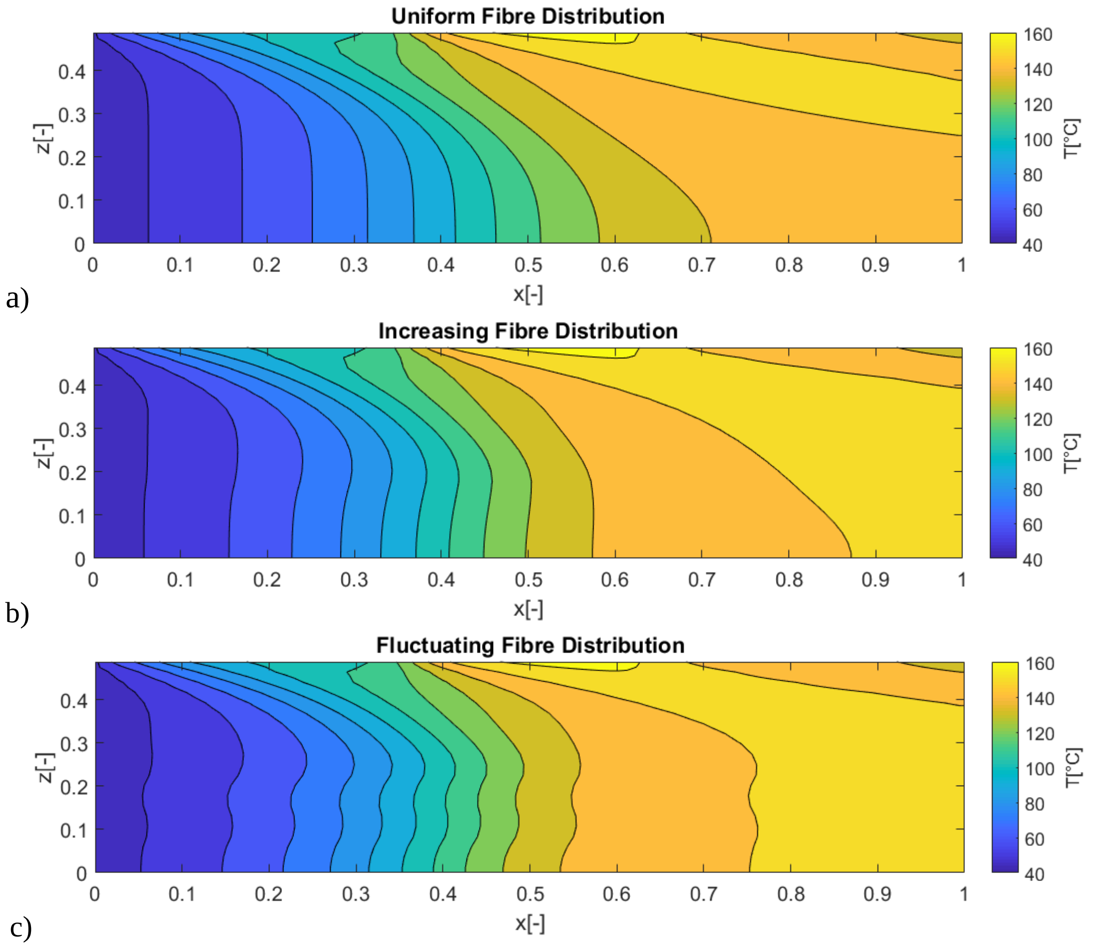

Figure 6. Steady state temperature field predictions inside the composite profile (y = 0) for: a) Uniform fibre dist. b) Increasing fibre dist. c) Fluctuating fibre dist. (cf. Fig. 3)

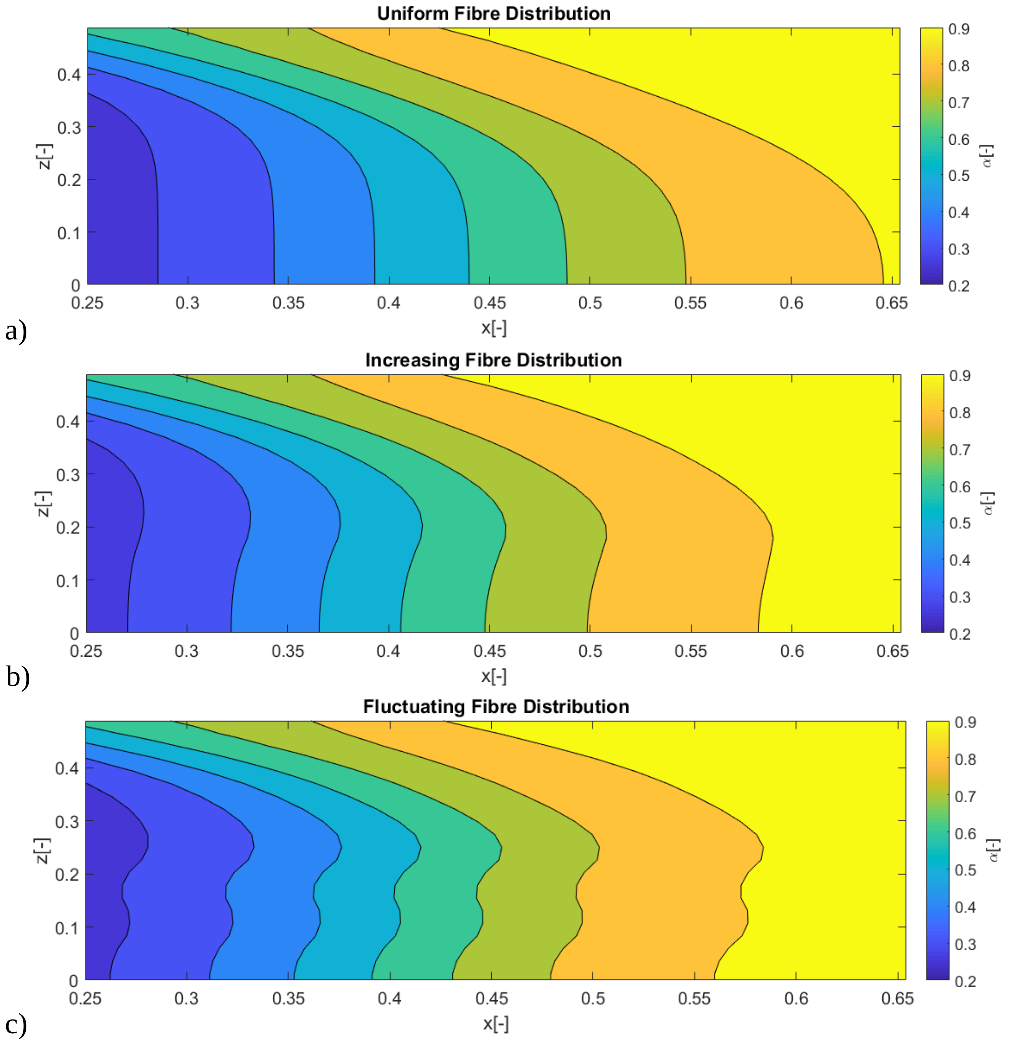

Figure 7. Steady state degree of cure field predictions inside the composite profile $(y = 0)$ for: a) Uniform fibre dist. b) Increasing fibre dist. c) Fluctuating fibre dist. (cf. fig. 3)

3.2 Discussion

Comparing the steady state temperature fields near the profile/die interface (x~0.45-0.5) for the three different fibre distributions no significant differences are observed (cf. Fig. 6). This is most likely because the temperature in this region is highly governed by the heater conditions. However, this trend does actually apply, not only for the surface of the profile, but also for the whole outer half of the profile (z~0.25-0.5). The similarity in temperature field in the outer half of the profile might still be a result of the heaters combined with a similar mean fibre volume fraction in that area (cf. section 3.1). Though, when considering the temperature fields of the center part of the profile, the change in fibre distribution has quite a significant effect (cf. Fig. 6, z~0-0.25). In the case of a uniform fibre distribution, the center of the profile is the last part of the profile to be heated up, hence cured (cf. Fig. 6a). This is not the case for the two non-uniform cases (cf. Fig. 6b and 6c). The reason for the increased heating of the center part of the profiles with non-uniform fibre distribution is most likely because a low fibre volume fraction is equivalent to a high volume fraction of matrix/resin and therefore a higher amount of heat generated due to exothermic curing.

As stated in the previous section, the degree of cure field and the temperature field are closely coupled and the major trends described above, regarding the temperature field, do therefore also hold for the DoC field (compare Fig. 6 and 7). However, the change in cure field is thought to have a more adverse effect on the final quality of the pultruded profile, since the chemical cure shrinkage is dominating the thermal expansion during curing [8,12]. Hence, the degree of cure field would be relatively more important when considering residual stresses and distortions [13]. In addition it should be noticed how the DoC gradients through the thickness seem to be more severe as compared to the corresponding temperature gradients (compare Fig. 6 and 7). From Fig. 7a, it should be noticed how the profile with a uniform fibre distribution is curing outside-in through the whole thickness, while this is only true for the outer half of the profiles with varying fibre distribution (cf. Fig. 7b and 7c). The reasoning for this follows the argument presented above regarding the temperature field. However, looking at the DoC field of the inner half of the profile it is clear how the cure behavior changes to inside-out in the two cases with varying fibre distribution (cf. Fig. 7b and 7c). Furthermore, it should be noticed how the inner half of the profile with fluctuating fibre distribution also has local swapping of cure behavior, even though the overall trend is inside-out. Such gradients can presumably cause local residual stresses, which might impose an increased risk of local defects, e.g. cracks [13]. In addition, it is assumed that local changes in effective mechanical properties due to non-uniform fibre distribution might further increase the risk of process related defects.

4. Conclusion

In the present study, numerical modelling has been used to assess the influence of non-uniform fibre distribution on the cure behavior in Resin Injection Pultrusion of an industrial glass-fibre/polyutherene profile. The fibre distribution over the square cross-section was investigated using the burn-out method and light optical microscopy (LOM). The burn-out tests indicate an increasing fibre volume fraction towards the surface of the profile, while the LOM investigations showed a somewhat more fluctuating pattern of fibre distribution, though the overall trend was similar to the burn-out tests (relatively low fibre volume fraction in the interior). The characterized fibre distribution trends were implemented in the numerical model and a comparative study was conducted. The results show a significant change in the cure behavior from solely outside-in to inside-out curing for the center part of the profiles with non-uniform fibre distribution as compared to the regular case assuming a uniform fibre distribution. The case with fluctuating fibre distribution showed additionally advanced cure gradients compared with the simple increasing fibre distribution. Further studies characterizing fibre distributions are recommended in order to validate if such fibre distributions are representative for a given pultruded profile. In addition, a more holistic numerical analysis is recommended, e.g. including the effect of non-uniform fibre distribution on effective mechanical properties and hence analysis of residual stresses and distortions.

Acknowledgments

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