SINGLE TEST DETERMINATION OF IN-PLANE PERMEABILITY AS A FUNCTION OF FIBER CONTENT USING DIGITAL IMAGE CORRELATION DURING VACUUM INFUSION

A. George[1*], D. Hoagland[1] M. Morgan[1]

[1] Manufacturing Engineering Technology, Brigham Young University, 265 CTB, Provo, Utah 84602, USA.
*Corresponding author (<u>andy_george@byu.edu</u>)

Keywords: *vacuum infusion, permeability, compressibility, flow modelling.*

Introduction

A complication of filling simulation is the need to not only test the permeability of the reinforcement in various directions, but also at various levels of compaction, to determine the relationship between permeability (K) and fiber content (v_F) for a reinforcement. This type of testing is required for process simulation under a flexible cover, as well as when the part geometry dictates non-uniform thicknesses. Traditionally, such a model is developed by repeating in-plane permeability tests at different thicknesses with samples having the same number of layers and dimensions. This can be quite tedious and relies on interpolation and sometimes extrapolation to predict the permeability at fiber contents that were not experimentally determined. This study presents a novel method to rapidly determine a continuous function of $K(v_F)$ in a single flow experiment. A sample is infused under a vacuum bag with a speckle paint pattern applied to the bag, while the sample's thickness gradient is continuously monitored across the bag surface using digital image correlation (DIC). The position of the flow front is sampled at various times similar to any traditional unsaturated permeability test. The resulting length-versus-time data is input along with the wet compressibility of the fabric (the relationship between compaction pressure and v_F) into a 1D flow model accounting for the variable thickness from the vacuum bag. This model is based on the work of Modi [1], and has been traditionally used to predict the filling time given $K(v_F)$ and compressibility functions. But in this case, the permeability, K, is fitted to the length-versus-time data and compressibility model. The $K(v_F)$ function used is a power law, $K=A(v_F)^B$; fitting the model thus entails iterating constants A and B.

Other published methods have produced the same continuous K models with plunger type tooling to change the sample thickness periodically during the flow experiment [2]. It is thought that the method presented here relies on simpler tooling, has less risk of plunger-seal leaking, and may require less test time as no tooling changes are required during the test.

Results

Three types of fabric reinforcements were evaluated: 1) a fiberglass unbalanced weave (JB Martin TG-15-N (518 g/m2) with PPG rovings), 2) a carbon +45/-45 biaxial non-crimped fabric (NCF) (VectorPly C-BX 1800 (580 g/m2)), and 3) a plain glass weave (805 g/m2). Samples were made of four plies of each fabric, cut to 400 x 250 mm. Transducers were placed at 20, 40, 60, 80, 100, and 200 mm along the flow path through the long direction of the fabric sample. Both the transducers and the DIC cameras sampled the resin pressure and sample thickness at a frequency of 0.5 Hz during infusion. Infusions were carried out under a vacuum bag with an atmospheric pressure of ~86 kPa and vacuum pressure ranging from 1 to 15 kPa (absolute). The bag was coated with speckle paint for DIC evaluation, except for a thin strip down the infusion length with which to measure the time to fill (t) given flow lengths (L) at 20 mm increments. Local v_F was calculated from the thickness supplied by DIC data, and the local compaction pressure on the fabric (P_C) was calculated from Terzaghi's balance given the resin pressure from the transducer data. The resulting fabric wet compressibility, $P_C(v_F)$, was fit to the Loos-Grimsley model [3] for at each transducer location. Fits for all six transducers are shown in Figure 1 for an example carbon NCF infusion.

The 1D compressibility model was setup in matlab, to iterate A and B for the power law of $K(v_F)$, given the calculated compressibility $P_C(v_F)$, to match the L vs t data. Figure 2 shows the power law function fits for each of three test infusions with the plain weave glass. The average fit (with power law

shown on the graph) was determined by averaging periodic K values along the 3 curves. Figure 2 also shows an example goodness of fit, with both the experimental and fit profiles for L vs t.
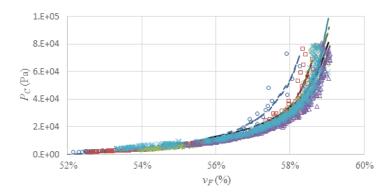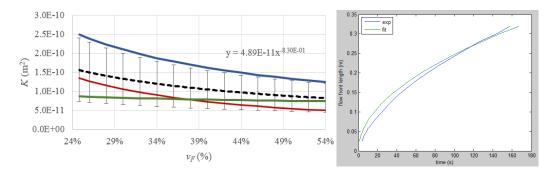

Figure 1: *Example compressibility data and model fits for each of the six transducer locations.*

Figure 2: *Left: fit permeability function K(v$_F$) for each of three infusions with plain weave glass, and average fit (black dashed line). Right: example goodness of fit for L vs t.*

The average fits for warp and weft directions for the glass unbalanced weave are presented in Figure 3, along with comparison data from both 1D traditional K tests, and calculated from P_{cap} measurement dip tests. The agreement is fairly good, or at least usually within the standard deviation of each other.
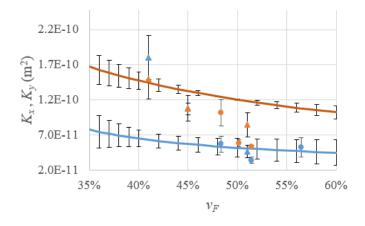

Figure 3: *Average fit of K(v$_F$) for glass unbalanced weave (blue: warp, orange: weft), with 1D permeability test (circles) and P$_{cap}$ test (triangles) results.*

References

[1] D. Modi, Modelling and active control of the vacuum infusion process for composites manufacture, Dissertation, University of Nottingham, UK, 2008

[2] H.C. Stadtdeld, M. Erninger, S. Bickerton, S.G. Advani, An experimental method to continuously measure permeability of fiber preforms as a function of fiber volume fraction, *J Reinforced Plastics and Composites*, 21(10):879-899, 2002

[3] B. Grimsley, Characterization of the vacuum assisted resin transfer molding process for fabrication of aerospace composites, Dissertation, Virginia Tech University, USA, 2005