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FABRIC COMPACTION AND FIBRE VOLUME FRACTION EVALUATION FOR VACUUM-ASSISTED RESIN INFUSION MODELLING

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Abstract

To consistently achieve high-quality and reliable composite laminates, reducing the defects introduced while manufacturing is crucial. One of the methods to help is obtaining an optimal infusion strategy that considers the local compressed state during the vacuum infusion process. To create a unique digital twin for infusion processing planning, both accurate and practical methods must be used to obtain the geometry of the preform. This study has considered blue-light scanning, digital image correlation and laser sensor measurements for non-destructive in-situ fibre volume fraction assessments. The obtained results have also been compared with post-mortem burn-off testing of specimens and subsequently evaluated for filling time calculations with PAM-RTM compared against the actual filling duration.

1. Introduction

Wind turbine rotor blades are usually made of fibre-reinforced composite materials that are manufactured by vacuum infusion processes. Manufacturing procedures can significantly influence the strength and lifetime of wind turbine blades. In the first year of operations and for wind turbines after five to ten years, wind turbine failures and downtimes are mainly caused by manufacturing defects, as illustrated by Mishnaevsky [1] and Boopathi et al. [2]. The manufacturing flaws include, among others, porosity, debonding, delaminations and heterogeneities (resin-rich regions and dry spots). Thus, the quality and consistency of the vacuum infusion process are crucial for reliable wind turbine blade operations. Infusion strategy is one of the most essential issues to pay attention to during manufacturing, as this can eliminate the development of resin-rich regions, dry spots and keep the cycle time at a minimum. Wrongly chosen infusion schemes may lead to manufacturing flaws, which will later lead to cracks and delaminations [2]. Moreover, as vacuum-assisted resin infusion is highly dependent on personnel, waviness and wrinkling may occur during the layup, especially in geometrically complex zones with stiff panels, which also affects the propagation of the resin. Lastly, an improved infusion strategy helps save time, increases production capacity, and increases manufacturing reliability. With proper infusion, there can be a significant reduction of initial flaws, meaning less of the common post-production blade repair is needed.

Simulation tools can help in the design, prediction, and control of infusion processes for large and challenging-to-manufacture composite structures, such as modern wind turbine blades with more than 100 m in length and root diameters of more than five meters [3]. The governing parameters to model the infusion processes accurately are the local pressure gradient, resin viscosity, and reinforcement fabric permeability. Permeability decreases as the fibre volume fraction increases and can be very challenging to estimate (especially as it can vary throughout different regions and during the infusion itself).

The fibre volume fraction of the preform is used to assess critical areas with an under- or over-compressed state. Many research groups have been focused on the prediction of resin propagation and laminate fibre volume fraction changes in VARTM processes, both during [4 – 6] and after the infusion [7, 8]. For experimental validation of such models, it is necessary to assess the thickness of the laminate to calculate the fibre volume fraction. Different in-situ methods can be used to create a digital replica of a preform geometry and can be generally divided into two groups: point measurement and field measurement techniques. Point measurement methods typically consist of laser sensors [9, 10] and Linear Variable Differential Transformers (LVDT) [7, 11], whereas field measurements can be obtained by digital image correlation (DIC) [4, 5, 12, 13] or other scanning methods [6]. As was pointed out by Yalcinkaya et al. [6], obtaining the full region of interest is preferable over the local measurement methods, but unfortunately, it is not always possible, especially for large-scale applications.

With knowledge of the fibre volume fraction and an experimental permeability curve, liquid composite moulding (LCM) simulations can help to predict the resin flow behaviour during manufacturing. However, for VARI processes, the fibre volume fraction can vary significantly before, during, and after manufacturing, especially on a larger scale. Therefore, it is crucial to obtain the correct initial fibre volume fraction values for the infusion simulation using robust methods that can guarantee good results with less effort.

In this paper, different fibre volume fraction assessment techniques are compared, including both non-destructive in-situ methods (DIC, laser sensor, and blue-light scanning) and destructive (burn-off method). The results are further used for infusion process modelling to predict filling time.

2. Fibre volume fraction and infusion experiments

2.1. Materials and methods

To evaluate different in-situ thickness measurement techniques, a series of six similar 150x150 mm laminates were produced by vacuum infusion. Each laminate consisted of five layers of biaxial glass fibre fabric with a nominal areal mass of 0.6 kg/m^2 and was infused with an epoxy resin system with a density of less than 1200 kg/m^3 without any consumables (e.g. flow mesh, peel ply etc.). The outlet pressure produced by a vacuum pump was 10±1 mbar, with the inlet resin reservoir left open to atmospheric pressure (1015±2 mbar). Before and after the infusion of each sample, measurements were taken at ten different locations using a laser displacement sensor, as shown in Figure 1. Additionally, surface scans of each sample's significant regions were taken using digital image correlation (DIC) and blue-light (BL) scanning equipment. For all three measurement techniques, it was necessary to include several measurement points from an area without fabric, where the vacuum bag was directly on top of the mould, to act as a reference plane (as shown in Figure 1).

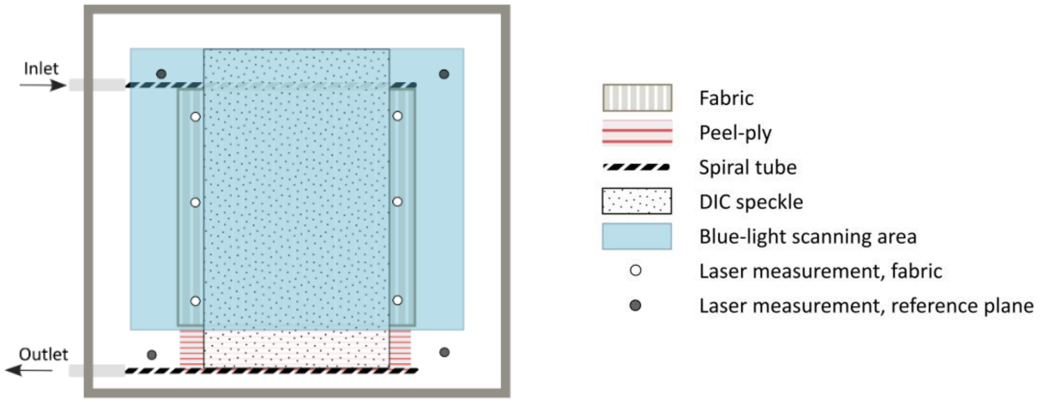


Figure 1. Measurement scheme and configuration of each laminate.

After infusion, the laminate samples were left to cure overnight under a heater blanket at 40°C and then post-cured in an oven for 12 hours at 40°C and 5 hours at 80°C. Once cured, five small 15x15mm specimens were cut from each laminate for the purpose of post-mortem fibre volume fraction determination by the burn-off method [14, 15]

2.2. Interpretation of measurements

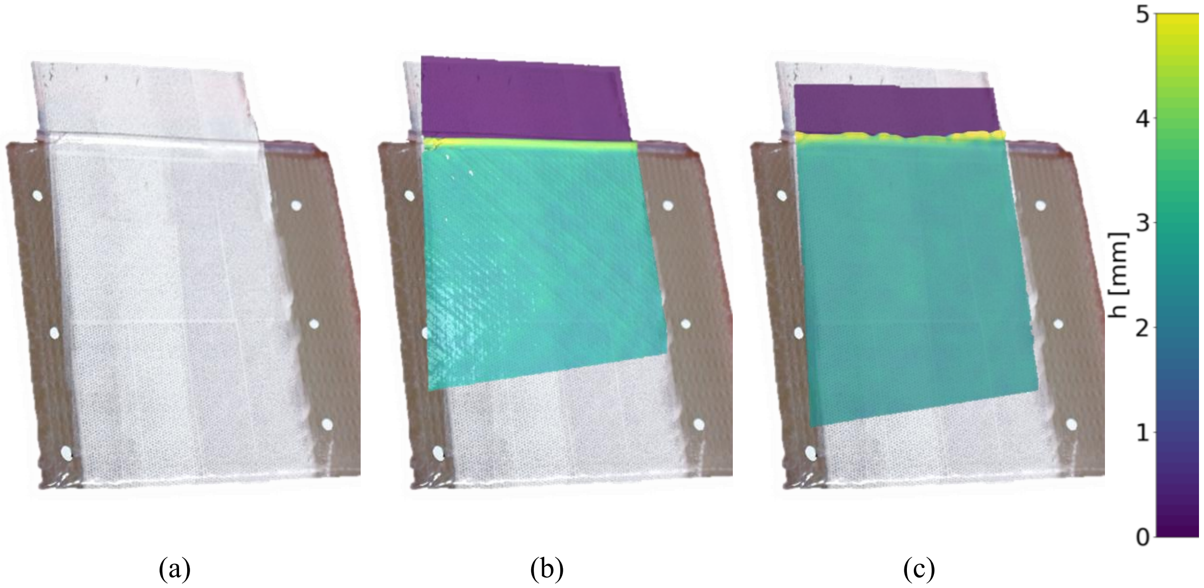
For the three non-destructive measurement techniques, the main parameter to be extracted was the height of the laminate, which was further converted into fibre volume fraction using Equation 1:

$$V_f = \frac{m}{w \cdot l \cdot h \cdot \rho_f} \tag{1}$$

where h is the height of the stack, w and l are the width and length of the specimen, m is the mass of the fabric stack (weighed prior to infusion), and ρ_f is the fibre density (2631 kg/m^3).

The laminate height from the laser sensor measurements was determined by subtracting the average distance from the sensor to the laminate surface (based on six measurement points) from the average distance from the sensor to the reference plane (four measurement points).

The Blue-Light scanner and DIC data were processed similarly as point clouds, with scans of each laminate including regions from both the top surface of the fabric and the reference plane surface, as shown in Figure 2. The average heights of the reference plane and fabric layup areas were measured, and one was subtracted from another to obtain the height.

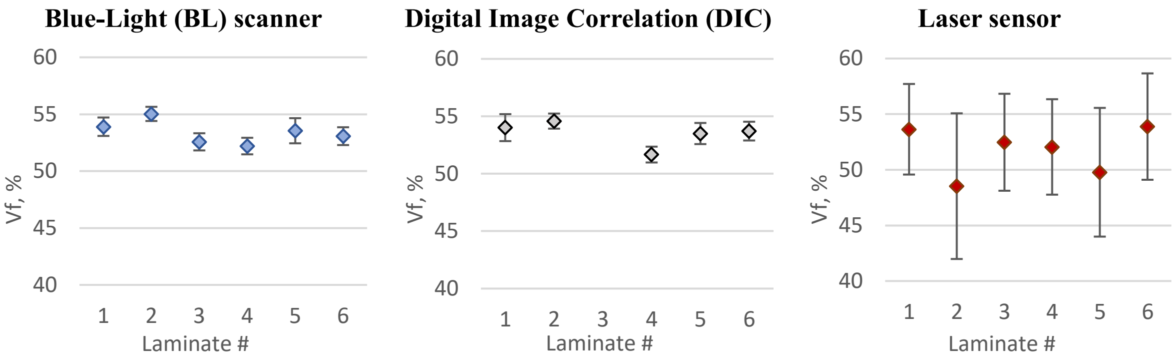


(a) (b) (c)

Figure 2. (a) The specimen and surface point clouds obtained using (b) Blue-Light scanning and (c) DIC.

2.3. Results

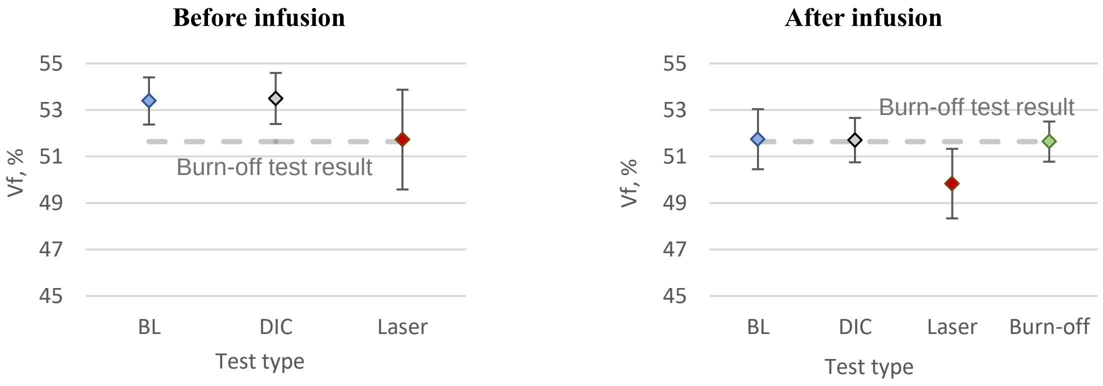
Figure 3 shows the fibre volume fraction values calculated using different techniques for each laminate before the infusion with standard deviations. It can be observed that both the blue-light scanner and the DIC results show average values and standard deviations within a close bandwidth. Even though DIC cannot capture features as small as the blue-light scanner, it still gives a good estimation of the surface geometry needed to assess fibre volume fraction. On the contrary, pointwise measurement using a laser sensor produces a high scatter in the observed values.



(a) (b) (c)

Figure 3. Comparison of fibre volume fraction values for the different laminates measured before infusion using (a) Blue-Light scanner, (b) Digital Image Correlation, and (c) laser sensor.

The average values of fibre volume fraction were also obtained for all used specimens; the result with standard deviations is given in Figure 4.



(a) (b)

Figure 4. Average fibre volume fraction obtained with different methods (a) before and (b) after infusion compared against post-mortem burn-off evaluation result.

The resulting average fibre volume fractions assessed using a blue-light scanner and DIC show good agreement with post-mortem results, deviating by only 0.6 and 0.06%, respectively. Both techniques also produced very similar average results from measurements before infusion, notably higher than the post-mortem fibre volume fraction. However, large deviations can be noticed while using a laser sensor, which can be explained by the fact that it captures only ten points in total and has high variability in the range of one specimen, which can be seen in Figure 3 (c).

3. Infusion simulation

Several simulations have been performed to assess the validity of different fibre volume fraction measurement techniques as a source for modelling input data. Here, the significance of using specific fibre volume fraction data, from before infusion, is evaluated in particular.

3.1 Model setup

PAM-RTM was used to predict the filling time during the infusion process of laminate #1 as a representative example of all cases. The model geometry and conditions, such as ambient pressure, pump pressure, and resin viscosity (as a time-dependent property), were carefully defined to match the experimental infusion. The varied parameters were layup thickness and fibre volume fraction, as obtained using all methods described before the infusion. For evaluating the source of the fibre volume fraction data, two cases were compared: either using averaged values from all six laminates or using average values specific to laminate #1 only. The variability of thickness measurements from the different methods were also considered by modelling additional cases using the data from ± one standard deviation. The results were compared to the actual filling times of laminate #1.

3.2 Results

The predicted filling times from the infusion simulations generally showed good agreement with the experimental case for laminate #1, as shown in Figure 5. It is important to point out that the simulations using averaged values (from all laminates) underestimated the actual filling time, as seen in Figure 5 (a), as a result of the average fibre volume fraction value across all laminates being 1.8% lower (in absolute terms) than that of laminate #1. The data obtained using the blue-light scanner and DIC that is specific only to laminate #1 fits the experimental filling times much better, with only a slight underestimation that could be caused by differences in actual resin viscosity during this test and the nominal curve used for simulation, or the permeability of this particular stack of fabric. Even though one of the aims of modelling tool development is simplification and generalisation, this result demonstrates the importance of considering each infusion case separately when accuracy is valued.

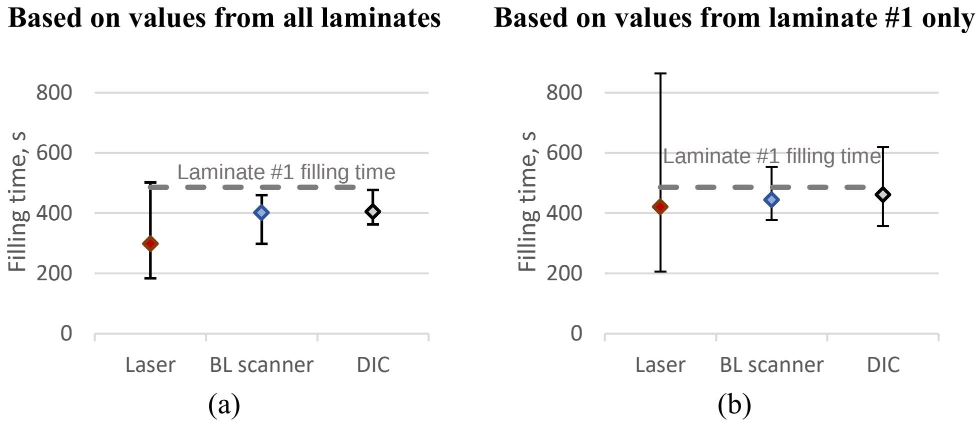


Figure 5. Finite element models filling times using data obtained from different measurement methods for (a) average values from all laminates or (b) values from laminate #1 only compared to the actual filling times of laminate #1.

4. Conclusions and future work

As different thickness measurement techniques were used, it can be concluded that the blue-light scanner and DIC give good results in estimating thickness and, consequently, fibre volume fraction. Laser sensors showed a large scatter in values both within an individual laminate and between laminates, which might be caused by the nature of this type of measurement – only a relatively small number of point-to-point measurements are taken compared with other methods that give full surface geometry with thousands of points. This issue could be solved by defining a larger field of points to do the measurements, but this would likely become very time-consuming unless automated. On the contrary, DIC and blue-light scanning require less time for the measurement during testing but instead require considerable preparation for the camera and scanner placement and calibration.

The observed compressed state of the fabric allowed for an assessment of the expected filling time, and it was shown that both blue-light scanner and digital image correlation data (from a specific test case) as input to infusion finite element models give a reasonable estimate of filling time for the same experimental case. Alternatively, if using the averaged values based on several similar tests, simulations resulted in a significant underestimation of filling duration. This is a result of the scatter of fibre volume fraction values, which significantly affect the permeability and, consequently, the filling time: a 2% absolute change in fibre volume fraction leads to a more than 30% change in permeability. It is, therefore, important to pay attention to the actual compressed state of the object and its variation in fibre volume fraction values when trying to model a specific case accurately.

As future work, to achieve a reliable prediction of the vacuum infusion process in the form of a digital twin, it is necessary to consider in-situ compression of the fabrics, to pay attention to methodology accuracy, and to implement fibre volume fraction progression models both during and after the infusion. It is also important to investigate the transition to a larger scale – both considering model applicability and large field-of-view methods for compressed state monitoring.

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