A COMPARISON OF DRY AND WET COMPRESSIBILITY MEASUREMENTS AGAINST IN-SITU VACUUM BAG DISPLACEMENT DURING INFUSION

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Introduction

This presentation regards instrumentation for compressibility measurement, to aid in flow simulation of vacuum infusion (VI), i.e. under a flexible membrane such as a vacuum bag. A worldwide benchmark on such compressibility measurement of composite reinforcements is underway and results are to be discussed at this conference. Both dry and wet testing has been specified for the benchmark exercise, in unidirectional compression under a universal testing machine (UTM).

Composite reinforcements, both dry and wet, exhibit classic time-dependency characteristics: 1) stress relaxation under load, 2) strain rate dependence, and 3) hysteresis [1]. In order to extract UTM compressibility that is relevant to VI, mimicking the applied pressure, time at dry compression before wetting, subsequent expansion rate and cycle number are intuitively important based on the time-dependency. Previous results have not shown strong agreement between UTM measured compressibility, and that measured *in situ* by digital image correlation (DIC) during actual infusion processing under a vacuum bag [2,3]. The suspected cause of the differences between UTM and VI compressibility models are 1) differences in hydrodynamic loading and 2) the small displacements being measured which imply a high dependence of the results on the accuracy and precision of thickness measurement [4]. This study aims to validate the use of UTM compressibility measurement in VI process simulation, by investigating the agreement between UTM and in situ VI compressibility measurement methods, and to develop an experimental methodology to minimize these sources of error and thus optimize that agreement.

Experimentation

The differences between these test methods were studied in the context of five reinforcements: fiberglass chopped strand mat (CSM), plain weave and unbalanced weave; carbon non-crimp fabric (NCF) and unidirectional (UD) weave. Both dry and wet UTM testing, as well as DIC testing during VI were performed, with both methods employing canola oil for the test fluid and an array of pressure sensors in an attempt to clarify the experimental distribution of the fluid pressure. A reinforcement's compressibility is usually presented as the function $P_C(v_F)$, similar to a stress-strain diagram, where P_C is the compaction pressure and v_F the volumetric fiber percentage. In DIC testing, the pressure sensors measured the sum of the vacuum and test fluid pressure during VI. Subtracting this from the ambient pressure yields P_C. The contribution of the fluid pressure during UTM testing was also measured from the sensors, and was modelled using Darcy's Law in cylindrical coordinates [4]. The UTM test was carefully arranged to match the VI test conditions as much as possible, e.g. similar displacement rates in compaction to the same maximum compaction pressure (86 kPa), and same duration (10 minutes) at that pressure before relaxation or start of the infusion. Further experimental details may be found in [5].

Results

Wet UTM testing with multiple pressure sensors verified the dependence of the fluid pressure on the displacement rate and reinforcement choice. While previous results on low permeability glass reinforcements showed no significant accumulation of fluid pressure during wet UTM testing, this study's carbon reinforcements, with much higher v_F, showed fluid pressures near, or exceeding the UTM

applied load. Negative (suction) pressures were sometime calculated by Terzaghi's Law and empirically validated during UTM relaxation.

The average compressibility function resultant from the replicate tests, with error bars denoting the standard deviation, is illustrated in Fig. 1. The VI compressibility shown here is the relaxation during infusion, following the transition from dry to wet while at full compaction. Both dry and wet relaxation UTM curves are displayed, as well as the compaction UTM curves for illustration of the hysteresis.

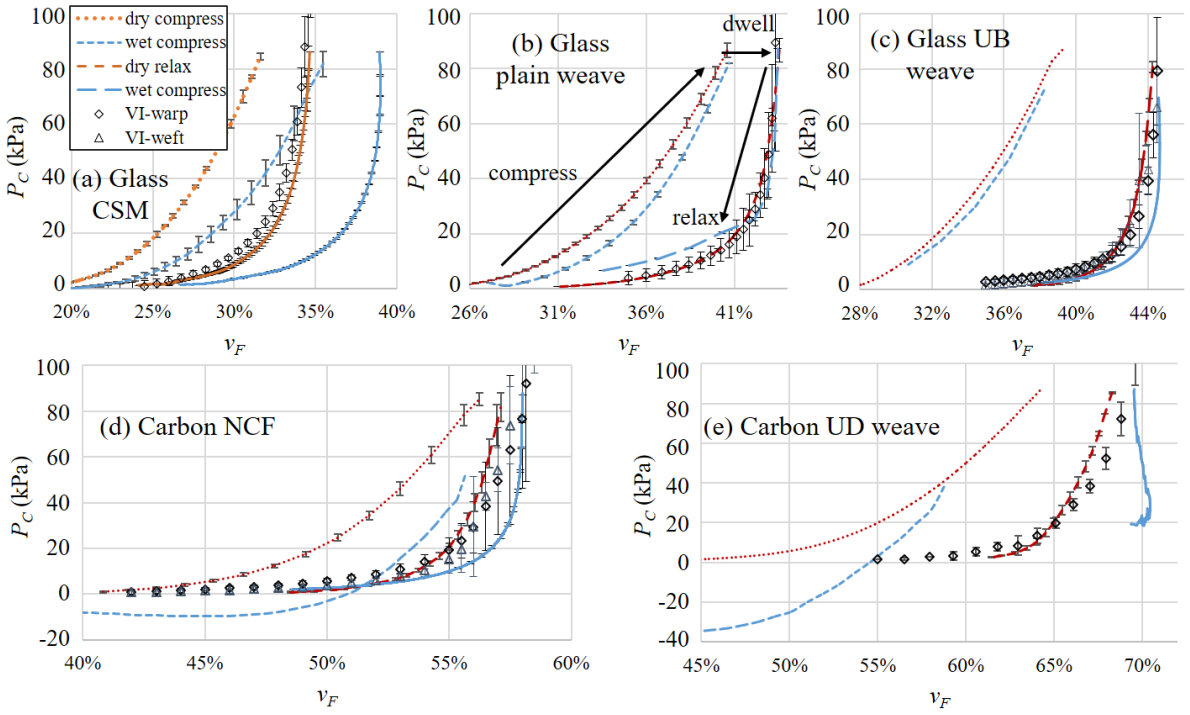

Figure 1: *Compressibility as determined by UTM (both compaction and relaxation) and VI (wet relaxation).*

In all reinforcement cases the UTM dry curves match significantly better with VI than the UTM wet curves. The wet UTM data is shifted to the right of both the dry UTM and VI data, suggesting higher lubrication than during VI processing. For all but portions of the curves for the glass CSM and carbon UD weave, the average UTM dry curve lies within the standard deviation of the average VI curve. The agreement seems to be a good fit despite the UTM data coming from non-lubricated testing.

The results from this study suggest that wet UTM testing is unnecessary for VI flow simulation:

1. Relaxation during VI infusion happens at very low strain rates, thus the fluid pressure build-up is small even for dense carbon reinforcements [6].
2. Wet UTM testing induced a viscous response beyond the predicted fluid pressure, which results in compressibility curves which are significantly different from *in situ* VI testing. Future work may ascertain and account for the differences, but the agreement is poor with current analytical models.
3. In contrast, the dry UTM and VI compressibility curves have good agreement with each other for these five reinforcements. The potential hydrodynamic differences between the two test methods seem to disappear when 1) the strain rate and compaction history are matched, and 2) a careful calibration of all thicknesses is performed.

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