NON-DESTRUCTIVE EVALUATION OF PREFORM INJECTABILITY AND COMPRESSIBILITY FOR QUALITY ASSESSMENT IN A PRODUCTION ENVIRONMENT

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Abstract
A non-destructive quality monitoring system to assess the injectability and compressibility in local planar regions of carbon fibre (CF) stacks and 3D preforms is currently under development. Injectability and compressibility of semi-finished textiles are known to be influential on mould filling processes. Compaction response has been studied extensively, with measurements being conceptually simple, and easily applicable in a non-destructive format. Flow resistance of fibre reinforcements, or "injectability", is commonly quantified by permeability, for which the vast majority of reported measurement techniques are destructive, requiring cutting of reinforcement to a specific sample size, and often involve infusion with a test fluid. The presented method provides a highly effective and reliable non-destructive characterization of semi-finished textiles applicable within an industrial production environment. General benefits and limitations of the measurement method are discussed, followed by a detailed analysis of presented injectability data and its' correlation to more classical permeability values. The paper concludes with a capability analysis, proving the sensitivity and robustness of the proposed measurement methods.

1. Introduction

Production methods for medium and high volume manufacturing applications are developed with a strong focus on costs, this being particularly true for the manufacturing of carbon fibre reinforced plastics (CFRP). The BMW Group has successfully implemented CFRP mass production through project i (new i3 and i8 models), and most recently the new BMW 7 Series. Both the i3 and i8 have a structural CFRP part count in excess of 50, which are produced either by preforming and high pressure RTM, or by wet-pressing. Each manufacturing process chain involves multiple production steps, resulting in a series of semi-products (e.g. textiles, stacks, preforms). With industrial CFRP mass production still at an early stage, fast and effective quality measurement systems are required, including assessment of important material properties of semi-products indicative of likely success in subsequent production steps. For RTM and wetpressing, the resin infusion process is the most influential step on finished part quality. The success of this process is mainly dependent on the permeability of the fibre semi-product. Fluid flow through porous structures, such as textiles, is restricted by the internal geometry of these materials. Permeability is an inverse measure of this resistance, determined with respect to various assumptions (flow regime, saturation etc.). This resistance is highly dependent on the applied fibre volume fraction of the semi-finished textile [1]. As a result permeability and

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compressibility of semi-finished textiles are two main characteristics for a comprehensive quality assessment [2, 3]. Simplification of quality control measurements is a key attribute for an effective and reliable manufacturing process [4]. The vast majority of available measurement techniques utilize fluid flow through a closed environment, which requires cutting of samples from semi-products to determine permeability. Techniques which utilize a transient filling approach are limited to providing permeability at a single fibre volume fraction from each sample. Existing methods are focused on accurate characterization for process simulation, and are too expensive (destruction of products, too time intensive) to be utilized for quality assessment in an industrial environment.

A non-destructive measurement system is under development in collaboration between the University of Auckland and the BMW Group, which measures both the "injectability" and "compressibility" of semi-finished textiles and is applicable within an industrial production environment. The air based measurement technique utilizes a transient air flow with open boundaries, enabling fast and non-destructive measurements. This paper presents the basic concept of the measurement method, its correlation to more classical permeability values, and highlights the benefits of its application.

2. Non-destructive Quality Assessment, Application and Limitations

Permeability and compaction response are important material properties for process simulation and design. However, existing methods are time intensive, laboratory based, and require the cutting of samples from expensive semi-products. In the context of material quality assessment, the limitations are:

- Sample cutting leads to the destruction of the semi-product, at significant cost.
- Relocation of samples to a remote laboratory causes significant time delays.
- Measurements are detailed, time consuming, and the results are not easily interpreted by non-experts (e.g. production staff, quality control).

These limitations motivate the development of fast, non-destructive characterisation techniques, which can be performed at the production line, or possibly inline within processing equipment. If measurements can be performed directly on semi-finished textiles without altering any property of the product (non-destructive), the following significant benefits are realised:

- Immediate feedback is provided by measurements made at the production line, to help staff identify the causes of failures in production.
- Characterised products can be reinserted into the remainder of the process chain, to directly correlate measured properties to the success of subsequent manufacture.
- Time and cost savings allow for efficient qualification of new material sources, and qualification of new production equipment.
- If implemented inline, 100 % testing of the products is possible, allowing for detailed analysis of cause and effect through the process chain.

This research is focused on the development of methods to non-destructively assess the resistance provided by the textiles, stacks and preforms to compressive deformation and fluid flow. Fast methods are developed without the requirement for cutting of samples, which have outputs that are easily interpreted by non-experts. While compressibility measures are relatively easy to define, the inability to cut samples significantly limits the direct measurement of permeability. Pure in-plane flow cannot be established, as holes cannot be cut into the semi-finished textile to ensure in-plane flow. Through-thickness measurements are influenced by the inability to seal the edges of the measurement area. Considering these limitations, permeability values are not the target of the measurements presented here. New definitions of injectability are established, based on transient air flows within two different geometries. The aim is to assess an "average in-plane injectability" with one tool, and the

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"through-thickness injectability" with another. However, purely in-plane, or through-thickness flow cannot be achieved without sample cutting. The limitations and applicability of the new injectability measurement are explored in this paper through correlations made to traditional permeability measurements.

2.1. Methodology

Simple and easy to interpret measures are vital requirements for the acceptance of a measurement method within an industrial production environment. In the proposed method, the textile product is compressed to a certain target thickness, while monitoring the required force of compaction. A transient air pressure pulse is then applied to determine injectability. Two different plate sets are utilized to measure either in-plane, or through-thickness injectability (see Figure 1.). Compaction response has been studied extensively, with measurements being conceptually simple, and easily applicable in a non-destructive format [5]. Here, "compressibility" is taken as the peak compaction stress measured at the instant the sample is brought to target thickness. As mentioned above, non-destructive measurement of permeability is problematic, and this paper is focused primarily on the definition and assessment of injectability measures. Due to commercial sensitivity, only limited data about the physical definition of the experimental setup can be provided.

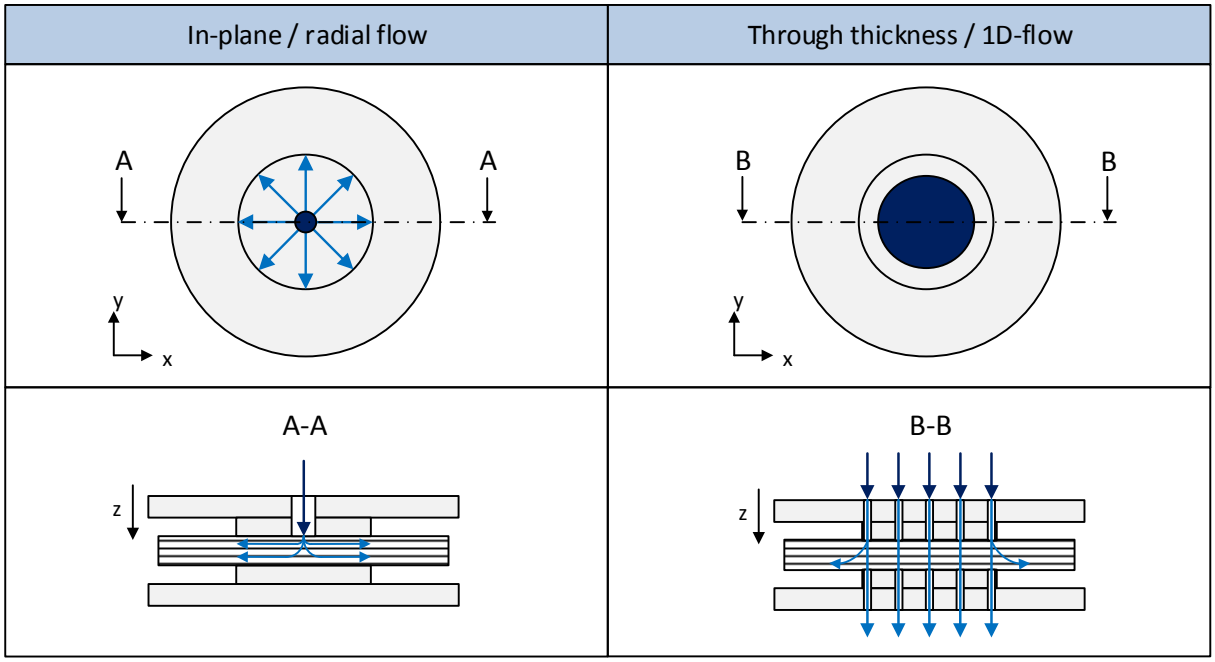

Figure 1. Schematic of in-plane and through-thickness injectability flow geometries.

A small pressure vessel, which is isolated from the flow measurement heads by a quick release valve, is charged to a specified initial pressure. The experiment is initiated by opening of the valve, releasing a pressure pulse of air through the sample. The transient decay of the pressure at the inlet to the sample is monitored against time (see sample data in Figure 2). Several possible measures of injectability can be defined from the pressure trace with time. No attempt is made to calculate permeability components, injectability being essentially defined here by a drop in pressure over a certain time.

Open sample edges, in combination with non-Darcian flow, lead to uncertain flow effects for which a classical permeability calculation is no longer valid. Of particular relevance are high velocities of the test fluid at the inlet of the measurement plates, and the complex 3D flow through the injection point and sample.

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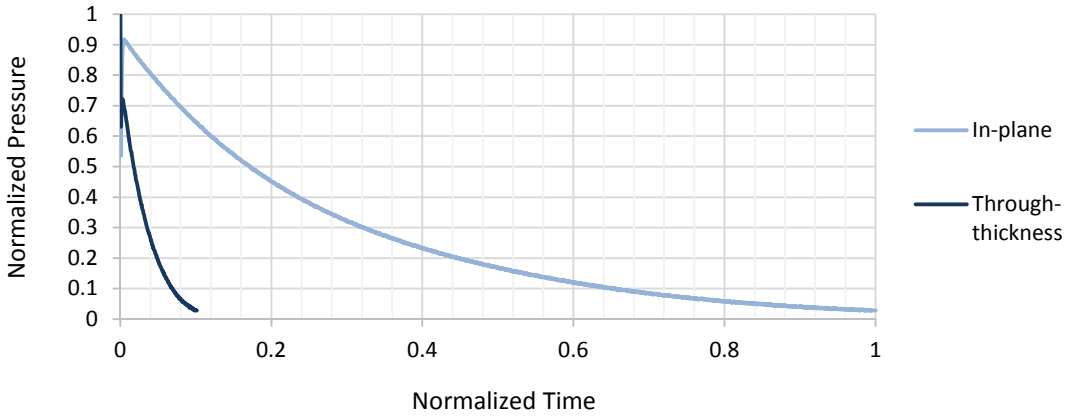

Figure 2. Sample pressure decay data from in-plane and through-thickness injectability tests.

The platen geometry to assess in-plane injectability has been designed with a focus on simplicity of flow, and simplicity of injectability definition. The stack or preform sample is compressed between two flat, circular platens with the air injection port being located at the centre of one plate. During the test, air flows initially through the thickness of the sample, but then flows radially outwards through the majority of the sample in-plane. As air flows outwards in all in-plane directions, the measured injectability provides a quantitative indication of the average of the two in-plane permeabilities. The platen geometry for through-thickness measurements was also designed with a focus on simplicity. A circular array of holes machined into the top and the bottom plate allows the air to flow through the thickness direction of the samples. Air leakage at the unsealed edge of the samples will influence the air flow through the sample, though diameters of the hole pattern and platens have been carefully chosen to minimise in-plane leakage. For both in-plane and through-thickness measurements, cutting of a stack/preform sample is not required, ensuring the non-destructive characteristic of the tests. A transition zone between the clamped und the non-fixed area of the part creates also certain fringe effects.

3. Experimental Program

Two experimental studies are presented here. The first is focussed on the correlation of more classical permeability values with the fast and non-destructive injectability measurement. This correlation is essential for the assessment of fringe effects (open boundaries, flow regime etc.). Secondly, the sensitivity and robustness of this measurement method will be demonstrated, as they are key issues for a reliable and convincing measurement system [6]. A selection of tests have been performed to prove the capability of the measurement concept.

3.1. Test Material

Different stack types have been assessed, each formed form multiple layers of a carbon fibre non-crimp fabric (nominally 330 g/m^2, 0° unidirectional NCF). Three layups were considered (denoted as A, B, and C; defined in **Error! Reference source not found.**) and tested at three different thicknesses and nominal V_f's (fibre volume fraction; based on standard areal weight, and material density). Stack type A and B have nine layers and are identical except for B having five layers laid at 0° in the centre. Stack type C is similar to A, but with a reduced layer count of six.

3.2. Correlating Injectability to Permeability

Seven samples were characterized for each stack type. First, samples were tested by determining the injectability and compressibility for in-plane and through-thickness measurements. Due to the non-destructive character, multiple target thicknesses (see **Error! Reference source not found.**) are

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measured to demonstrate the sensitivity of the measurement method. Subsequently the same samples were characterised using more traditional destructive permeability measurements, to explore the correlation to the measured air injectability.

Table 1. Definition of stack layups, and target conditions.

Stack	*Layup*	*Target Thickness (mm)*	*Fibre Volume Fraction*
A	+45/-45/0/90/0/90/0/-45/+45	3.44	Low
		3.12	Medium
		2.86	High
B	+45/-45/0/0/0/0/0/-45/+45	3.44	Low
		3.12	Medium
		2.86	High
C	+45/-45/0/0/-45/+45	2.30	Low
		2.08	Medium
		1.91	High

In-plane permeability has been determined using a radial flow, transient filling method. The advancing flow front was visually tracked and recorded using a digital CCD camera, with detailed output being provided for both in-plane principal permeabilities [7]. For comparison to the average in-plane injectabilities provided by airflow, an average in-plane permeability must be calculated. Average in-plane permeability can be calculated from (Eq. 1):

$$K_{ave} = \sqrt{K_{11} \cdot K_{22}} \quad (1)$$

Where K_{ave} is the average in-plane permeability, K_{11} is the major in-plane, and K_{22} the minor in-plane component of the permeability tensor. The sample size was 200 x 200 mm, with a measurement being possible at one V_f. with each sample.

Through-thickness permeability has been measured by application of a steady sate flow technique [7], in which the sample is compacted to a target thickness between two aluminium platens. These platens contain holes, through which the test fluid is driven at a steady state. The edge of the sample is sealed using a viscous grease, which eliminates racetracking flow around the edge of the sample. This system allows for measurements to be made at multiple target thicknesses for the same stack sample. It should be noted that the sampling areas were different for the air flow injectability and liquid based permeability measurements.

3.3. Sensitivity and robustness

Assessment of the measurement values provides information about the significance and accuracy, and aids in the understanding of the quality characteristics of the measurement method. These features are the basis for an accurate data analysis, and are the foundation for product quality improvement in a manufacturing production environment [8]. It is essential that the differences in the data are due to process differences (e.g. actual variations in the materials being characterised) and not to variation in the measurement method. To investigate the sensitivity of the new measurement method two sets of injectability measurements were performed. One with 25 fresh samples, to demonstrate the measured material variability. A second set of 25 measurements were performed on a single sample, repeatedly inserted, measured, and removed from the permeability rig. This measurement procedure follows the type-1 Gage R&R study to minimise the amount of variation and error introduced by the measurement with a focus on the parts variation [8].

4. Results and Discussion

Injectability, as applied here, is determined by measuring the time between two pressure values of interest. Figure 3 present plots of the typical outputs for stack type B for average through-thickness and

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in-plane injectability, as well as compressibility. The higher the injectability, the higher the pressure decay between those points, and as a result the lower the actual measured value.

In Figure 3 data from the low, medium, and high V_f's are compared. A clear distinction can be observed between the different V_f's using the proposed injectability measurement. The through-thickness measurement is comparatively quick due to shorter flow paths. Nevertheless, the measurement can distinguish between different V_f's. Results from the simple compressibility measure are extracted from the early stages of the transient in-plane injectability test. Random nesting increases the variability of the compaction force, and there is clear distinction between different V_f's.

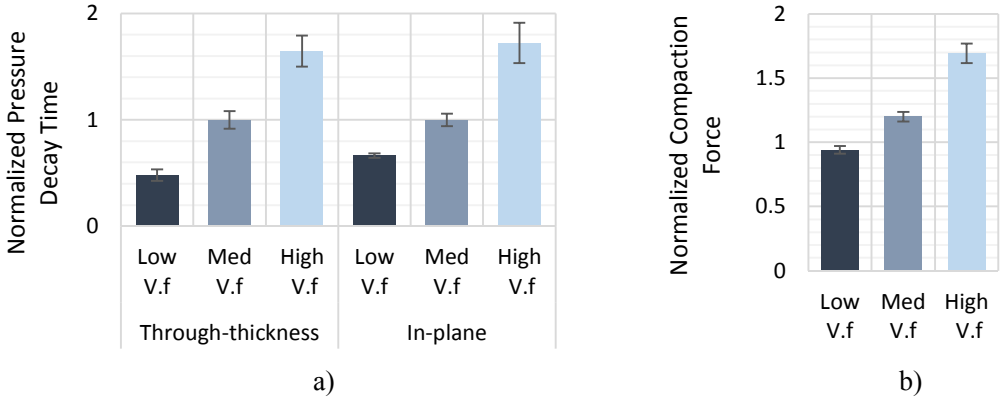

Figure 3. Sample injectability (a), and compressibility (b) data for stack type B.

4.1. Correlating Injectability to Permeability

Figure 4 presents the measured average in-plane permeabilities against injectability. For the in-plane permeability measurement, only one value could be obtained from each stack sample. Therefore, comparisons to air injectability can be made at a limited number of V_f's. The three different materials exhibit a similar form of correlation, with only a small offset between datasets. Each dataset has been fitted with a logarithmic correlation, and the R^2 value is provided as a measure of the quality of correlation. A very good correlation is demonstrated by stack types B and C, with R^2 values of 0.98 and 0.97 respectively. The value for A is lower at 0.81, indicating a less clear correlation. A changeover of a batch of oil made during the in-plane permeability measurements with stack A may be partially responsible for the weaker correlation.

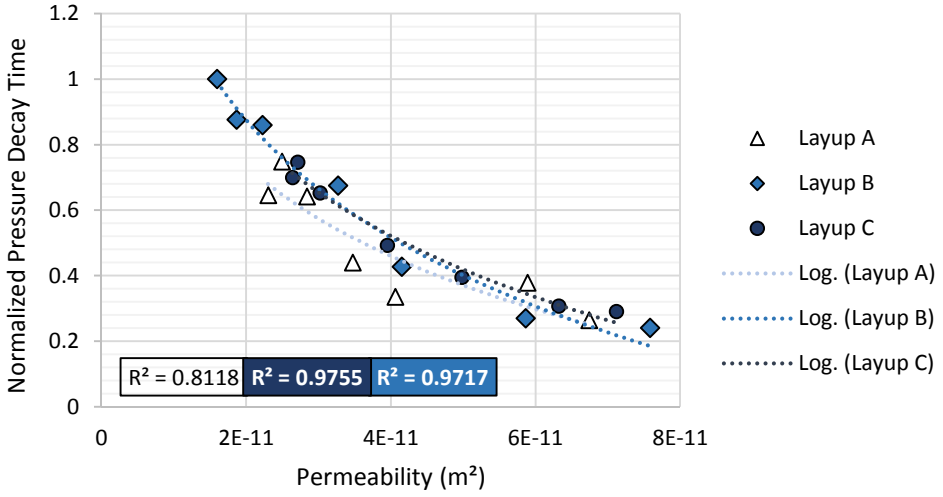

Figure 4. Correlation between transient in-plane injectability and average in-plane permeability.

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Figure 5 presents plots for stack types A, B, and C, of the measured through-thickness permeabilities against injectability. Data from the low, medium, and high V_f's are combined, and a logarithmic correlation is applied to each stack type. In each case, very good correlations are found, with R^2 values of 0.95, 0.94, and 0.90, for stack types A, B, and C respectively. Nonetheless, it can be noted that through-thickness measurements are more sensitive than in-plane, to differences in the flow behaviour of the stacks studied here. The pressure decay for low, medium and high V_f's of Layup B provides a very diverse behaviour. In contrast to layup A and C, layup B consists of 5 layers with the same fibre orientation stacked adjacently. This results in a large amount of fibre nesting at the centre of the stack, significantly reducing through-thickness injectability. It seems that the balance of in-plane leakage to through-thickness flow is changed relative to stack type A, changing the form of the shape correlation.

Overall it can be stated that the presented injectability data correlates very well with permeability. The reader should note that there were significant differences between the flow measurement areas of the air flow methods, and liquid based permeability measurements. Though different correlations were noted between stack types A and B, the proposed technique meets the project objectives. For an industrial quality assessment, comparisons will be made between stacks, or preforms of the same type.

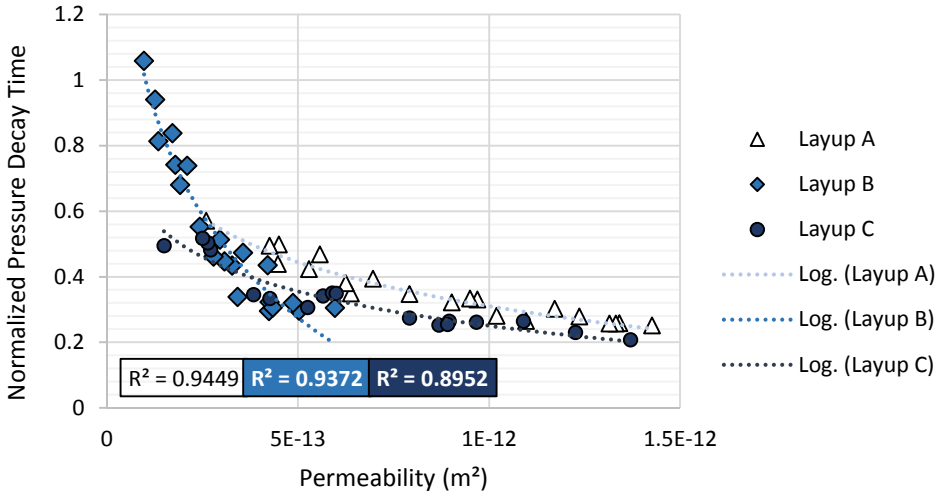

Figure 5. Correlation between transient through-thickness injectability and through-thickness permeability.

4.2. Sensitivity and robustness

The robustness and sensitivity of the in-plane and through-thickness injectability measurements is demonstrated in Figure 6. It is notable that the influence of the measurement method is very small relative to the exhibited material variability. In Figure 6 the data is presented as the deviation from the measured mean value. Comparing the standard deviations recorded for tests with the same sample, the variation between the measurements is almost negligible, when comparing to the set of experiments performed with 25 new samples. Therefore, the presented injectability measurements are sufficiently sensitive relative to the natural variability between stack samples. Considering the key results, the measurement method offers high accuracy. A standard deviation of 2.99 % for the in-plane and 1.24 % for through-thickness can be measured. When considering the measurement series using fresh samples for every measurement, the in-plane standard deviation raises to 32.1 % and the through-thickness to 6.2 %. The presented data demonstrates shows that the method is capable of measuring the natural variation in the material.

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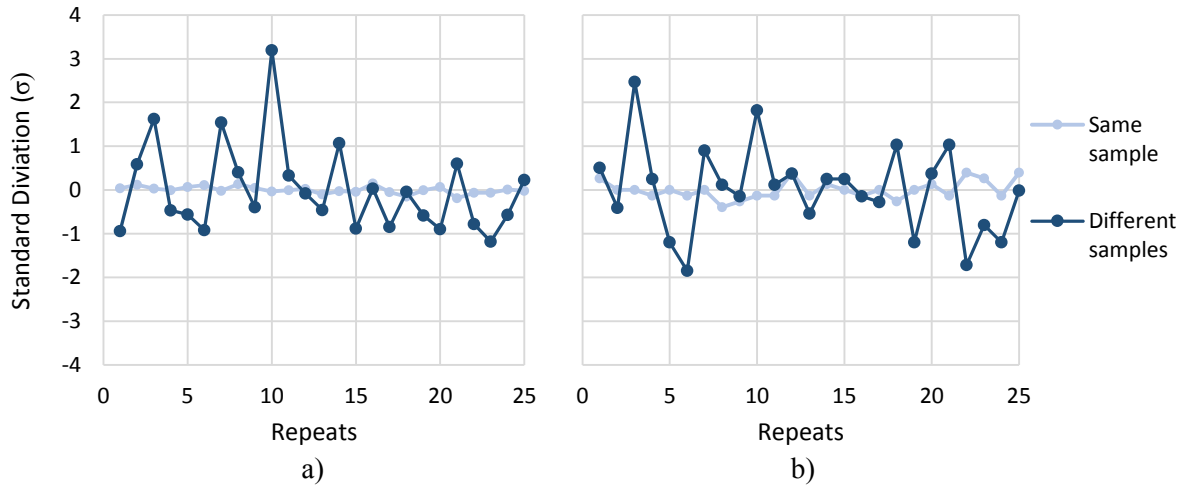

Figure 6. Sensitivity study on the injectability measurements – a) Through-thickness; b) In-plane.

5. Conclusion

A set of non-destructive compressibility and injectability measurement techniques have been proposed. The presented results provide a first overview of the capability of the proposed methods. Using transient air flow based injectability measures, clear distinctions are made between different stack layups, and across the tested fibre volume fraction range. By performing destructive permeability measurements on the same stack samples, very good correlations have been demonstrated with both injectability methods ($R^2 > 0.90$ in the majority of cases). It is also promising that the data analysis for the chosen measurement method demonstrates very good measurement accuracy and reliability. The fulfilment of this prerequisite is the main requirement for the qualification of a new measurement technique within an industrial environment.

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