Characterization of Capillary Pressure Effects In Liquid Composite Molding

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Abstract This study investigates a method to be used to determine capillary pressure between a fiber resin combination. It will be used in further research to help validate a model of for capillary pressure that can be incorporated into flow simulation.

Introduction

Aerospace Industry

The need for rapid methods to produce high-performance composites has become especially critical as the aerospace industry continues to incorporate composites into aircraft structures. In order to facilitate these changes, faster processes such as liquid composite molding (LCM) will be needed to produce parts with high fiber volumes and minimal voids comparable to those made with autoclaved pre-preg materials. A major factor in accomplishing high fiber volumes and minimal voids during resin infusion is understanding and controlling the resin flow. An important component of resin flow and the pressure gradient, is the capillary pressure between fiber and resin combinations. This study investigates a method to be used to determine capillary pressure between a fiber resin combination. It will be used in further research to help validate a model of for capillary pressure[1] that can be incorporated into flow simulation.

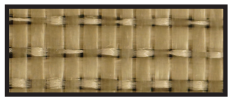
Pcap Measurement Method

Overview

A thorough review of previous work with capillary pressure in composite materials is found in [2]. Using a simplified approach similar to that illistrated in [2] capillary rise tests were performed with both a carbon and fiberglass fabric in the warp and weft direction. The test fluid used was store bought canola oil with a florescent dye added for increased visibility during tests. Samples were suspended over a container holding the test fluid, then lowered until the samples edge made contact with the fluid. The tests were performed inside a black room that was held at a consistant temperature. Samples were illuminated by a black light and images were taken in specified intervals using a macro lens camera. Once all tests were completed, the images were analyzed using Image J software.

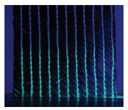
Fabrics

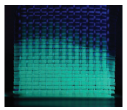
Carbon biax NCF
- VectorPly C-BX 1800 ± 45°
- 580 gsm



Fiberglass biax NCF
- JB Martin TG-15-N
- 518 gsm
- PPG rovings

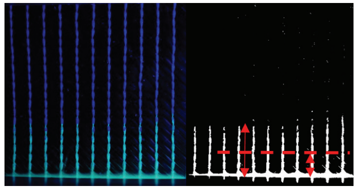
Fabric Dipping





- Experiments peformed in darkroom with blacklight
- Samples cut to 50mm x 50mm (warp and weft)
- Test fluid: canola oil mixed with flourescent dye
- Each test is ran for a total of 60 minutes
- Photos taken at 5 minute intervals for first 30 minutes, then at 10 minute intervals for last 30 minutes.

Image J Analysis



- Each sample had an initial photo taken with a ruler so that pixel/mm scale could be set
- The image channels were then split and only the green frame selected.
- An algorithm for the threshhold was then ran to create a binary image for ease in measuring.
- The lengths of the leading and trailing flowfronts were recorded

Results

Pcap

With only capillary forces moving the liquid, and with gravity acting against the flow, Darcy's law for the flow rate is [3] :

$$\frac{dh}{dt} = \frac{K}{\mu\varphi}\frac{P_{cap} - \rho g h}{h} \qquad (1)$$

where K, μ, φ, P_{cap}, ρ, and g are the permeability, viscosity, porosity, capillary pressure, liquid density, and gravitational constant, respectively. With a linear fit for h^2 vs t and intercept = 0(Figure 1), we can write an equation as:

$$h^2 = Mt \qquad (2)$$

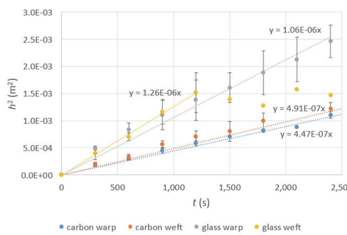


Figure 1

where M is the slope. Taking the derivative of h with respect to t and combining it with Eq. 1,

$$P_{cap} = \pm h\left(\frac{M\mu\varphi}{2K\sqrt{Mt}} + \rho g\right) \qquad (3)$$

By combining these two equations it has made P_{cap} and h related to each other in a very simple way. It is also noted that besides P_{cap} and h the only other variable that should be changing is t. After calculating the P_{cap} for each time interval, the average of these values of P_{cap} for each material/orientation were plotted against h to see how much the P_{cap} is changing as the flow travels shown in Figure 2.

In Figure 2 you can see that:
-capillary pressure is much higher for the tightly packed carbon fabric (φ = 50%) compared to the glass (φ = 33%)
-weft direction of the carbon has a ~50% higher P_{cap} than the warp at any given height or time

A classic equation to describe capillary flow in fibrous materials is:

$$P_{cap} = \frac{F}{D_f}\cdot\frac{1-\varphi}{\varphi}\gamma\cos(\theta_{CD}) \qquad (4)$$

where F, D_f, γ, θ_{CD} are a form factor describing the flow direction in relation to the fiber-orientation, diameter of a single fiber, the surface tension of the liquid, and the dynamic contact angle between the liquid and solid fiber surface, respectively.

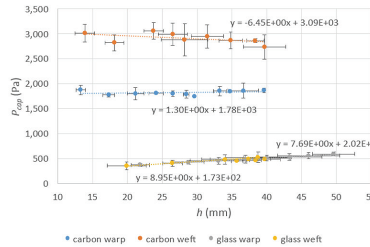


Figure 2

The major difference between warp and weft is the form factor. This number is hard to determine expect by experiment when you know all other variables in Eq. 4. In [4] "F is the form factor for alignment of the fibers to flow, being 4 for along the fibers, and 2 for perpendicularity." The carbon fabric is +/-45 biax NCF, with warp being the machine direction, parallel to the stitching lines. So the flow is actually +/- 45degrees to the fibers, whether warp or weft. Warp's only unique flow characteristic is that the flow is going parallel with the stitching fibers. If all the other variables in Eq. 4 remain nearly the same throughout the experiment as we assume they do, then F is the only thing that can change Pcap by so much, meaning F is about 50% greater in weft than warp. It is noticed in the carbon experiments that F hasn't followed the trend: flow along the stitching threads in a biax-bias NCF gives actually a lower F than perpendicular.

Conclusion

- Fabric dipping is an easy method to experimentally measure capillary flow in fiberglass. It can also be applied to carbon NCF's as long as there is glass fiber or another type of material that allows good translucence of the florescent dye.
- The maximum Pcap measured was about 3 kPa for carbon and 0.5 kPa for glass. These are small values that won't play too much a role in filling simulation (usually pressure gradients are around 100 kPa in vacuum infusion, more in RTM).

  However:
  -tests were performed with canola oil, as opposed to actual resin/fiber combinations where sizings are chosen specifically to aid in wetting and thus increase the contact angle and capillary pressure.
  -understaning capillary pressures will help further other work such as void formation.
  -goal is to have flow simulation accurate enough in the future that small corrections such as for capillary pressure will be desired.

References

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[4] Williams, J.G., Polymer Engineering Sci., 1973

Thanks to: VECTORPLY. Imagine. Innovate. build.