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**Compaction, flow and mechanical properties in lap joints
for large multilayer VARTM preforms**

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Abstract

Reinforcement preforms for the vacuum assisted resin transfer moulding (VARTM) manufacturing of large composite parts are made from different layers where presence of double curvature and varying fibre orientation imposes the use of superimposed lap joints. A series of tests were conducted to investigate the compaction of jointed preforms, flow through jointed preforms and the structural behaviour of composite parts featuring superimposed lap joints.

A variety of lap joint configurations was investigated, characterized by specific values of overlap length, OL, horizontal distance between joints, HD, and number of immediately superimposed joints, NS, for a random matt and a woven reinforcement.

The compaction of reinforcements was evaluated using a novel thickness measurement system for preforms. The thickness measurement system utilizes Hall effect sensors. The local fibre volume fraction, v_f , was derived from the readings of Hall effect sensors positioned at selected locations above the jointed preforms. Different v_f values were observed around joints; consequently, simulations of the manufacturing and performance of jointed composite parts must feature variable v_f at the joints.

The effective permeability to resin of jointed preforms parallel to the joints was investigated. The flow of resin in the preform was different from that in un-cut preforms. Specimens cut from cured panels were tested in four-point bending tests based on ASTM standard D790-03. The structural stiffness, maximum flexural stress and failure mode of specimens, were investigated. The structural stiffness and failure mode followed clear trends, while the maximum flexural stress was affected by local stress concentration at the joints.

It is concluded that the presence of lap joints in VARTM preforms changes the behaviour during manufacturing and in service. This should be considered in design of parts and simulation of VARTM manufacturing.

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CHAPTER 1

Introduction

1.1 Polymer composites

The performance of composite materials has progressed over the past few decades and industry has noted and used these strong, lightweight and damage-tolerant structural materials. Whilst polymer composites are currently used in a large variety of applications, continued study of these materials and their manufacturing is essential to the integration of composites in more applications.

The most common composite materials are FRP (Fibre Reinforced Plastics), MMC (Metal Matrix Composites) and CMC (Ceramic Matrix Composites). In general terms, composite materials are engineered materials that comprise two or more materials having different properties. In the case of structural polymer composites, the first component is stiff and strong fibres such as glass, aramid or carbon, that give the material its structural potential, while the second component consists of bulk polymer known as the matrix, which binds the fibres together. The matrix often is a thermosetting resin such as polyester or epoxy. The material used as matrix must be capable of conforming to complicated shapes through some manufacturing technique. It must exhibit good resistance to damage, to

temperature changes and to humidity. Typically, the matrix has low mechanical properties, and it is reinforced by the fibres. The fibres improve the structural properties such as tensile and compressive strengths, whilst the resin provides the overall shape to the fibre assembly. Fibres may be oriented in any direction within the matrix, and mechanical properties of the structure can vary widely. Composite materials offer a beneficial combination of the properties of the constituent materials. Figure 1.1 illustrates typical tensile stress-strain curves for fibres, resin and fibre reinforced polymer composites.

Historically, polymer composites have been used primarily in the aerospace sector. However, their unique combination of properties makes them ideal candidate materials for other applications where cost plays a larger role in overall performance assessment. The development of such applications requires research effort in determining how high quality structures can be produced reliably at limited cost. This thesis contributes to this effort for the case of large parts as discussed below.

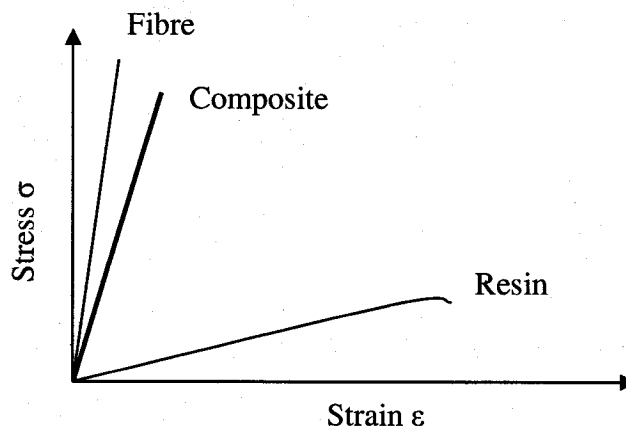


Figure 1.1 Mechanical behaviour of composites and their constituent.

1.2 Manufacturing processes

There are several options available for manufacturing polymer composite materials. Selection of the appropriate process depends on the required quality, performance and cost. The most common methods include hand lay up, pultrusion, filament winding, compression

moulding, fibre placement, resin transfer moulding (RTM), resin film infusion (RFI) and vacuum assisted resin transfer moulding (VARTM). Each of the above methods has different advantages and limitations. The hand lay-up process is economical but composite parts produced have very low quality and are not suited to structural applications. Currently, RTM and VARTM are widely used in industry. Much research has been conducted on these two processes to improve manufacturing and to better understand the behaviour of the resulting composites when subjected to different service conditions.

1.2.1 Resin transfer moulding (RTM)

In the resin transfer moulding (RTM) process, schematically illustrated in Figure 1.2, pre-cut reinforcement in the form of a fabric preform is laid in the lower part of the mould. The upper part of the mould is clamped over the lower part and liquid resin is infused into the mould cavity from an injection port. Vacuum can be applied to the mould cavity from vent ports to assist resin being drawn into the preform. Once the preform is saturated with infused resin the inlets are closed and the resin is allowed to polymerise, or cure. Both injection and cure can take place at higher temperature to hasten infusion and reduce manufacturing time.

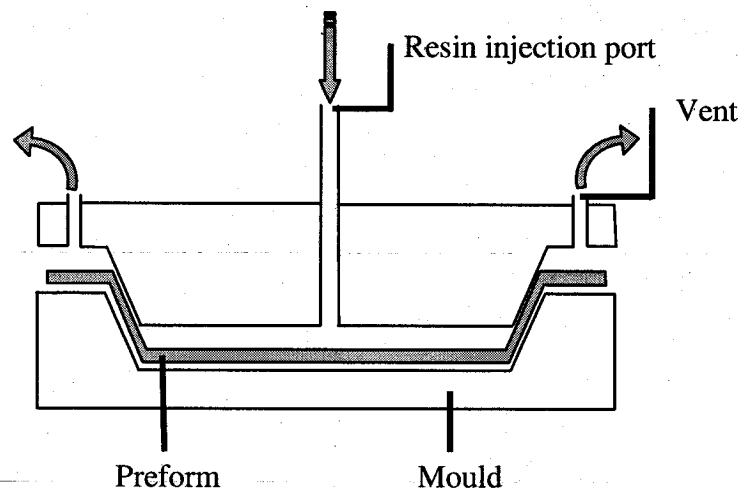


Figure 1.2 Schematic view of the resin transfer moulding process (RTM).

1.2.2 Vacuum assisted resin transfer moulding (VARTM)

Vacuum assisted resin transfer moulding (VARTM) is widely used for the manufacturing of structural and semi-structural polymer composite parts. The process is most appropriate for the production of large non-aerospace parts such as wind turbine blades, roofs for public transit cars or speedboat hulls.

In this process, textile preforms are laid up in the lower part of the mould as in RTM. The preform is then covered with distribution medium, typically an open plastic mesh. The stack is then placed under a sealed flexible vacuum bag. When all leaks are eliminated, resin is infused into the preform under negative pressure. The resin distribution over the whole preform is aided by resin flowing easily through the distribution medium and channels, followed by saturation of preform, Figure 1.3.

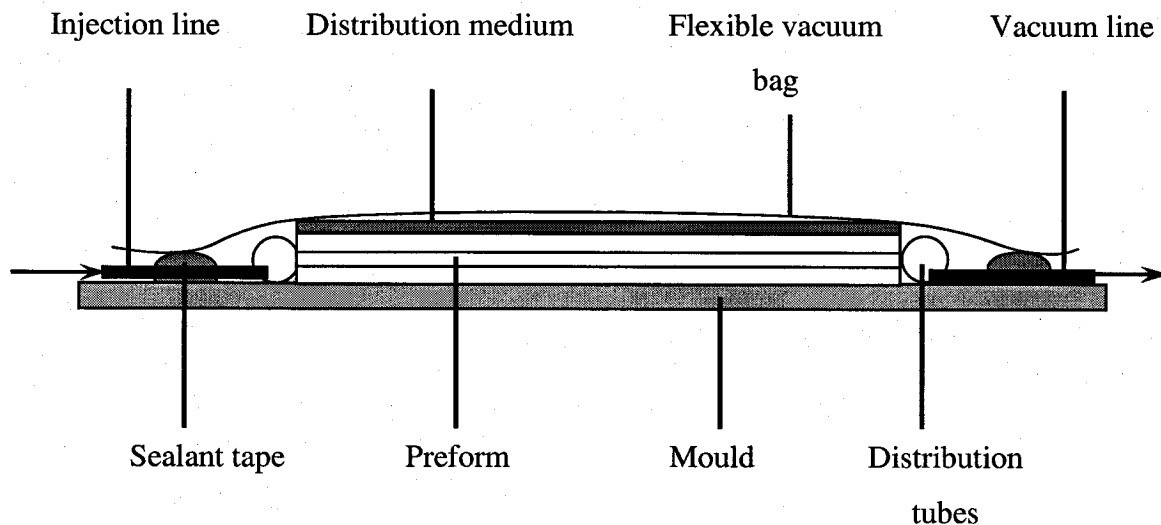


Figure 1.3 Schematic view of the vacuum assisted resin transfer moulding (VARTM) process.

1.3 Manufacturing large composite parts using VARTM

In applications involving very large and thick preforms such as wind turbine blades, multiple layers of textile reinforcements supplied in rolled form are preferred on the grounds

of improved productivity and reduced manufacturing costs. Therefore, the engineering of large composite parts includes the design of a preform made of many textile layers. Each layer is made of a number of pieces of textile reinforcement that are cut and laid along specified patterns with the aim of optimising mechanical performance and reducing weight. A schematic illustration of layering is shown in Figure 1.4.

The preform must also be designed for easy and repeatable manufacture. Reducing the variability of preforms is a very important consideration in all liquid moulding processes, and in VARTM in particular. Any preform feature that may reduce variability can offer potentially important benefits.

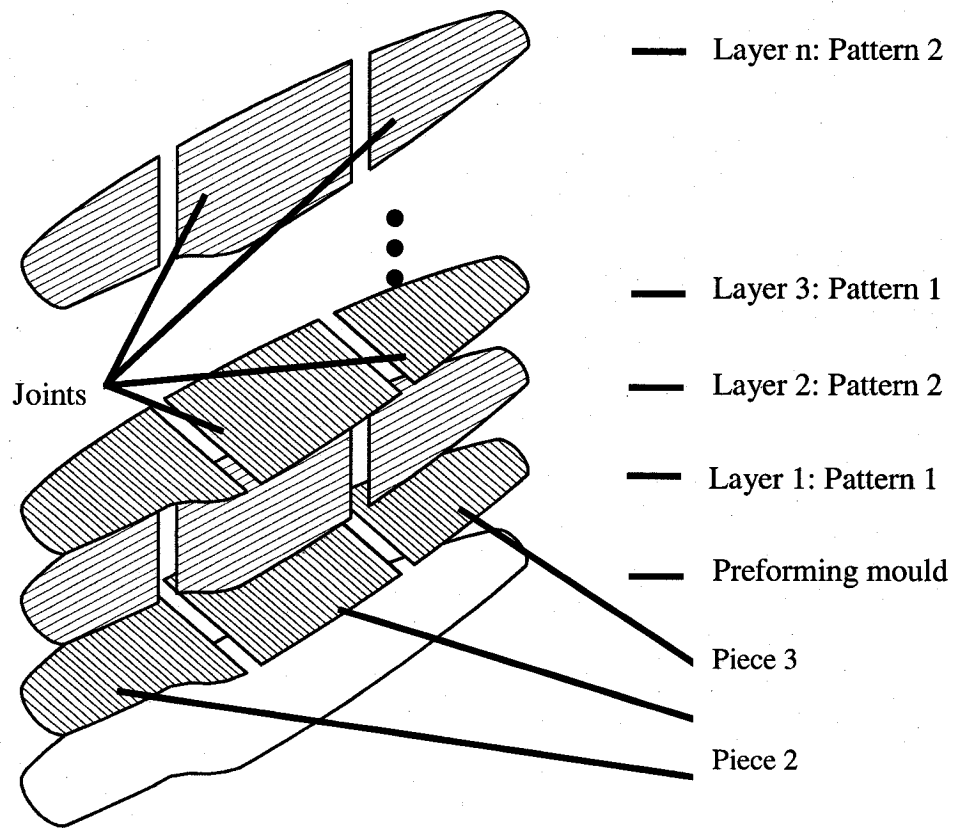


Figure 1.4 Patterns in a preform for VARTM process.

A number of factors must be considered when designing a preform for VARTM manufacturing. For large parts, reinforcement lay-up time is substantial and there is strong economic incentive in minimising the number of different pieces and patterns used to make up each layer through the thickness of the preform. Smaller pattern numbers reduce the

In many cases only 2 or 3 different patterns are used, Figure 1.4. As a result, preforms for large non-aerospace parts often feature superimposed butt joints; however, little information about their processing behaviour or performance is available. Compaction behaviour under vacuum at and around lap joints has not been quantified, no data on resulting distribution of local fibre volume fraction (v_f) at neighbouring points in the preform is available, and little is known on the resulting effect on resin flow or mechanical behaviour. Fibre volume fraction has significant effects on composite manufacturing processes through its relation with permeability and also on material properties including, modulus, failure mode and ultimate strength. Fibre volume fraction is discussed in chapter 3.

1.4 Objectives

This work aims at proposing a comprehensive study on overlap joints in large multilayer preforms for VARTM. The study shall evaluate different aspects of the processing and performance of joints in VARTM. The study considers compaction, flow and mechanical properties of the resulting structures. In order to achieve the main goal, several intermediate objectives are accomplished.

First, a measurement system is developed to measure the thickness of preforms locally during compaction and infusion of resin. The data can be used to determine the fibre volume fraction v_f of the composite material. The fibre volume fraction, v_f , has a direct impact on the permeability of preform and the mechanical properties of the final product.

Next, compaction of overlap joints in different configurations is measured. Flow in jointed preforms is monitored for different lap joint. After curing, the mechanical properties of the composite structures are determined to assess the effect of joints on performance.

CHAPTER 2

Operation principles and calibration of Hall effect sensors for composite preform thickness measurement

2.1 Introduction

When a current carrying conductor is placed inside a magnetic field, a voltage is generated perpendicular to both the current and the field. This principle is known as the Hall effect and the resulting voltage is termed Hall voltage, V_H . The interaction of the magnetic field and current can be expressed by the following equation:

$$V_H \propto I_c \times B \quad (2.1)$$

The Hall voltage, V_H , is proportional to the vector cross product of current, I_c , and magnetic field B . Hall effect sensors can measure the strength and polarity of a magnetic field. As the sensor approaches the field, both the strength of the magnetic field around the conductor and the output voltage increase. A simple relation between the position of the magnet relative to the sensor and the voltage is shown schematically in Figure 2.1. As the separation distance reduces, the absolute output voltage increases, regardless of whether the approaching pole is the north or south pole.

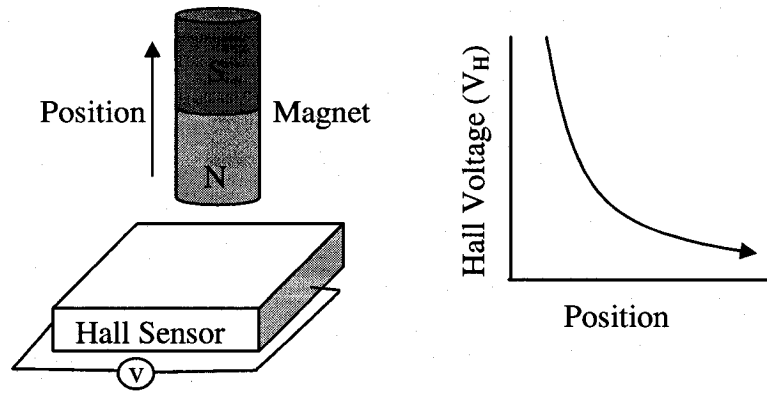


Figure 2.1 Schematic representation of Hall voltage as a function of magnet position.

For a given sensor orientation, a positive output voltage is produced when the north pole of the magnet points towards the Hall effect sensor and a negative voltage is produced when the south pole points towards the sensor. Based on Hall's theory, this phenomenon can be explained as follows. The presence of a magnet above the sensor leads to a concentration of electrons on one side of the sensor as shown in Figure 2.2 . This difference in the concentration of electrons causes an electric potential across the sensor. Depending on the approaching pole the electrons will move in a different direction, resulting in different voltage polarity.

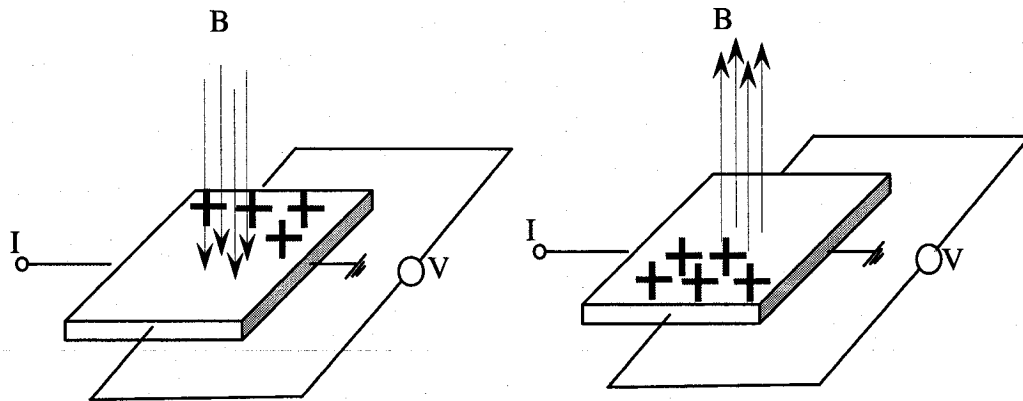


Figure 2.2 Gradient of electron concentration across the sensors.

Figure 2.3 shows a different configuration where the sensor is located between the north and south poles of a magnet; the relation between sensor position and output voltage is

illustrated. In this configuration changes in output voltage as a function of z will be mostly constant over some zone located between the poles, and smaller than their area; no measurable differences in output voltage will appear at different x and y coordinates inside that zone. This configuration has some disadvantages, including general packaging and the presence of two zones of possible sensor saturation close to each pole that limit practical usage.

A calibration curve can be obtained for any given magnet and magnetic field configuration by varying the position of the sensor in the field. These curves are used when converting output voltage into sensor position. Knowing the general trend shown by the curves and the expected behaviour of the sensor inside a specific type of field is helpful when the setup and experimental apparatus are designed.

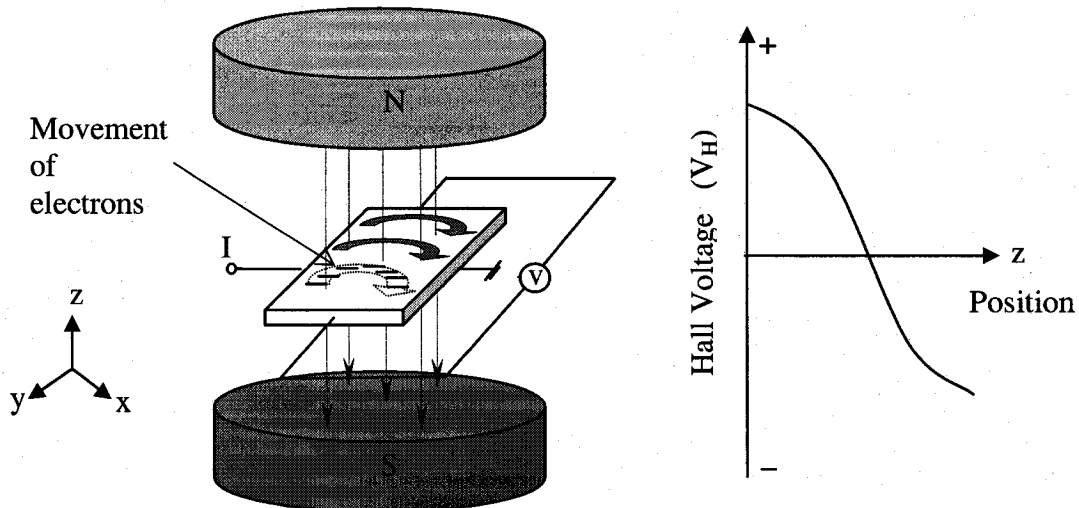


Figure 2.3 Schematic representation of Hall voltage versus position of conductor inside magnetic field.

2.2 Background and literature review

The composite manufacturing industry aims at producing high quality structures with decreased scrap parts, better surface finish, reduced cost and smaller environmental footprint. This requires a better understanding and control of production processes. VARTM, a manufacturing process which is seeing increased usage because of its ability to produce

high fibre volume fraction (v_f) structural parts with limited volatile emissions at low cost, is typical of composites manufacturing processes where good control over manufacturing operations is essential to repeatable and economical production. In VARTM the thickness of the preform varies during processing therefore the fibre volume fraction, which is the fraction of the volume in the composite part that is occupied by the fibres, fluctuates also. Fibre volume fraction, permeability, flow and mechanical properties are closely related in VARTM. Any change in the thickness of the preform during manufacturing changes the fibre volume fraction; in turn this strongly affects flow of the resin through the preform. To predict and/or control the process based on modelling or measurements, one must have good knowledge of each parameter at all times and all local positions including the fibre volume fraction, and therefore the preform thickness.

A variety of techniques were proposed for measuring the thickness of composites during or after manufacturing. A large body of literature exists in the latter case where measurements are made in the context of non-destructive testing (NDT) using ultrasound, microwave [1], optical fibres [2] etc. Ultrasonic testing is a widespread example where measurement of the thickness requires a fully consolidated composite plate. Some techniques developed for measuring the thickness during manufacturing apply to prepreg-based routes where typical changes in thickness are much more limited when compared to VARTM and happen over longer times. Other techniques apply specifically to the manufacturing of carbon-based composites as they rely on properties that are specific to these fibres. The techniques discussed below are based on linear variable differential transducers (LVDTs), strain gages, optical methods, eddy current and Hall effect sensors.

LVDTs have been used to measure the thickness of the composite plates during VARTM processing and cure [3, 4]. In order to measure the thickness of the composite, LVDTs were mounted on supports connected to the fixed part of the mould. The moving tip of the LVDTs were positioned in contact with the vacuum bag, above the desired points. During processing the tip of a LVDT follows the surface of the laminate as thickness varies. The primary concerns in using LVDTs are the relatively high costs of the equipment and set-up procedures. Tackitt and Walsh [5] used an array of 25 LVDTs arranged in 5 rows of 5 to monitor and capture the surface deformations that occur during the infusion of dry fibrous performs at discrete points over a surface of 609.6 by 609.6 mm. These surface deformations

correspond to thickness changes in the preform, so the net result was a quantification of dimensional changes that took place during processing. SMARTweave (Sensors Mounted As Roving Threads) were also used in their work to correlate resin flow with the surface displacements during infusion, using either a line resin source or point resin source. SMARTweave uses the conductivity of resin to determine if resin is impregnated preform, the circuit between the sensing and excitation is completed. Surface displacements were displayed as three-dimensional plots so that the entire surface of the part may be visualized during infusion.

Kim and Jun [6] proposed to measure the thickness of thick composite materials during autoclave manufacturing and cure using strain gauges. In this method, the thickness variation is measured by affixing several strain gauges vertically on the edges of the specimen or those of a hole located where the measurement is to be made. The difficulty of affixing strain gauges on an uncured composite is a major limitation to this method. Other disadvantages include changes in the structural properties resulting from the holes, and possible adverse effects of the gauges on the laminate.

Bayldon and Daniel [7] used Moiré topography, a technique for observing contour lines of an object, for monitoring thickness variation in wet and dry preforms for VARTM. Moiré topography is suitable for the non-contacting measurement of length, angle and surface shape changes from an initial form [8]. In this technique a series of patterns are used for measuring geometrical characteristics. Their operation is based on interaction between two different gratings. When these gratings are parallel, dark and light fields are not observed. A small misalignment leads to the appearance of dark and light fields; this can be quantified by measuring the distance between two successive dark fields. This principle can be used to derive the characteristics of a surface [9].

Bayldon calculated the intensity of light shined through a grid and on the preform, and reflected again through the grid and to a camera, for each point on the surface of the preform. Through mathematical equations they related the measured intensity to a number of quantities including preform thickness.

Anderson et al. [10] developed a stereoscopic digital speckle photography system (DSP) to measure thickness variations in VARTM. This stereoscopic technique is capable of recording three-dimensional visual information. In this technique two images are captured

by two different cameras and are filtered and divided into sub-images. Image processing methods provide measurement of height variation or out-of-plane movement. The noise control and set-up process are drawbacks of the method.

The Eddy current method is a technique where the circulating flow of electrons in the conductor caused by the motion of a conductor in a magnetic field is monitored. To measure the composite material thickness during the manufacturing process, the conductor is placed on top of the composite laminate, and the current is measured and used to find the position [11]. In Eddy current method, in contrast with Hall's method that measures the voltage in the conductor, the induced current in the conductor is measured to determine the position of the sensor.

Hall effect sensors have been used to measure the thickness of composite panels both during and after cure; most applications were in the context of autoclave prepreg manufacturing routes [12]. It was found that the panel's chemical state, reinforcement configuration, resin type and stacking sequence have little effect on sensor signal for various thermoset and thermoplastic composite structures. It has been indicated that sensors can be used to detect bag leaks and seal-offs through sharp increases in thickness in the affected regions of the part during the cure cycle. Also, it was pointed out that Hall effect sensors can be used successfully for on-line control of thickness during manufacturing within sensor fusion strategies [13].

Hall effect sensors enable the design of non-destructive measurement systems free of direct contact between sensor and laminate. There is no theoretical limit to their life, and they provide absolute readings so there is no need to recalibrate for every usage. A single calibration of the sensor for a specific setup allows repeated use. The calibration curve showing the relation between the voltage and the displacement can be used in actual test provided that the electromagnetic environment around the sensor is similar. This repeatable response is characteristic of Hall effect sensors operating in a temperature range as wide as -40°C to 150°C and in some cases detecting excitations with frequencies up to 100 kHz. These characteristics combined with their low initial cost make Hall effect sensors a suitable and interesting option for industrial thickness measurement. In this work, calibration and actual measurements were always performed at room temperatures of $21 \pm 2^\circ\text{C}$; sensor behaviour was constant over that range.

During the manufacturing process of Hall effect sensors, there is a possibility of a slight misalignment of the two contacts on the conductor installed to pick up the Hall voltage V_H . Due to this misalignment, a voltage known as offset voltage is present. In other words, after running the current through the conductor, a small output voltage can be read even when no magnetic field goes through the sensor. This offset voltage is known to be a major fabrication issue with Hall effect sensors. In order to minimize this, a common bridge configuration method is used where in effect multiple sensors are integrated into a single microchip.

One of the practical challenges of using Hall effect sensors consists in preparing comprehensive calibration data, including readings for different chip locations and angles in the magnetic field. To better understand the difficulty associated with this task, even within a single plane parallel to the magnet face an infinite number of readings would result from different positions and angular orientations of the sensor. In this work, it was decided to carry out tests and calibrations using sensors fixed in rotation that only moved axially relative to the surface of the magnets.

2.3 Apparatus for calibration and measurement

The apparatus used for local thickness measurement consisted of 12 Melexis MLX 90215 low-cost Hall effect microchip sensors with 15 Digi-Key 469-1006-ND permanent ferrite magnets measuring 25.4 x 50.8 x 6.4 mm, shown in Figure 2.4.

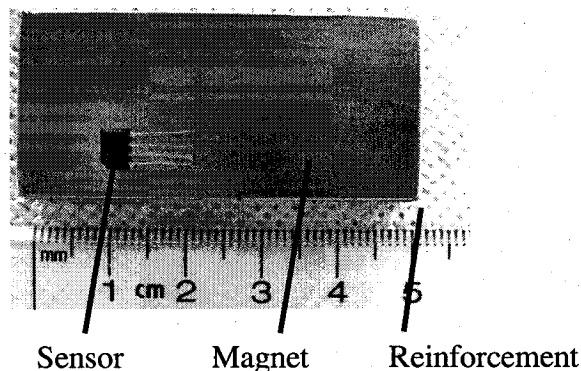


Figure 2.4 Melexis Hall effect sensor and Digi-key magnet.

Data acquisition was performed using a National Instruments LabView™ system made of a PCI-6224 32-channel input card, CB-68 LPR connector block and 2 SHC68-68-EPM shielded cables. Schematic set-up is shown in Figure 2.5 . Sensors located in the magnetic field are connected to the connector box through shielded cables.

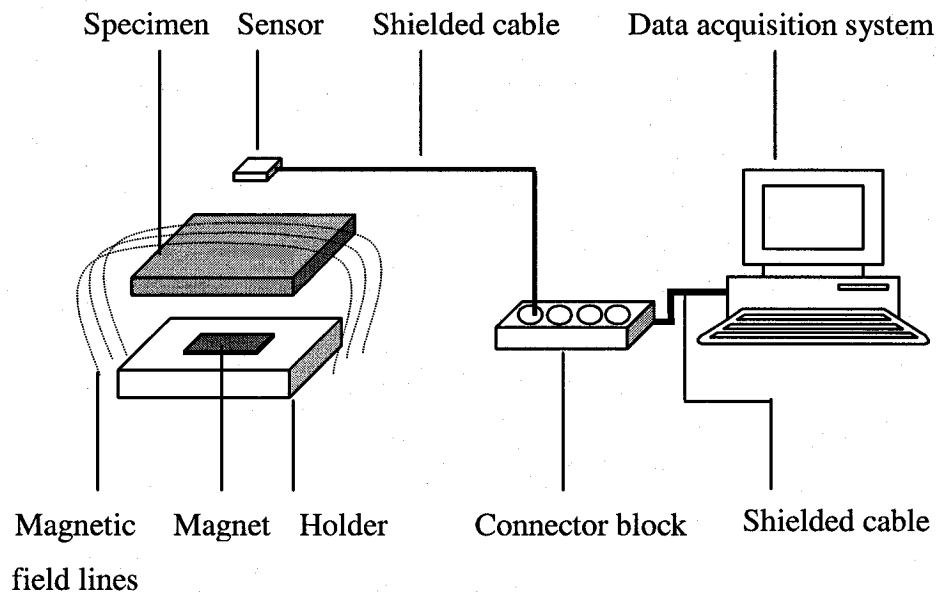


Figure 2.5 Schematic set-up for thickness measurement.

Sensor wiring compatible with this specific data acquisition card and application is shown in Figure 2.6 . The excitation input current supplied by the connector block enters through pin 1. Pins 2 and 3 are grounded through the ground channels in the connector block, and the voltage difference between pin 4 and ground is recorded as output by the data acquisition card. The characteristics of a typical MLX 90215 Hall sensor are listed in Table 2.1.

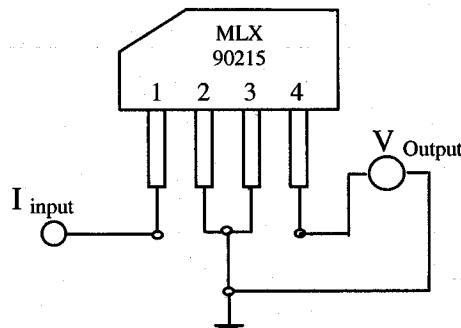


Figure 2.6 Melexis MLX 90215 Hall effect sensor wiring.

Table 2.1 Performance specification of Melexis MLX 90215 Hall effect sensor.

Parameter	Range
Maximum operating voltage (V)	5 + 10%
Magnetic flux density (mT)	Unlimited
Input current (mA)	12
Operating temperature range, TA(°C)	-40 to 150
Storage temperature range, TS (°C)	-55 to 165

A typical curve showing output voltage as function of magnetic flux density for this specific sensor is shown in Figure 2.7 [14]. This graph, supplied by the sensor manufacturer, features both aspects of the behavior discussed in section 2.2.

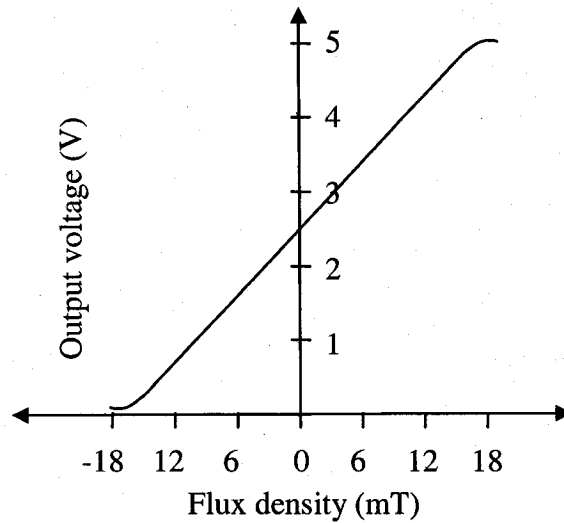


Figure 2.7 Output voltage as a function of flux density.

2.4 Calibration and results for local thickness monitoring

The sensor-magnet interaction is critical to the local thickness monitoring system. Figure 2.8 shows signal recorded from a sensor displaced along axes x, y and z above one

associated magnet using a 3-axis device. The 3-axis moving device was selected and designed carefully so as to ensure that it does not interfere with the magnetic field.

Due to the sensitivity of the sensor and the strong magnetic field in close proximity to the magnet, readings for distances lower than 40 mm from the magnet's top face gave a constant value. Therefore, point (0, 0, 0) was chosen 40 mm directly above the centre of the top face of the magnet. The sensor was carefully oriented and all rotations were locked.

The figure shows the readings from a Hall effect sensor displaced in 3D space above one quarter of the magnet. The sensor readings were recorded in steps of 10 mm along axes x , y and z until the effect of the magnetic field became negligible and readings did not show significant differences. It was observed that changes in signal are strongest for changes in height (z), within the region located directly above the magnet centre that was used as working range.

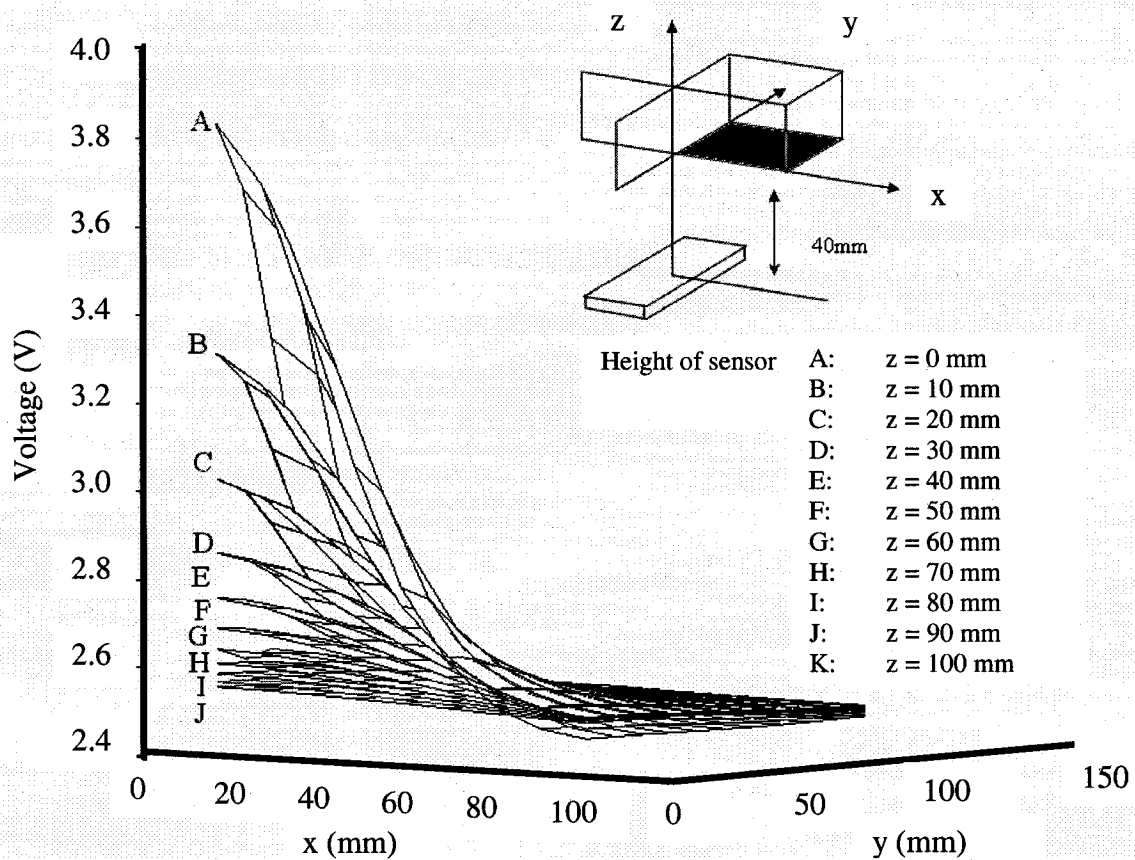


Figure 2.8 Recorded signals from a sensor displaced along axes x , y and z .

Above the centre of the magnet sensors are more sensitive to vertical displacements along z than to in-plane displacements along x and y , Figure 2.9 . This can be explained from the fact that above the centre, surfaces of constant magnetic flux density are generally parallel to the surface of the magnet while magnetic lines are perpendicular to it. As the point of interest moves away along x and y the magnetic lines become progressively less perpendicular to the surface of the magnet. Above the magnet centre, any movement in the z direction will result in positioning the sensor in a significantly more/less dense region of the magnetic field, compared with motions along the x or y directions. This characteristic is helpful as in a well designed measurement apparatus of the sensors will provide reliable position results along the z direction and the effects of any small displacements along the x and y directions will be negligible.

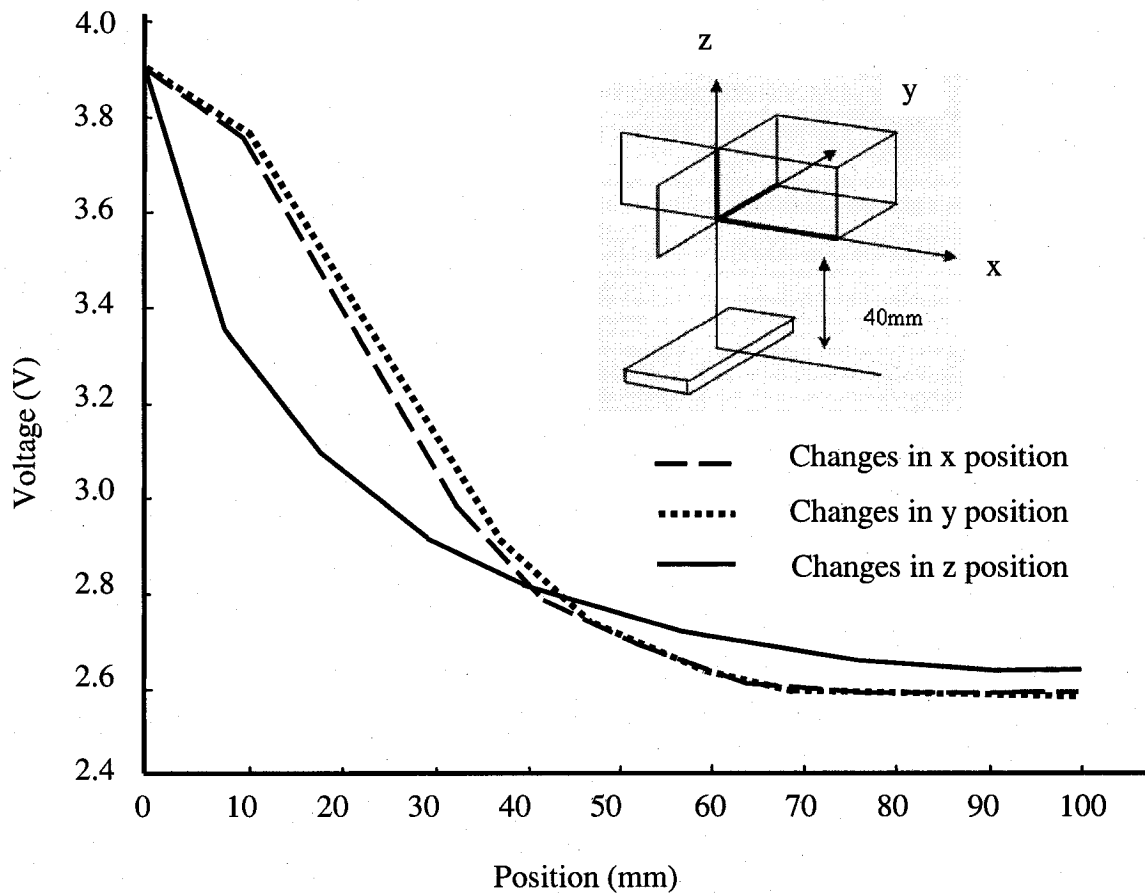


Figure 2.9 Comparison of changes in signal amplitude for displacements along x , y and z .

Figure 2.10 shows signals recorded with one sensor located at different heights (z) directly above different magnets. Each point on each curve is the average of 5 readings. The figure shows that for this simple configuration all curves show the same trend with only minor discrepancies. Furthermore, it was observed that a given sensor gives similar signal when used with different single magnets. The tests showed very good consistency.

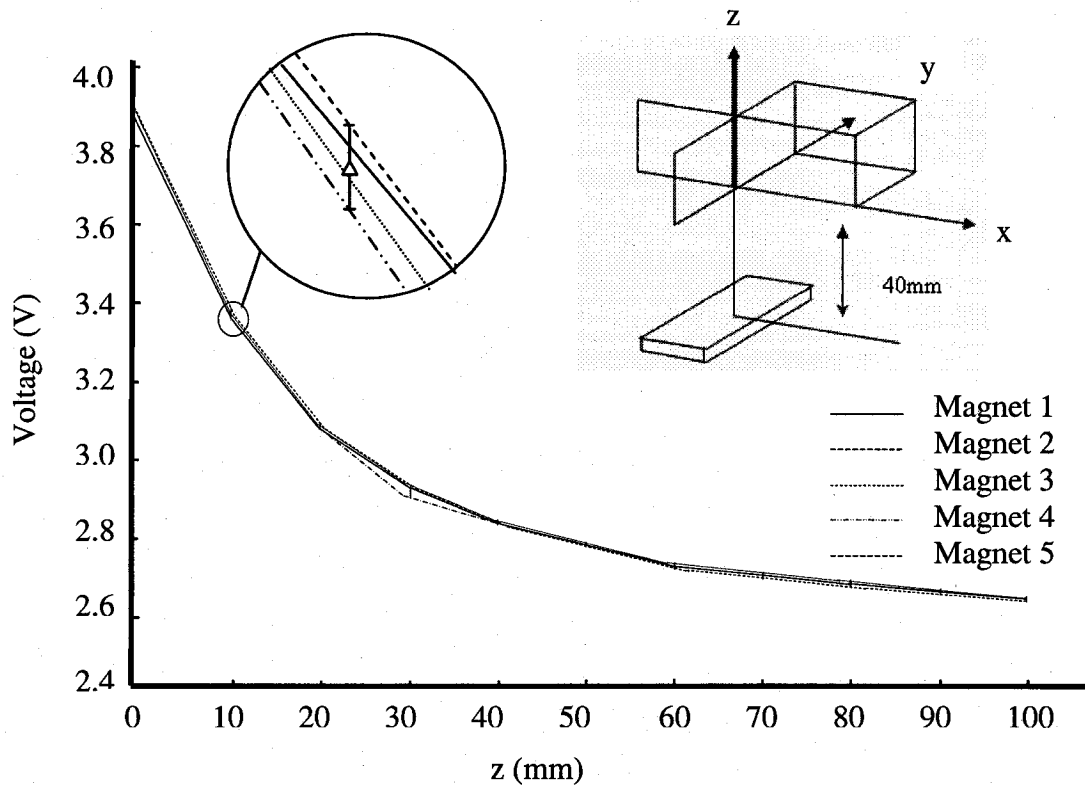


Figure 2.10 One sensor located at different heights (z) above different magnets.

Symmetry of the signal about the magnet centre was also verified, as shown in Figure 2.11. The 40 mm minimal vertical distance ensured saturation avoidance; in a practical context this indicates that the chosen setup can be used with magnets embedded fairly deeply in a non-metallic mould.

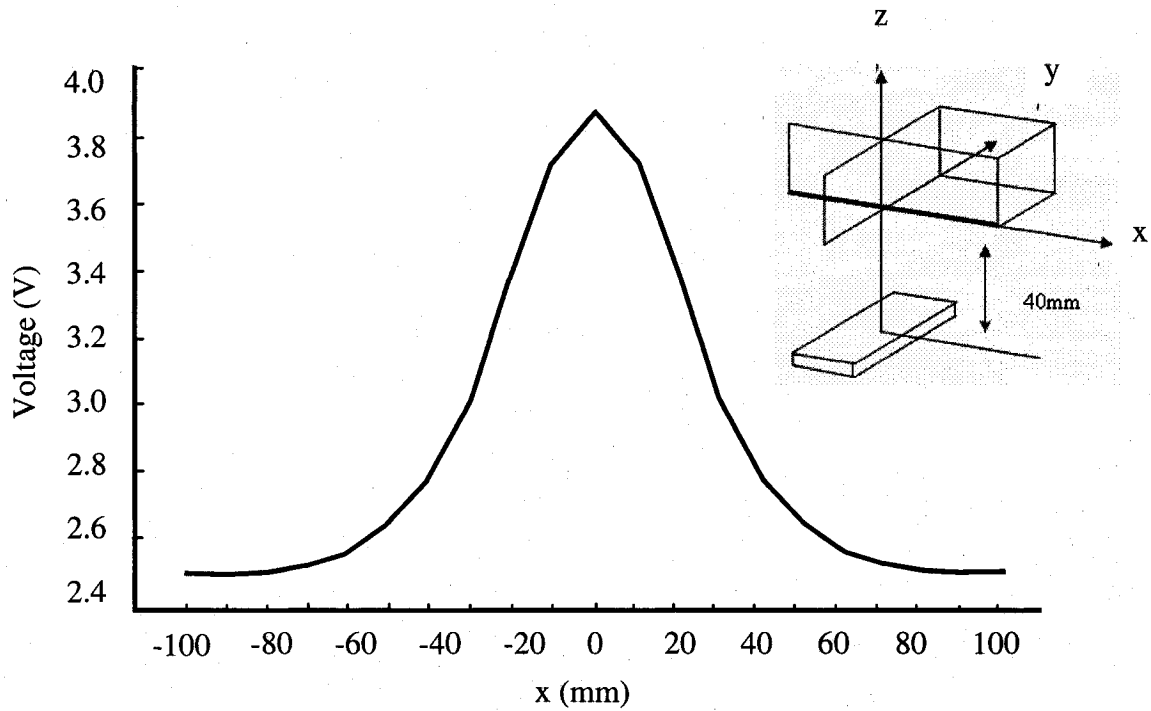


Figure 2.11 Symmetry of the signal about the magnet centre.

In order to have a large area covered by a more constant magnetic field, a holder was designed and made for positioning 15 magnets as shown in Figure 2.12 . Positioning of individual magnets in this magnet plate was ensured by inserting individual magnets in this CNC-machined PMMA support in 5 lines of 3 magnets separated by gaps 6.35 mm wide along both x and y, Figure 2.12 . The magnet plate area was 127.0 x 114.3 mm inside centres of the outermost magnets. The 12 sensors were grouped in 4 lines L1 to L4 of 3 units S1 to S3, S4 to S6, S7 to S9 and S10 to S12 respectively. Each sensor was positioned above the centre of a magnet. The area inside the centre of the outermost sensors was 95.3 x 114.3 mm. More detailed on apparatus appears in chapter 3.

The next step consisted in investigating the behavior of sensors displaced along x, y and z above the magnet plate. Figure 2.13 shows signal from sensors displaced along x and y between the centers of neighbouring magnets and along z above the magnet plate, using a 3-axis positioning device. When using the 15-magnet plate, $z = 0$ corresponds to a vertical distance of 40 mm above the surface of the magnets. The variation of signal with z shown in Figure 2.13 compares with the variation observed for a single magnet (Figure 2.8), whilst variation of signal as a function of x and y depends on the position on the plate: in the centre

this variation is virtually null whilst at the edges of the magnet plate it is of similar amplitude for x , y and z . Discontinuities are present in the signal, indicating that different sensors give somewhat different signals as a function of z over the magnet plate.

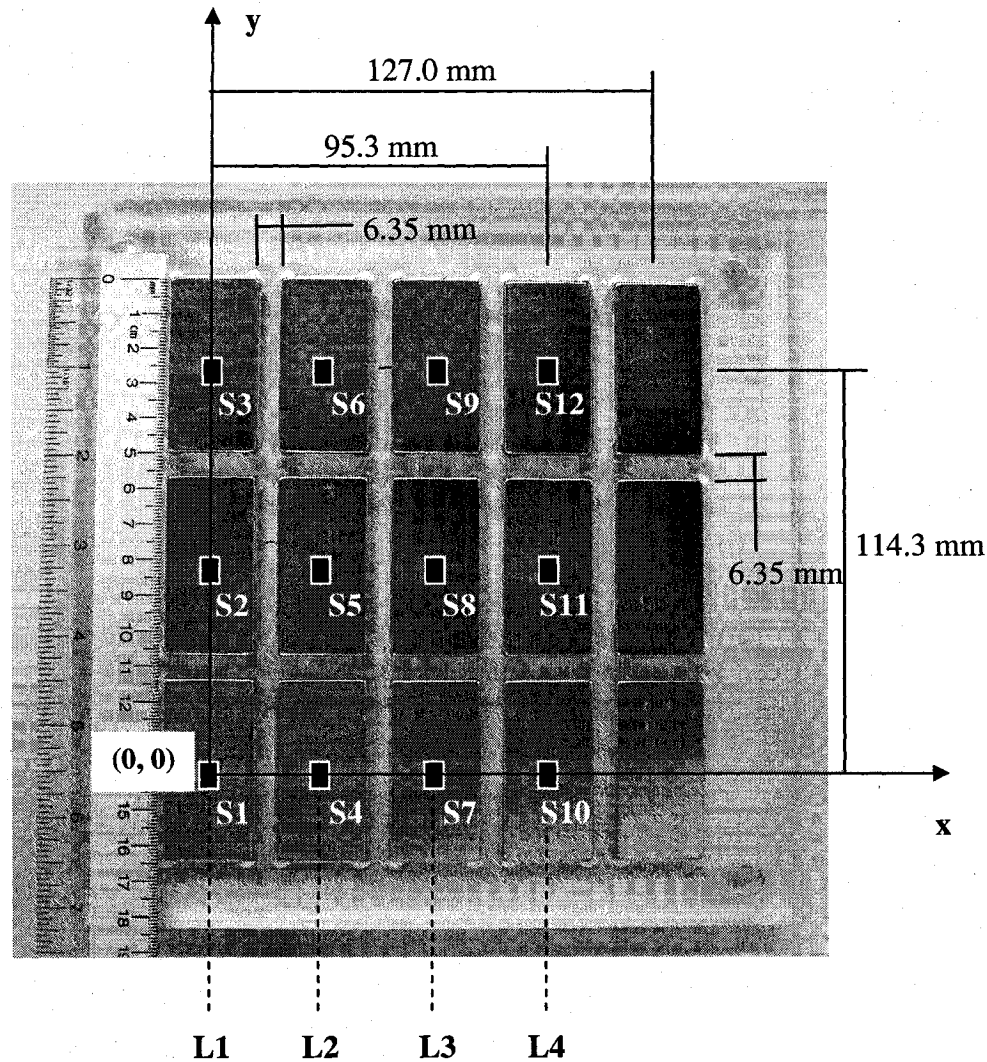


Figure 2.12 Labelling and positioning of the sensors.

In this work, each sensor was carefully positioned above the centre of its corresponding magnet and was always used in the same x - y position; calibration of each magnet was performed in that precise x - y position over the magnet plate, as discussed below. Three complete and independent sets of signal data were gathered for the magnet plate and showed repeatability with negligible fluctuation.

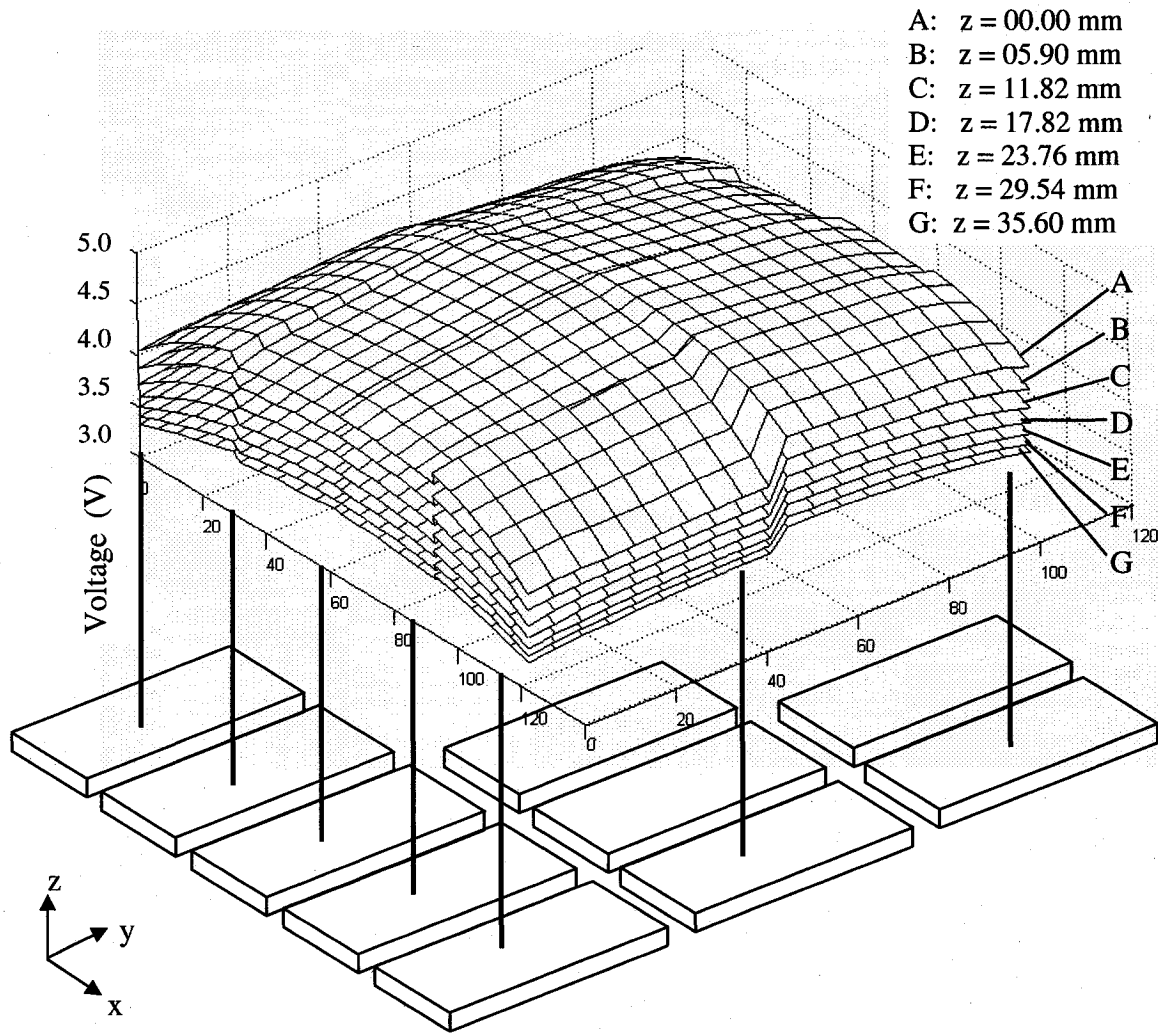


Figure 2.13 Signal from sensors displaced along x, y and z.

Calibration of each sensor as labeled in Figure 2.12 was conducted using a digital positioning table. Both the sensor and magnet plate were positioned away from parts that could interfere with the magnetic field, using non-magnetic holders. The z co-ordinate was expressed as a function of signal using a 3rd degree polynomial. One calibration curve appears in Figure 2.14 where 30 data points were recorded at each z co-ordinate. All calibration curves for all sensors are shown in Appendix A. Minimal sensor-magnet

separation was 40 mm ($z = 0$) with the sensor still effective at $z = 100$ mm; this range easily covers typical mould and preform thicknesses.

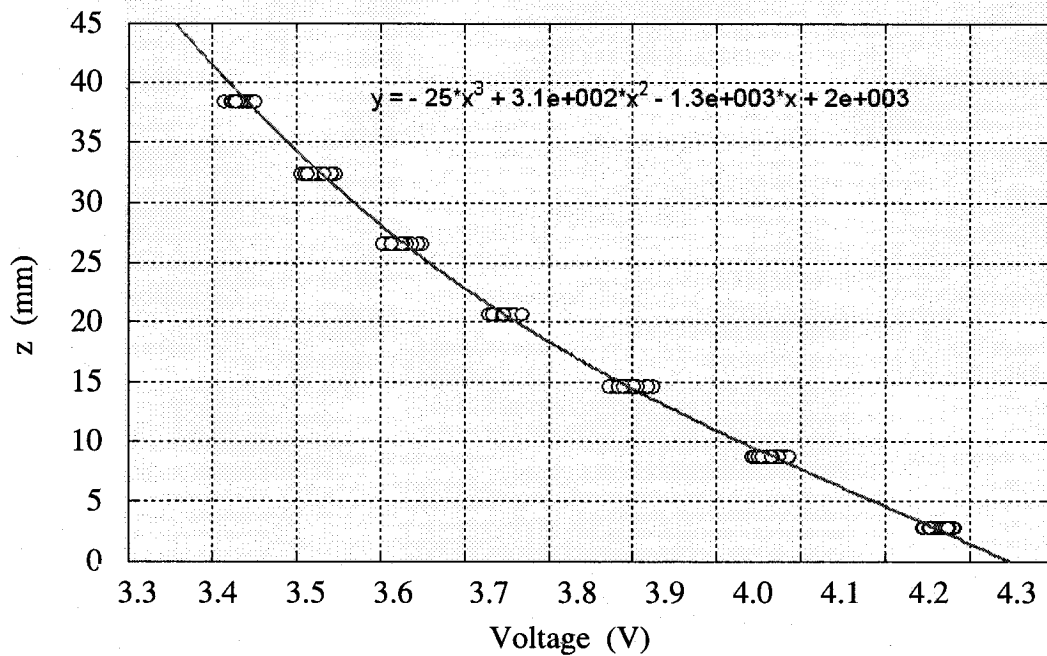


Figure 2.14 Co-ordinate z as a function of output voltage, 3rd degree polynomial.

Thickness measurements obtained from Hall effect sensors were compared for accuracy with measurements made using a linear variable differential transducer (LVDT). In order to evaluate and compare results of Hall effect sensor and LVDT in one sample test, LVDT calibration was necessary. Therefore, displacements of the tip of the LVDT were measured using a micrometer using an experimental setup shown in Figure 2.15.

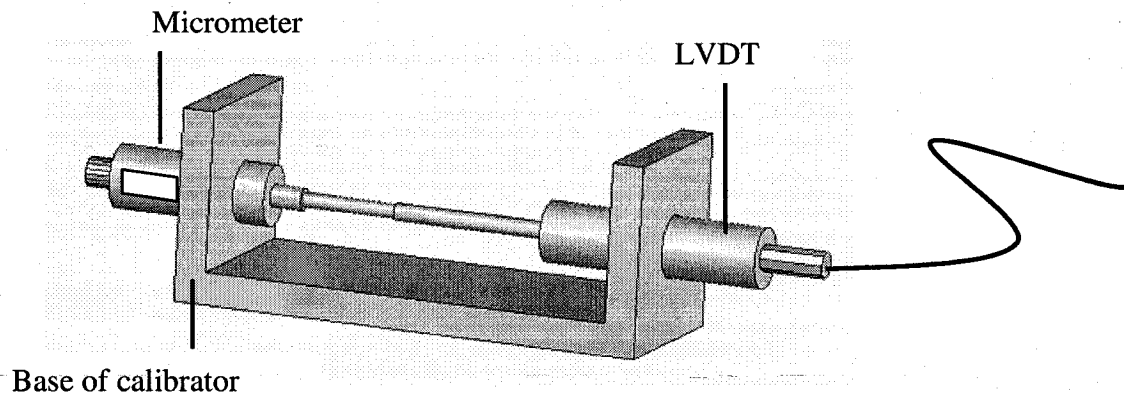


Figure 2.15 LVDT calibration experimental setup.

A series of positions and the corresponding signals were measured and recorded; the voltage corresponding to each position was recorded 50 times and the average voltage was obtained. Displacement as a function of voltage is plotted in Figure 2.16 .

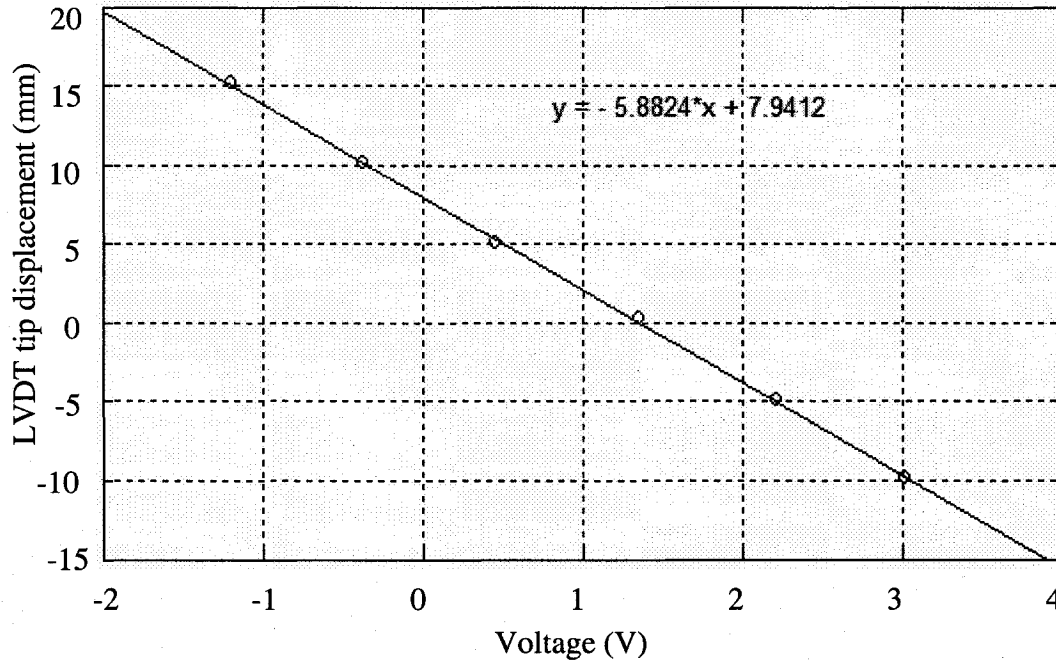


Figure 2.16 Calibration curve for LVDT.

Initial validation of thickness measurements obtained from the Hall effect sensors was performed with Hall effect sensor and LVDT placed in the exact same location in generating successive, full compaction curves. Figure 2.17 shows the evolution of thickness as a function of pressure for a preform made of 24 layers of reinforcement matt fibreglass (R1) covered under a flexible vacuum bag. Detailed technical information on reinforcement R1 is provided in Chapter 3. In a first group of five compaction cycles, vacuum was applied to the preform until absolute pressures moderately close to zero were reached under the bag. Data from the Hall effect sensor was recorded during the 5 cycles and vacuum was removed each time. After the 5th cycle the sensor was removed from the bag, and a 6th compaction cycle was applied. During this last cycle LVDT measurements were gathered. These compared very well with the average trend obtained from the sensor. Hall effect sensor data contained noise. Therefore, to reduce the noise, a larger number of the readings was taken and averaged.

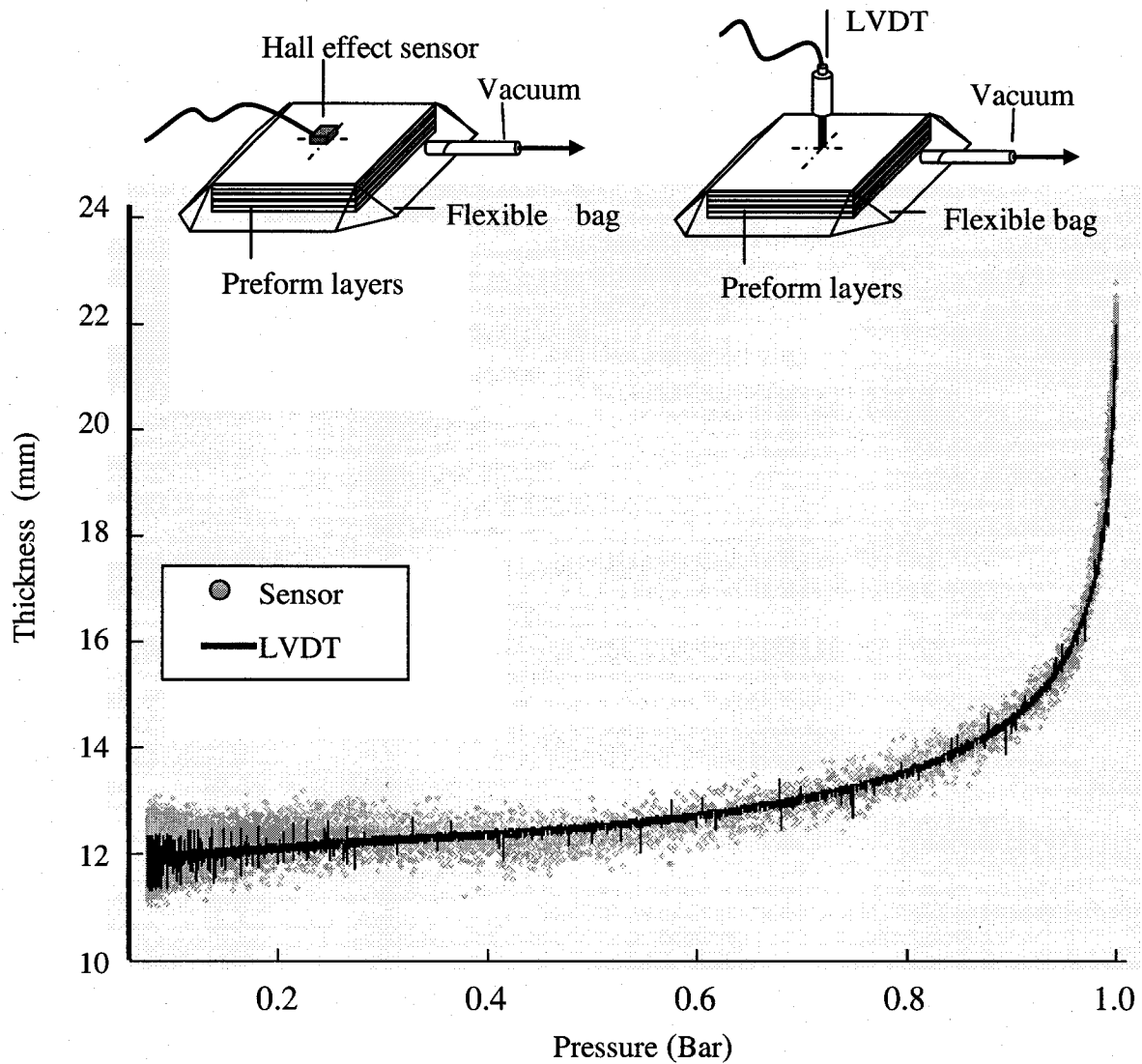


Figure 2.17 Comparison of LVDT and Hall effect sensor thickness measurements.

Preforms were compacted to near zero absolute pressure five times whilst equipped with Hall effect sensors. Compaction data was recorded for each cycle. Whilst time and cycling are known to affect reinforcement compaction at higher pressure [15, 16], repeated compaction tests confirmed that compaction of selected matt and woven reinforcements under vacuum are essentially unchanged upon cycling, Figure 2.18.

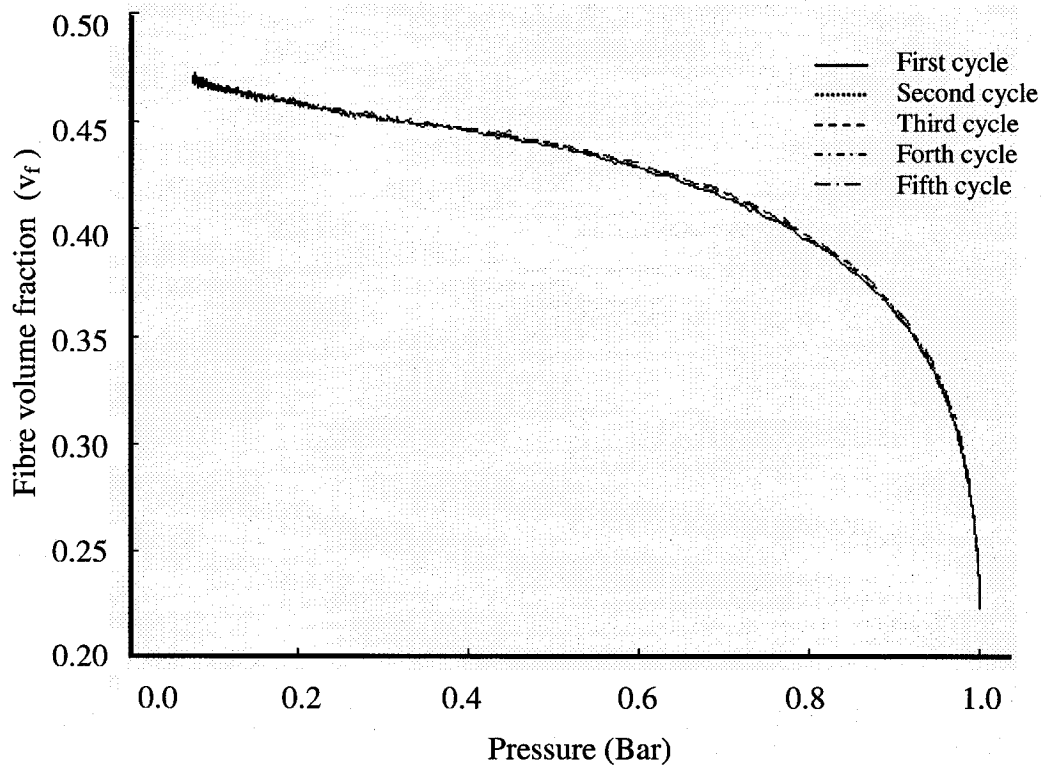


Figure 2.18 Repeatability of vacuum cycles.

2.5 Results of fibre volume fraction measurements

The same test procedure used for comparison of LVDT with Hall effect sensors was used in conducting initial tests on two reinforcements, one random matt, R1, and one woven fabric R2. Results of extensive tests performed on using these reinforcements appear in the following chapter, along with detailed technical information on the reinforcements. The initial tests reported here were conducted to validate the above apparatus in the actual experimental context: 12 sensors were used simultaneously in each test, no repeated compactions were recorded, and the final thickness at each point was verified after compaction using an LVDT (Figure 2.19). Data points were acquired every 1 ms for each sensor with typical tests lasting 180 s and 90 s respectively for random matt reinforcement

R1 and woven fibre glass reinforcement R2. Noise from the Hall effect sensors was reduced using numerical data averaging through pooling of groups of 50 points in the first case and 25 points in the latter.

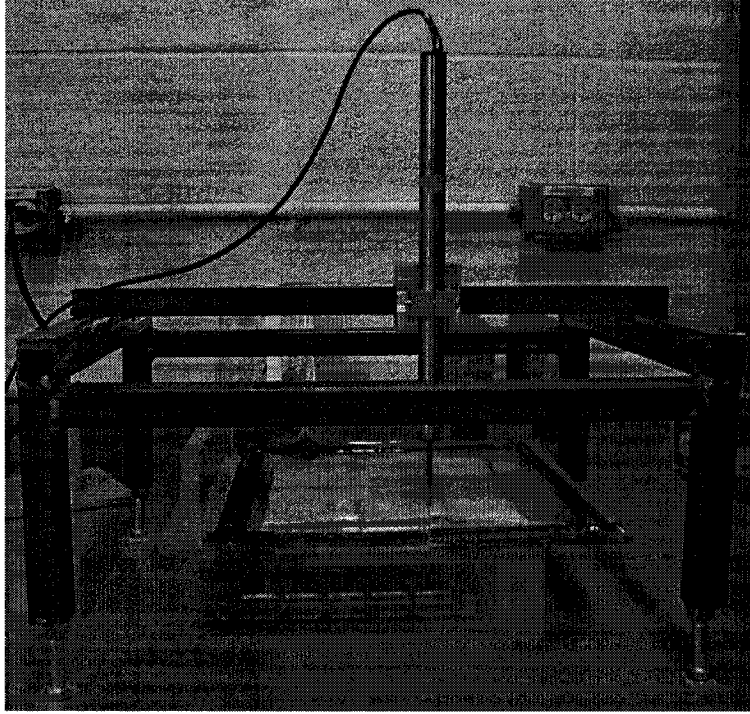


Figure 2.19 Verification of measured thickness with LVDT.

One of the most important characteristics of a composite material is the volume rate of fibres in the material to the total volume of the composite. This ratio, known as the fibre volume fraction, v_f , evolves during compaction in VARTM manufacturing. Equation (2.2) was used to calculate fibre volume fraction, v_f , as a function of thickness for matt and woven preforms.

$$v_f = \frac{\text{surface density} \times \text{number of layers}}{\text{thickness} \times \text{density of material}} \quad (2.2)$$

Surface density is defined as textile mass per unit area; the actual measurement technique is explained in more details in chapter 3. The density of material, glass, was 2.560

g/cm^3 . Curves of the local fibre volume fraction v_f as a function of vacuum level appear in Figures 2.20 and 2.21 for preforms made of matt reinforcement R1 and woven reinforcements R2, devoid of joints. For each test, individual curves are presented only when compelling agreement between values of the final thickness measured using the Hall effect sensors and the LVDT was obtained. This verification technique was used for all compaction tests presented in this thesis. It is assumed that cases where poor agreement in the final thickness was obtained resulted mainly from rotation of a sensor around one of its axes; this has been observed physically on some occasions.

Figure 2.20 presents results for random matt R1. The expected stiffening behaviour was observed. Stiffening describes the increase in stiffness of preform observed as compaction proceeds; practically, preforms progressively become increasingly difficult to compact as v_f increases. The maximum fibre volume fractions recorded at pressure levels close to 0 bar (absolute) were in the expected range. Furthermore, variability of v_f was satisfyingly low. Similar results were observed for the woven reinforcement R2, Figure 2.21. However, fluctuations in v_f values were generally higher, and so was variability. This could result from the reduced numerical averaging of thinner R2 reinforcement preforms made of the same number of layers; it is also possible that the larger spread in v_f data results from the more pronounced surface topology of woven reinforcements. LVDT data was generally well validated with reinforcement R2 but again some curves had to be discarded.

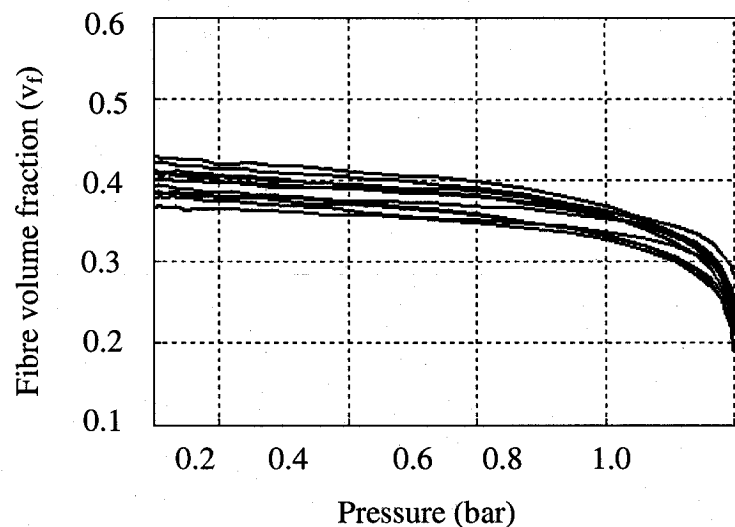


Figure 2.20 Local fibre volume fraction v_f as a function of vacuum level for matt reinforcement R1.

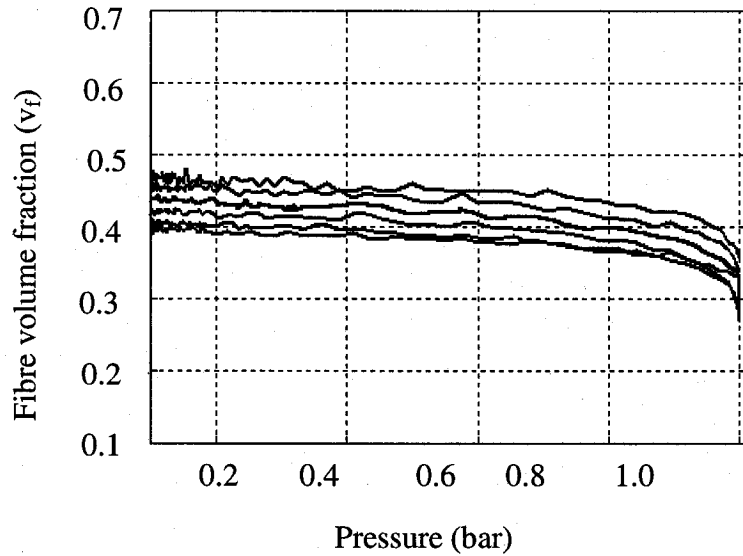


Figure 2.21 Local fibre volume fraction v_f as a function of vacuum level for woven reinforcement R2.

The recorded fibre volume fraction close to 0 bar absolute pressure is in the expected range for both materials, with v_f values around 40% for matt R1 and above that value for weave R2.

2.6 Discussion

This chapter reports the characteristics of Hall effect sensors to be used for monitoring the thickness of VARTM preforms during composites manufacturing. Extensive calibration data was reported, comparison with LVDT measurements were presented, along with initial results of compaction tests where an array of sensors was used to measure local v_f over part of two preforms. The work shows that Hall effect sensors can be used in this application.

During calibration, carefully oriented Hall effect sensors were displaced in translation using a positioning device with all rotations locked. Such well-controlled displacements generally correspond to the measurement of compaction in composites using

Hall effect sensors depicted in the pioneering work of Saliba et al. [13] where stacks of 10 to 15 plies of prepreg were consolidated under a stiff caul plate. Even in that case, the authors mention a flotation issue where displacements of the caul plate in its plane lead to some fluctuation in the signal read from the Hall effect sensors. Given the nature of the work presented in this thesis, one cannot guarantee that all sensors moved along a normal to the laminate and did not rotate along their axes, especially in the vicinity of joints. This limitation was overcome in the compaction trials reported here by using LVDT measurements to validate the final thickness of the preforms systematically in all trials and at all points.

Sensors used in the trials reported in this chapter should theoretically lead to similar thickness measurements for a given reinforcement R1 or R2. This was not always the case and some of the curves were removed from the results presented, as mentioned above. Curves only had to be removed when the corresponding data was very clearly outside of limits that one may reasonably associate to physically possible thickness values, along with clear lack of agreement with LVDT final thickness measurements; sensors that were rotated or displaced in the horizontal plane were clearly identifiable.

Despite of this, there is necessarily some noise associated to secondary sensor motion in the curves presented above. The results show clear and reproducible trends, and they are well validated by LVDT measurements. Furthermore, the overall variability of v_f in the retained curves is perfectly acceptable for the type of reinforcements used. Finally, sensors were used in a configuration where they are significantly more sensitive to displacements along z than along x or y . Still, improvements remain possible. Hall effect sensors offer appealing advantages such as good repeatability, limited size, low cost, absolute distance measurement and non-contacting operation.

CHAPTER 3

Compaction behaviour of lap joints in preforms for VARTM

3.1 Introduction

The expression Liquid Composite Moulding (LCM) identifies a group of manufacturing processes including resin transfer moulding (RTM), vacuum-assisted resin transfer moulding (VARTM) and resin film infusion (RFI) among others. Manufacturing operations can be summarized into three main steps: performing, infusion and resin cure. The introduction of a fluid (typically a thermosetting polymer resin) into a preform under a negative fluid pressure gradient is called infusion. In VARTM the infusion is defined and controlled by two phenomena: the compaction of the preform and the flow of resin. Their interaction is a major and unique characteristic of VARTM processing. Typically, the behaviour of preforms in compaction is not linear. The resistance to flow, which is quantified by Darcy's law, is characterized by permeability values that vary with position and time. Both phenomena are linked by the local fibre volume fraction.

VARTM is a well-suited manufacturing process for large parts; however, preforms for large parts can not be made from one piece of textile reinforcement because of reasons related to draping double curvature of part surfaces and the size of textile rolls. Draping textile reinforcement onto complex shape featuring double curvature leads to complex

redistribution and reorientation of the yarns in the preform. To reduce the risk of tearing or wrinkling the reinforcement when manufacturing larger parts, preforms must be made from several layers of smaller textile pieces joined together usually by overlapping. Manufacturing parts from preforms made from smaller textile patches raises several issues, the first one being the way in which overlapped joints compact when vacuum is applied in VARTM manufacturing and how this affects resin infusion. Gaining a proper understanding of compaction behaviour is therefore of prime importance.

Not only does the local compaction of the preform affects the ability of the resin to flow through the preform, but the edges of the layered textile sheets also create small localised channels in the preform which also aid the flow of resin through the preform. The relationship between non-uniform compaction and resin flow is discussed in chapter four of this thesis. The structural behaviour of the joints is also investigated and defined in terms of final structural properties. These results are covered in chapter five of this thesis.

3.2 Background and literature review

Fuelled by consumer demand and economic growth, manufacturers are driven to produce goods quickly and at favourable cost. To reach this goal, companies are looking at manufacturing processes that are cost effective and enable the production of repeatable and high quality composite parts and structures. These lightweight structures can withstand high loads whilst offering outstanding specific properties.

The manufacture of large composite parts made from textile reinforcements is most commonly done by vacuum assisted resin transfer moulding (VARTM), also known as vacuum infusion (VI). As opposed to the stiff moulds used in resin transfer moulding (RTM), VARTM only uses one stiff mould with the second mould being replaced by a flexible vacuum bag. The configuration of textile reinforcement layers has a strong impact on the processing properties of VARTM preforms because heterogeneity in local fibre volume fraction (v_f) distribution can lead to the creation of channels for resin flow, resin-rich areas in parts and other similar features [17-19]. As the vacuum bag is not rigid, differences in local resin pressure from the inlet to the outlet results in different compaction levels from

point to point of the preform, with a reduction in preform thickness from inlet to the outlet. This continuously affects the local fibre volume fraction in VARTM. In turn this non-uniformity causes local changes in the permeability of the preform, leading to change in the velocity of the resin front during infusion.

In addition to the above effect where thickness and permeability vary in a generally predictable manner from the inlet to the resin front during infusion, intrinsic variability of preform thickness during compaction also affects permeability and flow. Whilst the local preform thickness depends on the position of vacuum and injection lines and on the vacuum and resin pressures, a random variation in local preform thickness is also observed. This random variation in thickness is superimposed on the predictable variation. Figure 3.1 shows thickness data measured using Hall effect sensors for a 12-layer woven preform measuring 188 mm by 188 mm. The preform was compacted to approximately 10 000 Pa absolute pressure inside the sealed vacuum bag and thickness was measured at 125 points once the infusion and cure was completed. Both predictable and random differences in thickness are clearly visible in the part. A general reduction in thickness is observed from the inlet to the outlet. Superimposed to this predictable general trend is random variation in thickness which results from inherent variability in the preform and process.

A similar study was done by Grimsley et al. [20] who used LVDTs to measure the thickness of a composite panel made by VARTM in three points located respectively near the inlet, in the middle of the part and near the outlet. Whilst in that case the random variability could not be assessed, the authors found that thickness reduced progressively from the inlet to the outlet, showing that preform compaction is higher near the outlet as a result of vacuum and resin pressure distribution. Correia et al. [21] measured the preform thickness of a cured panel made by VARTM using a vernier calliper. Measurements were obtained at 26 different points. It was found that the thickness of their panel was dependent on position, and that it reduced from the inlet to the outlet. Superimposition of random thickness fluctuation over the general reduction from the inlet to the outlet was also observed by Correia et al. It should be noted that a non-uniform thickness in the cured panel is not always an assured outcome as thickness can equilibrate in the infused part between the end of infusion and the beginning of cure. In this case, some of the non-uniformity generated during manufacturing may remain in the final part. Data obtained using the Digital Speckle

Photography (DSP) system developed by Andersson et al. [10] provides a complete history of thickness variations observed during the processing of a panel made by VARTM. Similar trends were observed with higher resin pressure, lower compaction of the reinforcement, and an increase in thickness during processing, all observed near the inlet. Tackitt et al. [5] used linear variable differential transducers (LVDT) to measure and record the thickness variation during infusion of flat panels using the VARTM manufacturing process. The authors used 12 transducers; thickness was measured simultaneously at 12 different points of the part as it was infused. Their conclusions were similar to those reached by the above authors.

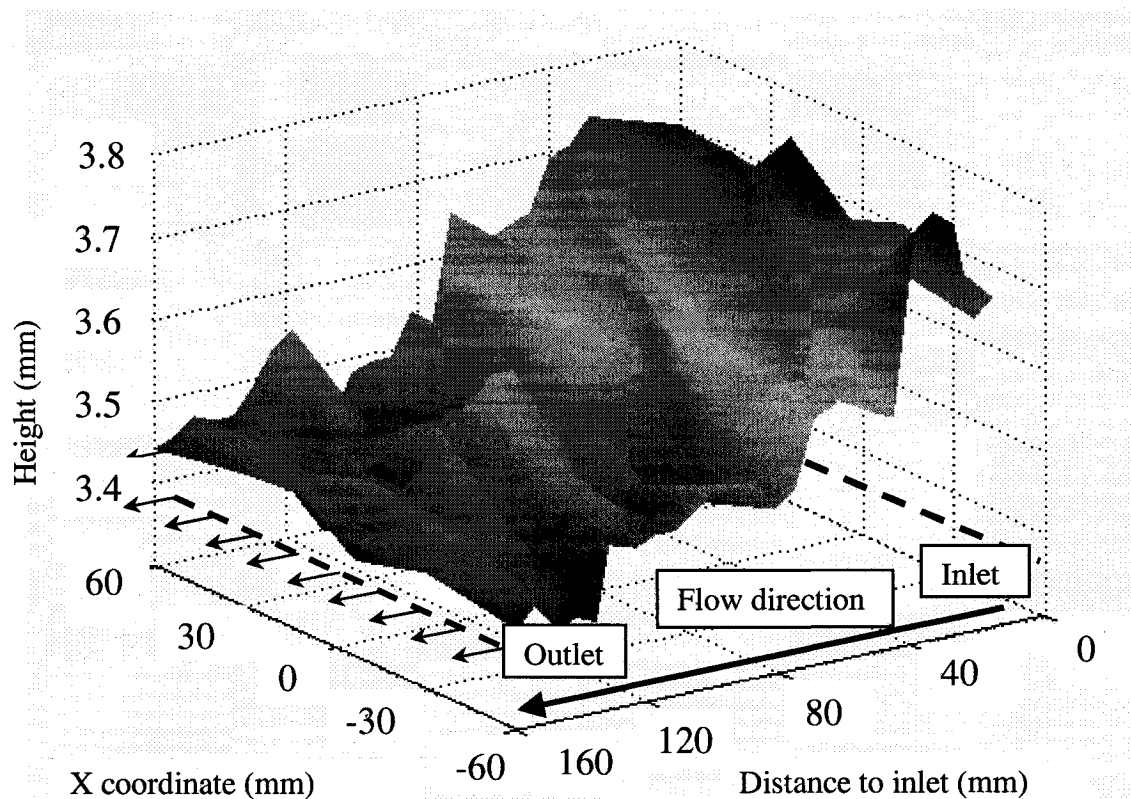


Figure 3.1 Thickness variations in a part infused using the VARTM process.

Modelling VARTM as discussed in [17-19] has proved to be complex as the level of compaction changes significantly with position and between repeated manufacturing trials of simple parts. These difficulties are compounded for complex parts. Regarding compaction of the preform, a number of general trends are well established from observation. In commercial reinforcements the well-known stiffening behaviour changes with the structure of textiles, with random mats showing weaker stiffening and non-crimp fabrics showing a quick increase in compaction rigidity as v_f increases [22]. There is also a strong relation between the initial fibre volume fraction observed under low compaction pressure and the stiffening index defined in power-law models. This simple empirical model has been used by numerous authors for providing a simple description of the relation between the compaction pressure P and the fibre volume fraction v_f ; more details appear in Section 3.4.4.

Phenomena described at the microscopic, mesoscopic and macroscopic scales must be considered in formulating a thorough understanding of compaction. Different entities are defined at each scale, namely the fibres, yarns and textile unit cells, and textile layers respectively. The geometry of these entities will affect the way in which reinforcements and preforms react to imposed deformations. Mechanical interactions and dimensions defined at various scales also affect other properties of textile reinforcements [23].

Experimental compaction and relaxation data for textile preforms were published [15, 16, 24] where uniform preform thickness converted into v_f and compaction pressure P were measured at the macroscopic scale. The papers also discuss a number of macroscopic compaction models proposed in the literature. Most of these models are empirical, curve-fitting type models. All these models assume constant thickness and v_f throughout the preform. In some studies, different reinforcements were compared based on these empirical models. The effects of changes in selected experimental variables on the numerical values taken by the model's parameters were discussed. For example, Figure 3.2 presents a typical thickness-pressure curve represented using an empirical model proposed by Chen [25]. Here it is assumed that the relation between thickness and pressure can be described as a function made of two linear and one non-linear segments. In this model, which is discussed in Section 3.4.3, it is assumed that the compaction behaviour is independent of parameters such as the number of layers, though clearly this is not the case in reality. Whilst such an effect could be

represented by changes in the model's fitting parameters, there is no clear relation between these values and what happens physically as the reinforcement is compacted.

Microscopic models that apply to yarns only were also proposed, with geometrical features of individual fibres as parameters. The most widely used of these models was developed by Gutowski [26] and is described in Section 3.4.2. These models do not include descriptions of textile reinforcement structures or macroscopic geometrical parameters, nor do they include the case of lap joints with overlaps and different numbers of layers. Hence they can not be used in describing localised phenomena related to compaction or other aspects of VARTM processing such as the creation of localised channels for resin flow.

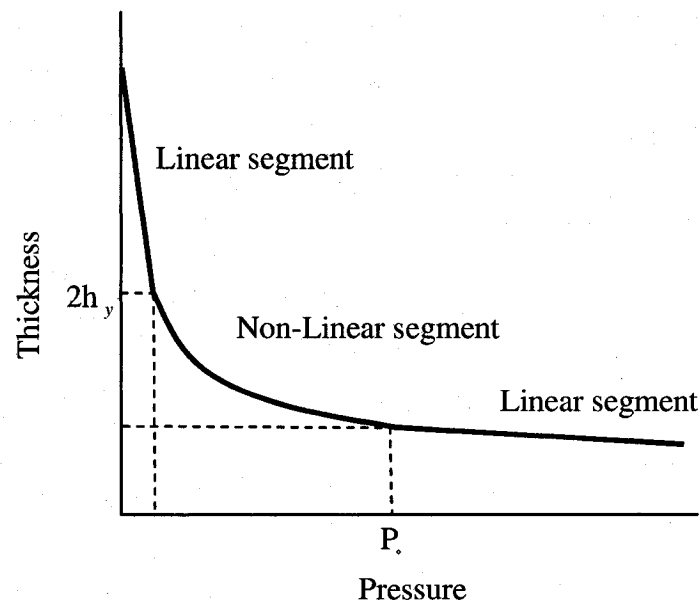


Figure 3.2 Compaction curve for woven preform.

Insightful contributions to the understanding of compaction in textile preforms were made in recent years. Potluri et al. [27] measured the deformation of yarns upon forming. Parameters such as tow shape, tow widening and crimp reduction were quantified for different load cases and weaves. The authors showed that changes in the geometry of the preform at the mesoscopic scale have a measurable effect on the mechanical properties of the resulting composite materials. Furthermore, the authors found that the finer geometry of

reinforcements is much more complex than what is assumed in most analytical or semi-empirical models. Merhi et al. [28] arrived at similar conclusions on the effect of preform compaction on tow sections in reinforcements used for moulding compounds. The authors also showed the effect of a lubricant on the compaction behaviour and the ability of the power-law model to represent this effect. Rugg and Cox [29] provided good insight on the mesoscopic mechanisms involved in simultaneous compaction and shear of dry reinforcements. In the words of the authors, sliding, buckling, compression and shear deformation in textile reinforcements are observed to originate from the single fibre and yarn, at microscopic and mesoscopic scales. Shear includes deformation transverse to the axis of the yarn with accompanying changes in cross-sectional shapes, as well as axial shear in tow segments defined as short beams. Liu et al. [30] provided unique data for multiple layer specimens with flipped plies of multi-axial fabrics, accompanied with data for the individual reinforcements. The compressibility and in-plane permeability of the reinforcements was measured. It was found that the effective in-plane permeability of multi-layer hybrid preforms is primarily determined by the orientation of fibres and fibre volume fraction of the outer surface plies. The interaction between the mould surfaces and reinforcements has little effect on the effective compressibility of the reinforcement; the same conclusion was drawn for interfaces between the different reinforcement layers making the preform.

Chen et al. [25, 31, 32] conducted related work for single- and multiple- layer preforms with a stronger emphasis on the analysis of weaves. The work focused on the unit cell of an orthogonal plain-weave preform composed of two sets of mutually orthogonal yarns. The authors proposed a 3D model of the unit cell to predict the compressive behaviour of yarns. Analytical expressions relations the fibre volume fraction, the applied compressive force and the preform thickness reduction were presented. These expressions are discussed in more detail in Section 3.4.3.

Lomov et al. [33, 34] published compaction data for multilayer stitched preforms obtained with the Kawabata Evaluation System (KES) testing apparatus. The behaviour of textile preform in compression showed common features including low initial stiffness. Stiffness was observed to increase when thickness reached about 70% of its initial value, under pressures of approximately of 50 kPa. When pressures increased to the maximum

imposed value of 200 kPa thickness decreased to about 60% of its initial value. The compressive stiffness significantly increased after the first compressive cycle, becoming stable in subsequent cycles. Hammami [35] investigated stacks of combined reinforcements with differing structures. The author investigated the effect of the reinforcement structure on the overall compaction behaviour, as well as the effect of a flow enhancement layer on the compaction response. The work aimed at increasing the manufacturability, reducing fill time and increasing laminate stiffness. Outcomes confirm that the compaction rate and regime are among the main parameters affecting the compressive response.

Dasilva and Chen [36] considered individual strands in braids and Weimer [37] provided compaction data for custom-engineered sewn preforms. Data featuring valuable information on experimental scatter for different reinforcements was published by Batch et al. [38]. Experimental and mathematical data were presented for woven reinforcements, random mats, loose fibre rovings used for pultrusion, and for uniaxial and biaxial roving mats. The average volume fraction in each reinforcement layer was predicted assuming that different layers of reinforcement do not interact. It was observed that most combinations of reinforcements have fibre volume fractions greater than expected at pressures lower than 344 kPa (50 psi) and that those reinforcements of various types showed marked differences in their compaction behaviour. Reinforcement compaction showed a linear behaviour at low pressures followed by nonlinear behaviour at higher pressures.

Additional, generally related work was published by other authors. Kelly et al. [39] and Bréard et al. [40] demonstrating the novel and promising use of rheological models that allow the description of stiffening and time-dependent effects through usage of various spring and damper elements; the former reference complements an interesting and complete experimental account of viscoelasticity in preforms by Bickerton [41]. In parallel to the above, Norman et al. [42] and Hubert and Poursartip [43] proposed alternative methods for testing the compaction behaviour of fibre beds. New models such as [44] extend the analytical approach beyond works described in [15, 18, 19, 45]. Progress was also achieved on the numerical front through works such as [22, 46-48].

Generally, and more specifically in the case of superimposed lap joints, there is a need to go beyond the assumption of uniform v_f to measure different local thickness and v_f values. This was also recognised by Bayldon et al. [7] and Andersson et al. [10] who have

applied a shadow Moiré method and speckle pattern photography for full field thickness monitoring of VARTM preforms as mentioned in chapter two. The techniques require either one light source and camera along with a fine grating placed close to the preform and displaced during measurement, or two cameras and a speckle pattern that is applied on the bag and can be read continuously during moulding. The techniques apply well to samples of limited dimensions and experiments performed in a laboratory.

This chapter presents experimental results on the compaction behaviour of superimposed lap joints in multilayer preforms for large parts made by VARTM. Local thickness measurements were made using Hall effect sensors as described in chapter two, and validated using a linear variable differential transducer (LVDT) and micrographs. A large array of results obtained using these experimental techniques are presented in this chapter. The experimental plan used for joint design is provided and followed by results and analysis of results based on the power law model, which is highlighted below. The general behaviour of joints compacted under vacuum is described. Effects of overlap length, neighbouring joints and lay-up sequence are quantified. Effects on resin infusion and on the mechanical properties of the resulting laminates will be discussed in chapters four and five.

3.3 Fibre volume fraction, v_f

The properties of composites are strongly dependent on the relative proportion of fibres and matrix. This is quantified by the fibre volume fraction. Generally, the fibres occupy the greater part of the volume of the composite and thus are the key material with regards to composite stiffness and strength. Preform geometry can be characterized at several scales. A schematic diagram of a preform appears in Figure 3.3. At the macroscopic scale, length L is indicative of overall preform size. At the microscopic scale, length ℓ is defined as the diameter of individual fibres. Between these, the length l quantifies a typical yarn width at the mesoscopic scale. These different scales and lengths are considered in defining and calculating various fibre volume fractions in a preform or composite, as discussed below.

On the microscopic level it is commonplace to notice small voids in composites, referred to as porosity. The level of porosity in carefully manufactured composites is generally lower than 1% by volume [26]. When considering the compaction of preforms the notion of porosity becomes irrelevant, hence it will not be discussed further in this chapter.

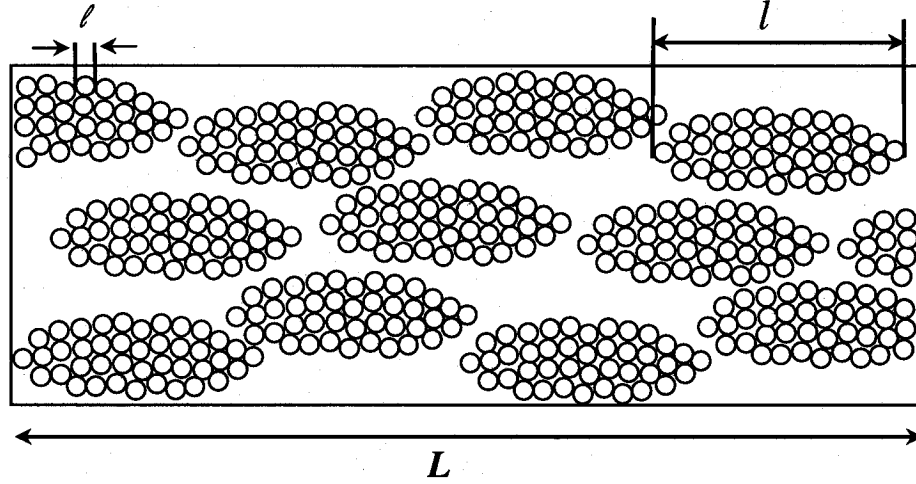


Figure 3.3 Schematic diagram of scale in textile preform.

If porosity is neglected, the volume of a composite part V_c is the sum of the volume of the fibres V_f and resin V_m making up this part:

$$V_c = V_f + V_m \quad (3.1)$$

When considering a preform devoid of resin, the fibre volume fraction of the preform will be defined based of the volume of the composite part V_c . In the case of a preform, V_m is not zero but the volume is occupied by air under some level of pressure.

The overall fibre volume fraction v_f of a preform is expressed as:

$$v_f = \frac{V_f}{V_c} \quad (3.2)$$

The density of a composite can be estimated from the rule of mixtures:

$$\rho_c = \rho_f V_f + \rho_m V_m \quad (3.3)$$

The fibre volume fraction v_f is used in micro-mechanics calculations because it is mathematically relevant. However, convenience dictates that quantities defining composite material used in practice are sometimes reported using weight fractions:

$$v_f = \frac{\frac{W_f}{\rho_f}}{\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}} \quad (3.4)$$

$$w_f = \frac{W_f}{W_f + W_m} = \frac{\rho_f V_f}{\rho_f V_f + \rho_m V_m} \quad (3.5)$$

where ρ_f is the density of fibres, ρ_m is the density of the matrix, W_f is the mass of the preform, W_m is the mass of the matrix and w_f is the fibre fraction by weight.

The overall fibre volume fraction is simply defined as the volume of the fibres making the preform divided by the volume of the part that will be made from that preform. This definition does not consider that the fibre volume fraction varies locally in preforms made from textile reinforcement as a result of the presence of yarns and gaps between these yarns. The yarn fibre volume fraction $v_{f,y}$ is defined for yarns, at the mesoscopic scale, as the volume of the fibres in a yarn $V_{f,y}$ divided by the volume of the yarn V_y :

$$v_{f,y} = \frac{V_{f,y}}{V_y} \quad (3.6)$$

The nominal fibre volume fraction $v_{f,n}$ is defined as the volume of the yarns V_y divided by the volume of part V_c :

$$v_{f,n} = \frac{V_y}{V_c} \quad (3.7)$$

It follows that:

$$v_f = v_{f,y} \cdot v_{f,n} \quad (3.8)$$

Considering the preform at the microscopic and mesoscopic scales, the maximum fibre volume fraction that may be reached during compaction can be estimated using the idealised square and hexagonal fibre arrangements shown in Figure 3.4:

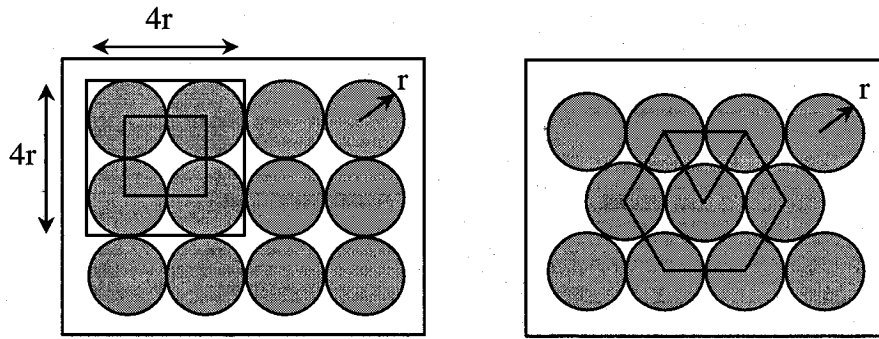


Figure 3.4 Idealized square and hexagonal fibre arrangement.

For the square and hexagonal arrangements with fibres of radius r touching each other, the yarn fibre volume fraction $v_{f,y}$ can be calculated respectively as:

$$v_{f,y} = \frac{4(\pi r^2 / 4)}{(2r)^2} = 0.785 \quad (3.9)$$

$$v_{f,y} = \frac{\pi}{2\sqrt{3}} \left(\frac{r}{R}\right)^2 = 0.907 \quad (3.10)$$

In reality, maximum values of $v_{f,y}$ that may be reached in compacted aligned fibres will be between these two values, as perfect alignment of the fibres is not possible. Overall fibre volume fractions in composite parts and preforms v_f will be significantly lower as

fibres are assembled into textile reinforcements by methods such as weaving or braiding, resulting in crimping and gaps between yarns. Actual fibre volume fractions in parts depend on the method used for manufacturing the reinforcements and preforms. Typical values of v_f in parts made from stitched non-crimp unidirectional aligned fibre is 0.60-0.65 [26]. For woven fabric this is typically equal to 0.40 to 0.55, and to 0.25-0.40 for random mats. Fibre volume fractions in parts made from different processes appear in Table 3.1.

Table 3.1 Fibre volume fraction for different processes [26].

Process	v_f
Contact moulding	0.3
Compression	0.4
Filament winding	60-80%
Vacuum moulding	50-75%

The overall fibre volume fraction, v_f , can be calculated from the thickness of the preform and from the surface density of the reinforcements. The total volume of preform is expressed as the surface area of preform A_c multiplied by thickness of the preform t . Reinforcement samples can be pre-cut and weighted, and a correlation can be made between the surface area of the sample and its weight where m_{ut} is the mass of textile per unit area or surface density of a single layer, and n is the number of layers in the preform. The total mass of a preform made of a given number of layers is:

$$m_f = m_{ut} \times A_c \times n \quad (3.11)$$

v_f can be calculated by:

$$v_f = \frac{m_{ut} \times n}{t \times \rho} \quad (3.12)$$

In this thesis, equation (3.11) was used to determine the fibre volume fraction from the thickness of the preform during and after the compaction.

3.4 Compaction models

Different analytical and empirical models were proposed for predicting the compaction behaviour of reinforcements featuring various structures, expressed as the compaction pressure P_{comp} as a function of the fibre volume fraction v_f . Van Wyk's analytical model [49] applies to homogeneous 3D random assemblies of fibres. Gutowski's analytical model [50] applies to aligned homogeneous unidirectional fibres, and Chen's empirical model [25, 31] applies primarily to weaves. The power law model was introduced mainly because it is simple and allows clear physical interpretation of the values taken by its coefficients; hence meaningful trends can be identified from the experimental data. This latter feature is uncommon among empirical compaction models. The power law model was used to analyse the compaction results in this thesis, hence in this case the physical meaning of the fitting coefficients is discussed.

3.4.1 Van Wyk's analytical model of compaction of random fibre assemblies

Starting from the random distribution of orientations for straight, short segments of wool fibres in 3D, Van Wyk derived the following equation based on three main assumptions: fibres bends like beams without relative motion, twisting, slippage or extension; there is no crimp in the fibres; and fibres are uniform in diameter. For randomly oriented, uniformly packed fibres:

$$P_{comp} = \frac{C_v \times E_f \times m^3}{A_s^3} \times \left(\frac{1}{t^3} - \frac{1}{t_{w0}^3} \right) \quad (3.13)$$

where E_f is the fibre's Young's modulus, m is the mass of the preform, A_s is surface area of the preform and t the thickness of the preform. In this formula C_v is a coefficient of

proportionality which must be determined experimentally, along with the volume occupied by the sample at zero pressure, t_{w0} .

As one can notice, Van Wyk's analytical model relies on experimental measurements and some curve-fitting. Phenomena such as load hysteresis, load orientation, slippage at contacts in the assembly and the effect of crimp are not considered. In reality, non-recoverable strain results from initial compression, and a mechanical hysteresis is present during compression-release cycling. Furthermore, Van Wyk's model cannot take account of the structure of fibrous reinforcements.

Other researchers developed Van Wyk's model further. Komori et al. [51] modelled assemblies of fibres that are not randomly oriented, and bending units that are not straight. Fibre slippage and hysteresis during compression-release cycling, which is indicative of energy dissipation, were also modelled. These phenomena were also studied experimentally by Dunlop et al. [52] who investigated the relationship between compaction rate and hysteresis. These authors recognized that losses are of frictional nature, and proposed models featuring non-linear springs and friction blocks assembled in series and parallel to replicate the behaviour of fibres under compaction. Itoh and Komori [53] included frictional effects in their study of contact between fibres. Carnaby and Pan [54] separated fibre contacts as slipping and non-slipping based on a critical orientation criterion. The stiffness, Poisson's ratio and other mechanical properties of assemblies of fibres of both categories were considered separately and integrated into a more realistic model.

Whilst these latter models offer interesting insight into the behaviour of fibre contacts in homogeneous assemblies of fibres subjected to compaction, they are not yet sufficiently advanced to model the compaction of complex, industrial reinforcements and preforms. Furthermore, their mathematical complexity makes them unsuitable for the work performed in this thesis.

3.4.2 Gutowski's analytical model of yarn compaction

One of Gutowski's main contributions was to demonstrate by direct observation that fibres assumed to be straight are effectively wavy [26, 50]. Gutowski also showed that when

composites are being consolidated, the compaction behaviour is mainly affected by fibre lubrication and fibre waviness. Considering that the experiments reported in this chapter were made on dry layers of reinforcement this section will discuss effects associated with waviness. It will be assumed that the compaction of preforms is time independent. Gutowski uses Equation 3.14 to represent a wavy fibre using a sinusoidal function, Figure 3.5.

$$y = \frac{a}{2} \left(1 - \cos \frac{2\pi x}{L} \right) \quad (3.14)$$

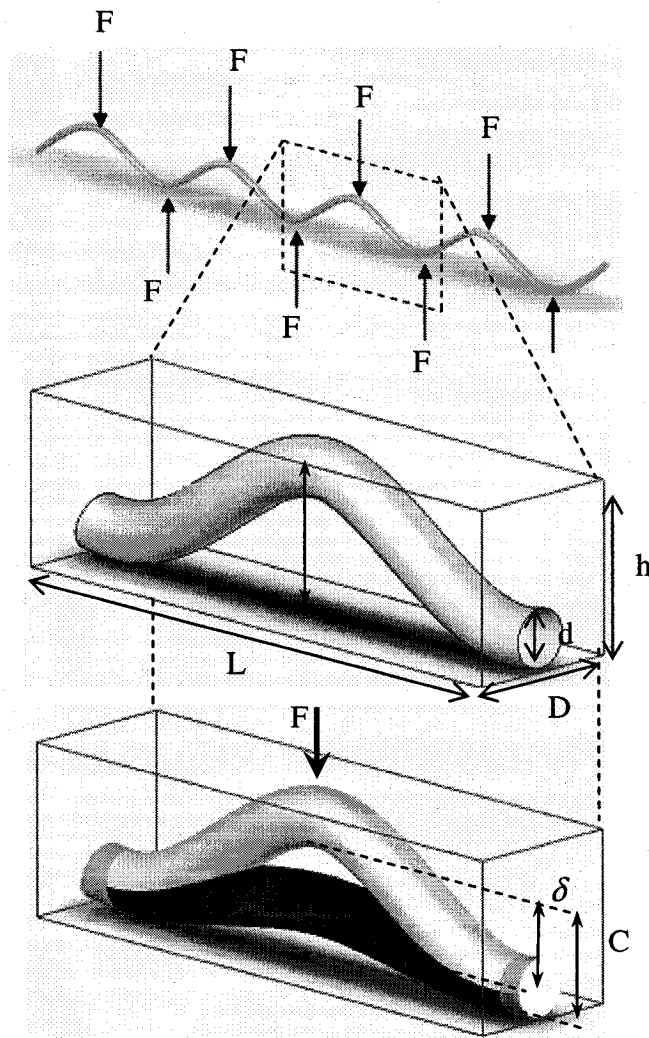


Figure 3.5 Schematic shape of fibres and dimensions in Gutowski's compaction model.

The ratio of arch length L to height a , termed parameter β , is in the order of 100, hence typically $\frac{L}{a} \geq 100$. Other functions could be used to represent the initial fibre shape; these would give similar results.

One may expect L , which the projection of the fibre on a horizontal line, to increase slightly during compaction. Because of the high value of β , it may be reasonably assumed that the lengthening of the projection during compaction is insignificant.

Considering a beam in bending, Figure 3.6, the deflection δ at the centre of a beam with modulus E , length L and second moment inertia I is:

$$\delta = \frac{F_y L^3}{192EI} \quad (3.15)$$

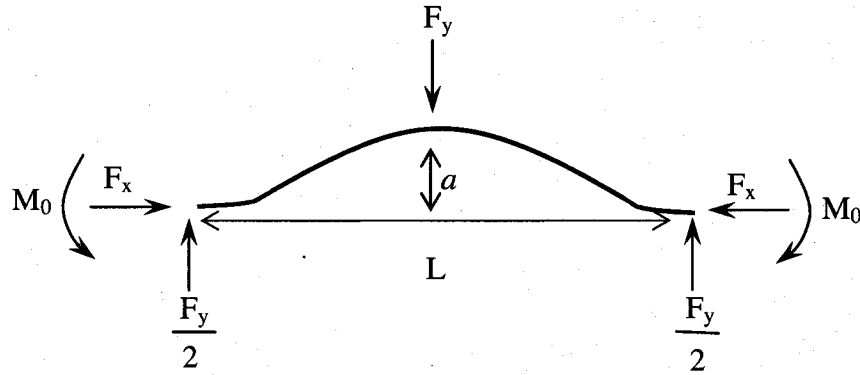


Figure 3.6 Schematic diagram of a fibre in three-point bending.

Considering applied force F_y , and resultant forces F_x , the deflection matrix for the fibre is:

$$\begin{Bmatrix} \delta_x \\ \delta_y \end{Bmatrix} = \begin{bmatrix} \frac{a^2 L}{8EI} + \frac{L}{EA_f} & \frac{-aL^2}{4\pi^2 EI} \\ \frac{-aL^2}{4\pi^2 EI} & \frac{L^3}{192EI} \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} \quad (3.16)$$

where A_f is the cross sectional area of the fibre and δ_x , δ_y are the displacements in the x and y direction at the points application of forces F_x and F_y . Since displacements in the y direction are large in relation to displacements along x, only the former will be considered. The fibre volume fraction is:

$$v_f = \frac{\pi d^2}{4h \cdot D} \quad (3.17)$$

where d is the diameter of fibre. Assuming that the sides of the end faces of a box surrounding the fibre stay equal to one another during compaction, one can calculate the fibre volume fraction v_f , the initial fibre volume fraction v_{oy} and maximum fibre volume fraction v_{ay} at $h=d$ with the following equations:

$$v_f = \frac{\pi d^2}{4h^2} \quad v_{oy} = \frac{\pi d^2}{4h_0^2} \quad v_{ay} = \frac{\pi d^2}{4d^2} \quad (3.18)$$

The pressure on the yarn is:

$$P_y = \frac{F_y}{DL} \quad (3.19)$$

Rearranging equations (3.15) and (3.16) leads to:

$$P_y = \frac{1}{DL} \cdot \frac{192\delta EI}{L^3} = \frac{\pi d^4}{64} \cdot \frac{E}{\alpha DL^4} \delta \quad (3.20)$$

where α is a constant equal to 1/192. Taking C as the height between the lower and upper points on the fibre centreline:

$$L = \beta.C = \beta(h-d) \quad (3.21)$$

where β can be found from experiment.

Since the equation for pressure has an L^4 term, the equation 3.21 can be rearranged as follows:

$$L^4 = \beta^4.(h-d)^4 = \beta^4.\left(\frac{h}{d}-\frac{d}{d}\right)^4 d^4 \quad (3.22)$$

$$\frac{L^4}{d^4} = \beta^4.\left(\frac{h}{d}-\frac{d}{d}\right)^4 = \beta^4.\left(\sqrt{\frac{v_{ay}}{v_f}}-1\right)^4 \quad (3.23)$$

Substituting into equation 3.19:

$$P_y = \frac{F}{DL} = \frac{\pi E \delta}{64 \alpha \beta^2 D \left(\sqrt{\frac{v_{ay}}{v_f}}-1\right)^4} \quad (3.24)$$

For the following conversion:

$$\frac{\delta}{D} = \frac{\delta}{h} = \frac{h_0-h}{h} = \frac{h_0}{h} - \frac{h}{h} = \sqrt{\frac{v_f}{v_{oy}}} - 1 \quad (3.25)$$

Gutowski's compaction model is obtained:

$$P_y = \frac{F}{DL} = \frac{\pi E \sqrt{\frac{v_f}{v_{oy}}} - 1}{64 \alpha \beta^2 \left(\sqrt{\frac{v_{ay}}{v_f}}-1\right)^4} \quad (3.26)$$

In a laboratory setting, empirical values for v_f are very difficult to read. In their place, an estimation of v_f can be obtained from the thickness of the preform and the surface density of the material. v_{oy} and v_{ay} values must be evaluated for each new material. As these numbers must be obtained empirically, Gutowski's model does not reduce the experimental effort needed. It does, however, provide interesting insight into preform mechanics and stiffening. Another limitation of Gutowski's model originates from the fact that this was defined for preprag featuring homogeneous reinforcement, and does not model textile structures as used in this thesis.

3.4.3 Chen's empirical model of the compaction of woven reinforcements

Chen derived the empirical model described in Equation 3.27 from experimental observation. This model represents compaction of woven reinforcement in terms of applied pressure P_{comp} , where t_0 is the initial thickness.

$$P_{comp} = \frac{1}{C_b \times t} \times \left(1 - \frac{t_0}{t} \right) \quad (3.27)$$

Bulk compressibility C_b is expressed as a complex function of porosity ϕ and five other parameters C_{p0} , C_s , ϕ_0 , ϕ_f and k . Use of this model is limited to specific reinforcements and relies on experimental measurements; also, one can not associate a clear physical meaning to the values of the aforementioned parameters.

3.4.4 Power law model

Robitaille et al [15] used a simple empirical power law to describe the relation between the compaction pressure P_{comp} and the resulting fibre volume fraction v_f :

$$v_f = v_{f0} \times P_{comp}^B \quad (3.28)$$

where parameter v_{f0} is the fibre volume fraction at 1 Pa and B is indicative of stiffening (non-linear) behaviour which varies with material and test conditions. In practice, Equation 3.28 can reproduce compaction data sufficiently well for the modelling of processes such as VARTM, with coefficients of correlation of 0.98 or higher commonly encountered.

3.5 Experimental studies

This section discusses the behaviour of lap joints compacted under vacuum, similar to preform consolidation in VARTM manufacturing. The effects of different geometric parameters defining the joints are studied.

3.5.1 Apparatus and set-up

Joints in preforms made from two different reinforcements were investigated in this work; precise joint configurations are described in a following section. Reinforcement R1 is continuous filament glass matt M8610-450 from Owens Corning with measured surface density $\rho_m = 465.4 \pm 29.5 \text{ g/m}^2$ measured on 10 samples (manufacturer's value 450 g/m^2). Reinforcement R2 is glass plain weave 0154/139 from Saint-Gobain Technical Fabrics with measured surface density $\rho_w = 315.8 \pm 1.9 \text{ g/m}^2$ also measured on 10 samples (manufacturer's value 324 g/m^2). Warp and weft spacing are 63 picks and 54 ends per 100 mm respectively; hence the reinforcement is lightly unbalanced.

The physical apparatus consisted of a clear 500 x 500 mm, 6.5 mm thick PMMA plate and vacuum infusion film Airtech WL5400 sealed with vacuum infusion sealant tape Airtech AT-199. Vacuum was generated using a Welch 1399 pump and transparent flexible piping, 8.5 mm inner diameter. Typical preform size was 210 x 210 mm. The setup, Figure 3.7, consisted of the pump, a trap equipped with a valve opening to atmosphere, an on/off valve

and a flow control valve on the vacuum line, and a t-joint connecting to a pressure transducer located close to the preform. The flow control valve ensured relatively slow compaction, with typical test duration of 180 s. The pressure transducer allowed control of the maximum vacuum level. In most trials resin was not infused in the preform hence a single pipe was placed under the film. Vacuum levels were measured using a Cole-Palmer 68073 high-accuracy pressure transducer.

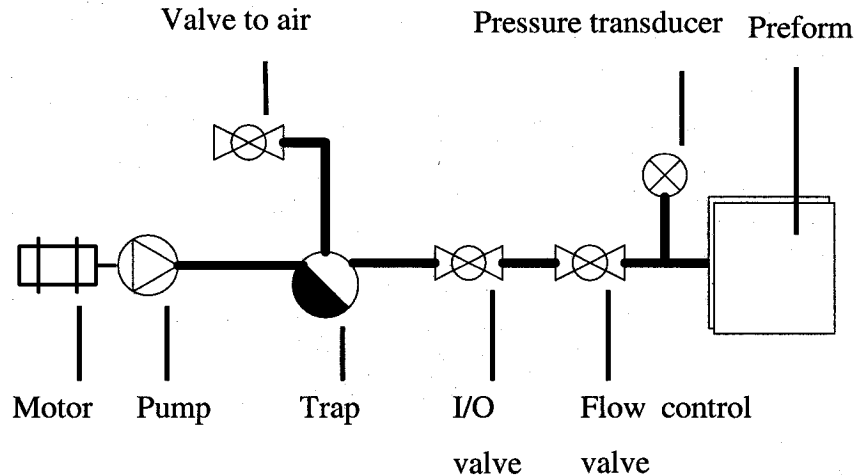


Figure 3.7 Schematic set-up for compaction test.

The apparatus used for local thickness measurements consisted of 12 Melexis MLX 90215 Hall effect microchip sensors and 15 Digi-Key 469-1006-ND permanent ferrite magnets measuring 25.4 x 50.8 x 6.4 mm, Figure 2.4. Positioning of the magnets was similar to that explained in Section 2.4 and Figure 2.12.

Figure 3.8 describes sensor setup in an array; 12 Hall effect sensors were used for all tests. The sensors labelled S1 to S12 were grouped in 4 lines labelled L1 to L4. Each line contained three sensors which should, in theory, give comparable results. Lines L1, L2, L3 and L4 feature sensors S1 to S3, S4 to S6, S7 to S9 and S10 to S12 respectively. All curves presented in following section are identified by their corresponding sensor number. Sensor lines L1, L2, L3 and L4 were distanced by 31.75 mm. Sensors on each line were distanced by 57.15 mm. The measurement area was well within preform in-plane dimensions, ensuring sufficient distance between sensors and preform edges. The sensors and cables were positioned to minimise unwarranted displacement of sensors on the vacuum film; the sensors were also secured using double-sided adhesive tape between the film and sensors and single-

side adhesive tape above the sensors. Thickness of the vacuum infusion film and double-sided tape were measured as 0.059 ± 0.001 mm and 0.252 ± 0.005 mm respectively using 10 samples in each case. Sensor behaviour, calibration and vertical range are discussed in a following section.

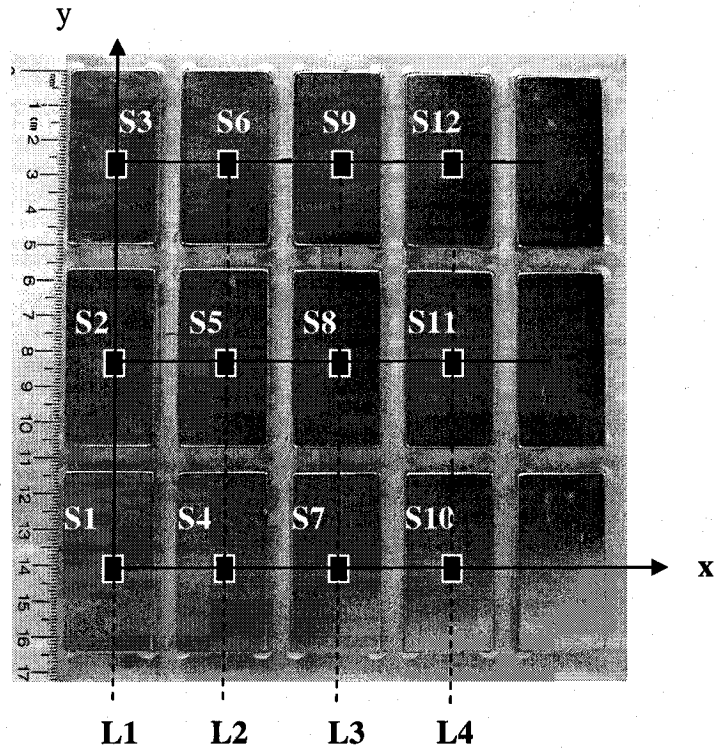


Figure 3.8 Magnet and sensor configuration.

Data acquisition was performed using the same software used for calibration described in chapter two. Signals from the pressure transducer and Hall effect sensors were recorded every 1 ms. Signal processing is discussed below.

3.5.2 Joint design

A total of 20 joint configurations were investigated with 10 configurations labelled as C1 to C10 for each reinforcement type. All preforms featured 24 plies, with each ply featuring one butt joint. Joints were separated in two groups and stacked in two columns

hence all preforms other than C10 counted either 24 or 36 layers locally. C10 is a preform devoid of joints that was used for comparison purposes. The number of joints stacked immediately on top of each other within a given column was either 1, 3 or 6 and did not change within a given preform, Figure 3.9. Each configuration was characterised by an overlap length OL of 20 or 40 mm, in-plane horizontal distance between overlaps HD of 31.7 or 63.4 mm, and number of joints immediately superimposed NS of 1, 3 or 6. The 10 configurations C1 to C10 and their geometric characteristics appear in Table 3.2. Preform length (x axis) was either 210 mm (C10, no joints), 190 mm (C1, C2, C3, C7, C8, C9; OL = 20 mm) or 170 mm ((C4, C5, C7; OL = 40 mm), whilst preform width (y axis) was always 210 mm. All plies were brought to size using straight single cuts made in a long shear.

Table 3.2 Geometric parameters for preform configurations C1 to C10.

Configuration	Overall Length OL (mm)	Horizontal distance HD (mm)	Superimposed joints NS
C1	20	63.4	1
C2	20	63.4	3
C3	20	63.4	6
C4	40	63.4	1
C5	40	63.4	3
C6	40	63.4	6
C7	20	31.7	1
C8	20	31.7	3
C9	20	31.7	6
C10	-	-	-

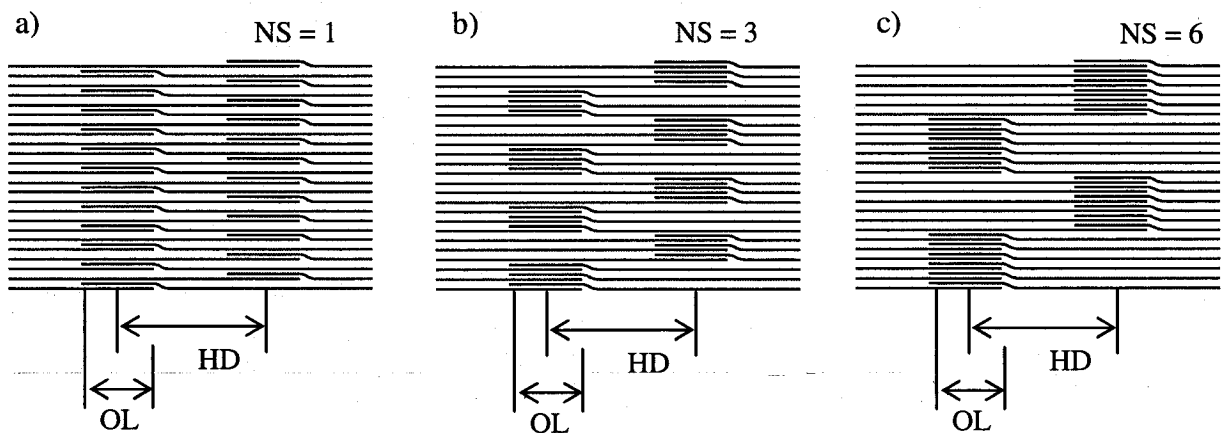


Figure 3.9 Different configurations for joints.

3.5.3 Tests and Results

Curves of the local fibre volume fraction v_f as a function of vacuum level appear in Figures 3.10 to 3.13 for preforms configurations C1 to C10 made of reinforcement R1. Similar curves appear in Figures 3.14 to 3.17 for reinforcement R2. For each test, individual curves are presented only when compelling agreement between Hall effect sensors and LVDT was obtained. This indicates limitations to the sensors which are discussed below.

Figures 3.10 to 3.13 show that curves representing local fibre volume fraction data in random matt preforms are segregated more or less strongly for the different configurations. For cases with clearly grouped curves such as C1 variations in v_f between sensors located above the same number of layers (24 or 36, lines L1 and L3 vs. L2 and L4) can be as low as 3% to 5%, which is remarkable for random mats. Comparing Figure 3.13 for configuration C10 (no joints) to other configurations shows significantly higher v_f values in the overlaps. Configurations C7, C8 and C9 show somewhat lower v_f values away from the overlaps. Overlaps are thicker but not so much that v_f remains constant in them. On the other hand, for the same vacuum level the presence of overlaps does not reduce v_f significantly away from the overlaps.

Figure 3.10 shows results for configurations C1-C3 featuring short overlaps OL with joints under sensor lines L2 and L4. Individual curves are strongly grouped for C1. Weaker grouping is also present for C2 and C3 with progressively wider spread within each group. Preforms with short overlaps OL separated by a wider distance HD (C1-C3) show clear differences in v_f in the overlaps and next to them. Configuration C1 shows that laying uninterrupted plies between joints leads to more repeatable v_f values, whilst fluctuations arising from local distortions and possible imprecision in cutting are magnified when multiple joints are stacked consecutively as with C2, and more so with C3. It can be concluded that interlaid continuous plies will lead to more predictable manufacturing and properties.

Figure 3.11 show results for configurations C4-C6 featuring longer overlaps OL and wider in-plane distance HD. Joints are located under sensor lines L2 and L4. Grouping is present with a different behaviour; here curves associated to line L3 (sensors S7, S8 and S9) with 24 superimposed reinforcement layers generally show v_f values between those of

overlaps (36 layers, L2 & L4) and those associated with line L1, at pressure level close to 0 bar absolute.

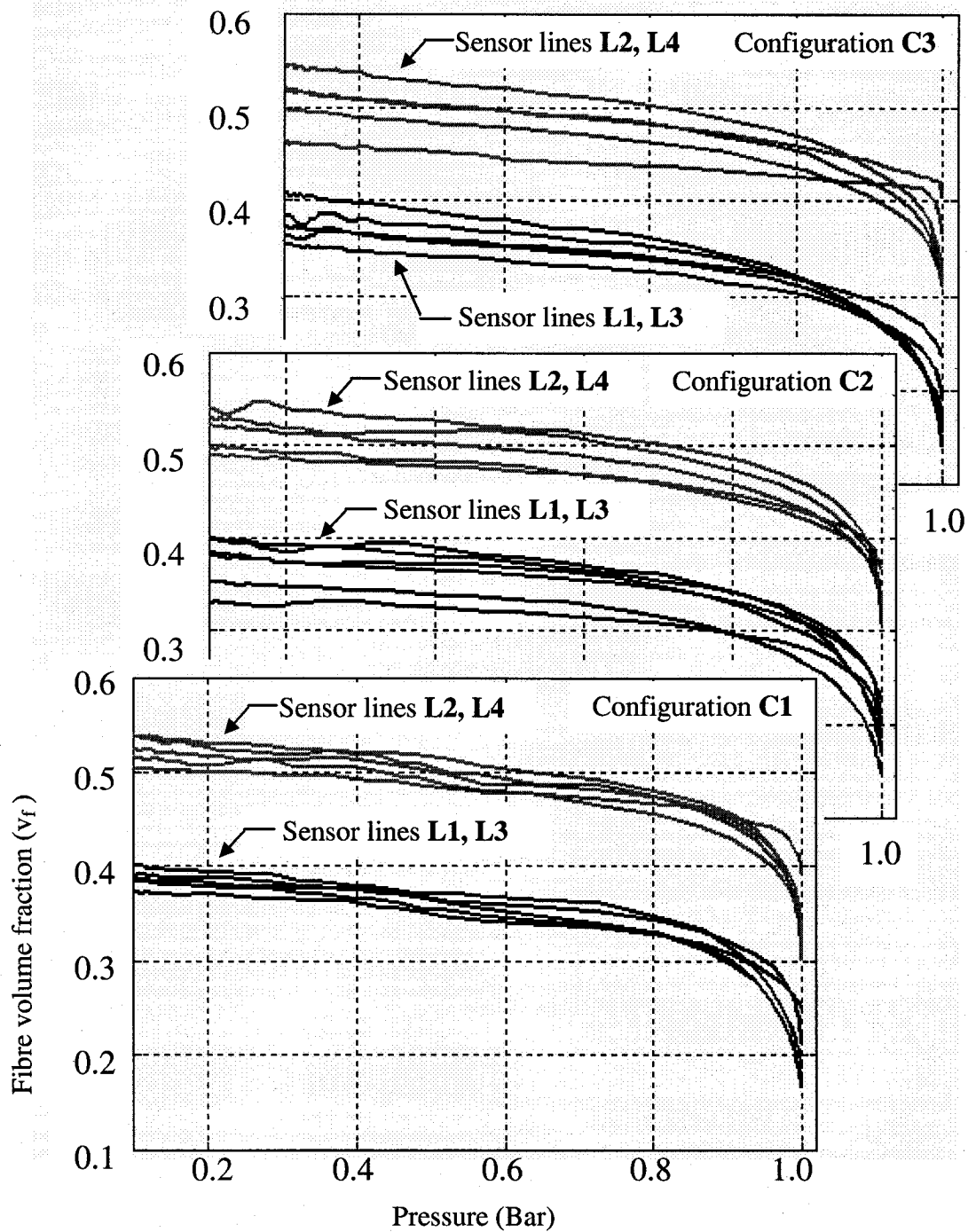


Figure 3.10 Results: reinforcement R1, configurations C1 to C3.

Regardless of physical causes results show a consistent trend where the preform compacts less in the region located between columns of overlaps. This was not observed for

configurations C1-C3 where the ratio of the in-plane distance between overlaps HD to the overlap length OL was greater, indicating a different influence of the overlaps on v_f on their surroundings. Here again grouping was generally clearer and repeatability better with interlaying of continuous plies. Maximum v_f values observed in the overlaps compare to those observed for shorter length OL.

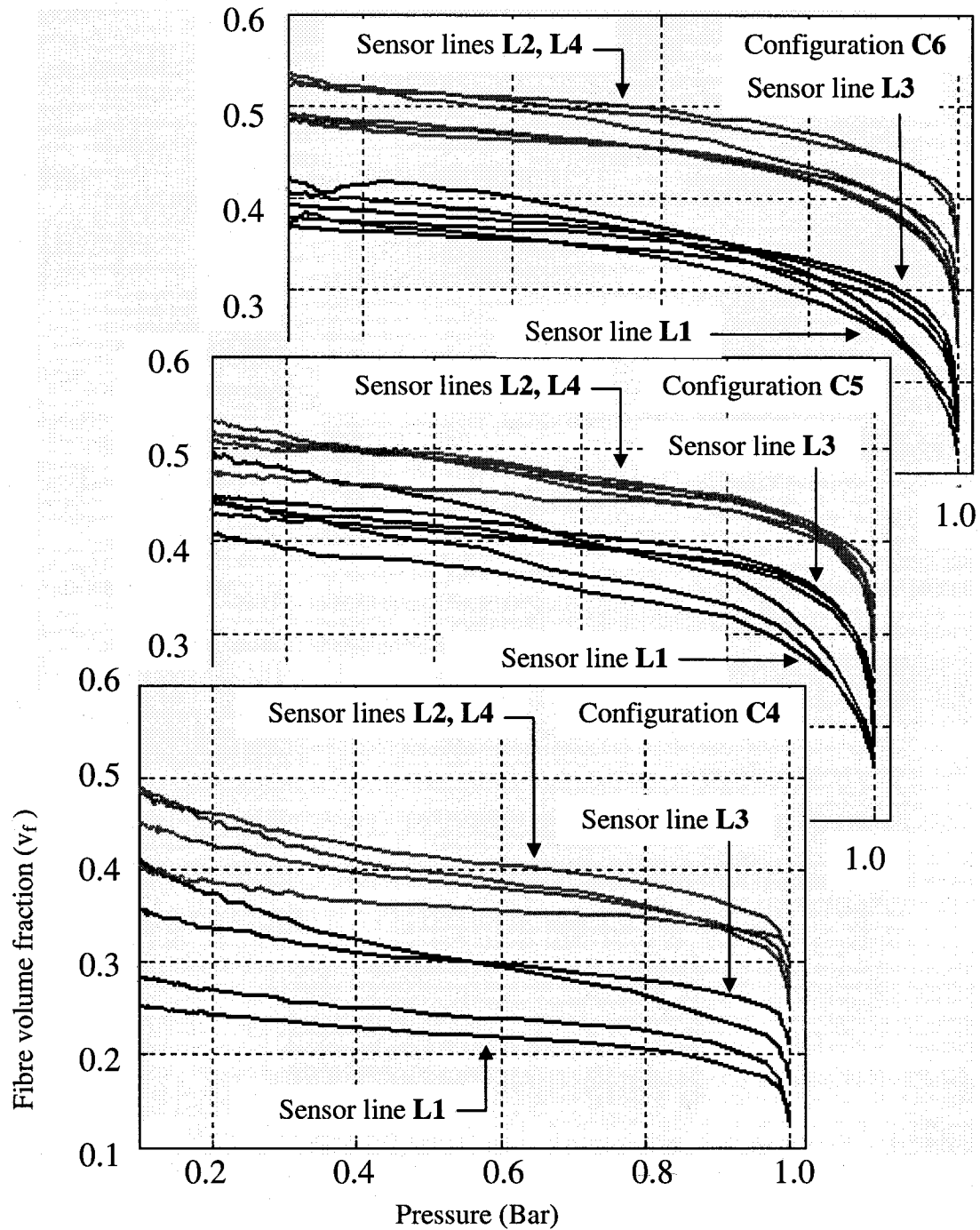


Figure 3.11 Results: reinforcement R1, configurations C4 to C6.

Figure 3.12 shows results for configurations C7-C9 which mirror C1-C3 with reduced in-plane distance HD and short overlaps OL. Joints are located under sensor lines L2 and L3. The figures show weaker grouping of the curves and wider spread, notably for the lower v_f curves corresponding to zones of the preforms away from the overlaps (lines L1 and L4).

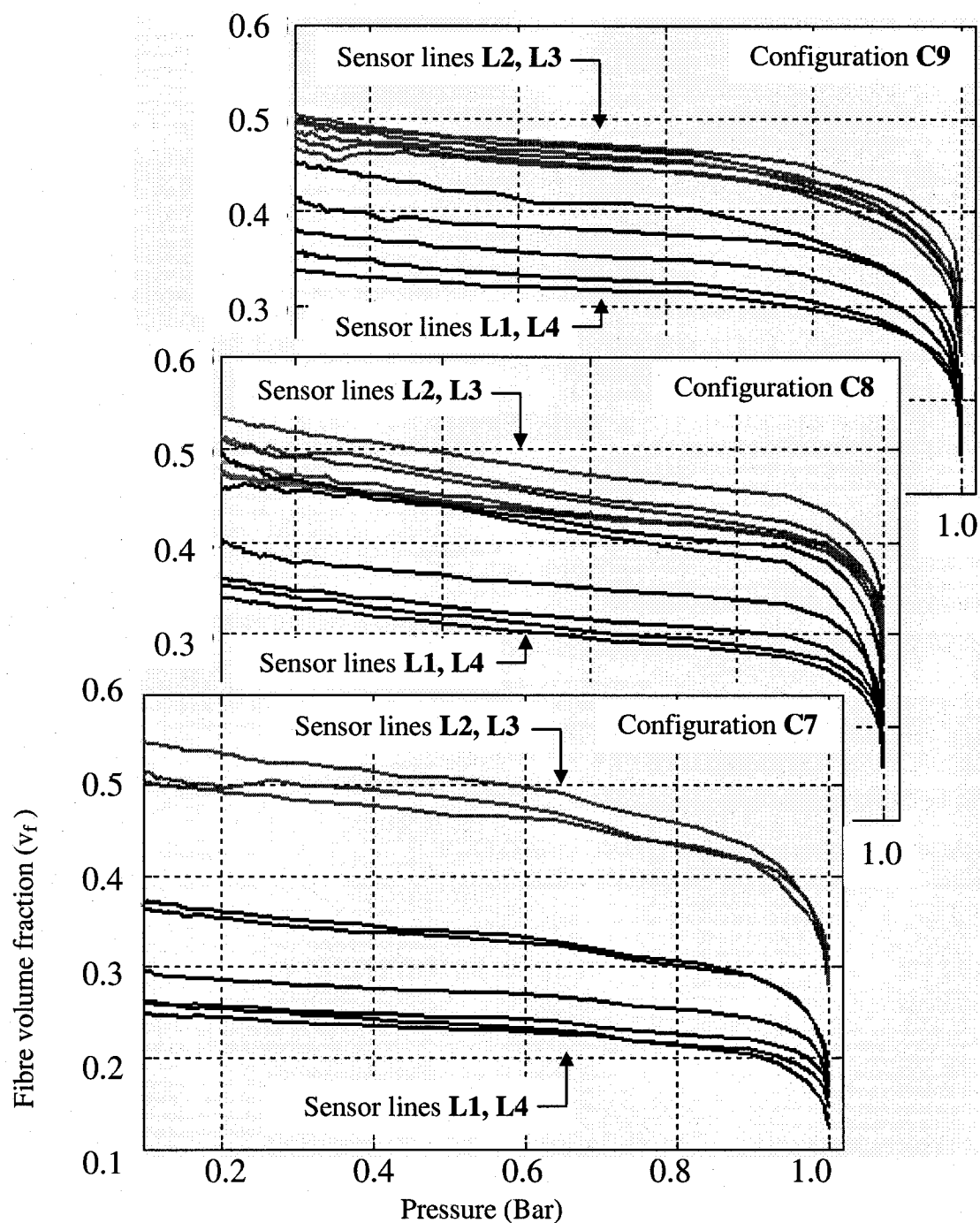


Figure 3.12 Results: reinforcement R1, configurations C7 to C9.

In Figure 3.12 measurements on the overlaps (lines L2 and L3) are generally better grouped and repeat better. Distance HD was varied with the aim of quantifying a possible zone of influence on v_f around individual joints; results show that joints in close vicinity lead to a somewhat less clear transition in v_f and to a possibly larger zone of influence in the preform. Also noteworthy are the slightly higher maximum v_f values observed for C7 than for C8 and C9, confirming that interlaid continuous plies lead to better compaction in addition to better repeatability. Increased overall variability for configuration C7 indicates that despite comparable maximum v_f values, configuration C1 is superior. LVDT lead to more individual curves being discarded for the smaller HD value, again pointing to limitations of the Hall effect sensors that are discussed below.

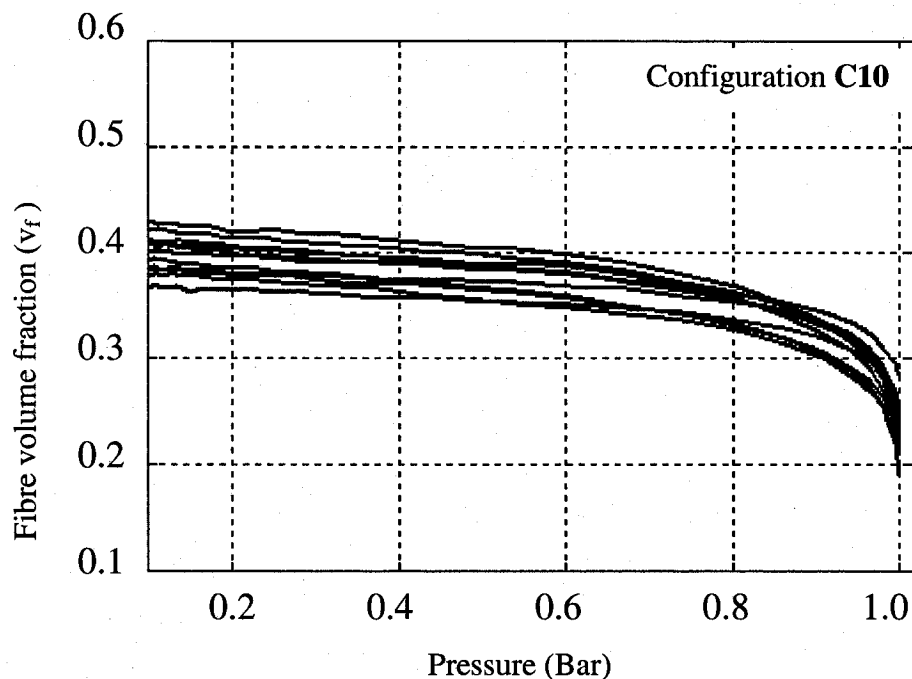


Figure 3.13 Results: reinforcement R1, configuration C10.

Some of the trends observed on mats were repeated with woven reinforcement R2. Trends are generally less clear as a result of the reduced numerical averaging of thinner preforms made of the same number of layers; variation of v_f for sensors with similar locations is typically between 5% and 10%. Here again, v_f values away from the overlaps in configurations C1-C9 are broadly similar to those recorded in configuration C10 (no joints, Figure 3.13) with higher v_f values in the overlaps.

Figure 3.14 shows results for configurations C1-C3 with joints located under sensor lines L2 and L4. The general behaviour is similar to that observed for reinforcement R1 with grouping and repeatability becoming progressively weaker for higher number of successive joints. Interlaying of continuous plies promotes repeatability for intrinsically less variable reinforcement R2. Similar results were obtained in each case for lines L1 and L3, and for lines L2 and L4. Conversely, recorded maximum v_f values seem to increase from C1 to C3, in a reverse of the trend observed with reinforcement R1.

Figure 3.15 shows results for configurations C4-C6 featuring longer overlaps OL and long horizontal distance HD; joints are located under sensor lines L2 and L4. Grouping remains present but behaviour specific to line L3 was not observed, indicating the effect of joints on the surrounding preform differs for this thinner reinforcement. Compaction curves were again better grouped for the smaller numbers of consecutive joints, configurations C4 and C5.

Figure 3.16 shows results for configurations C7-C9 with short overlaps OL and reduced in-plane distance between joints HD and joints located under sensor lines L2 and L3. Grouping is weaker on all lines L1-L4 (see C8, C9) with a higher number of curves rejected on the grounds of LVDT data (C7).

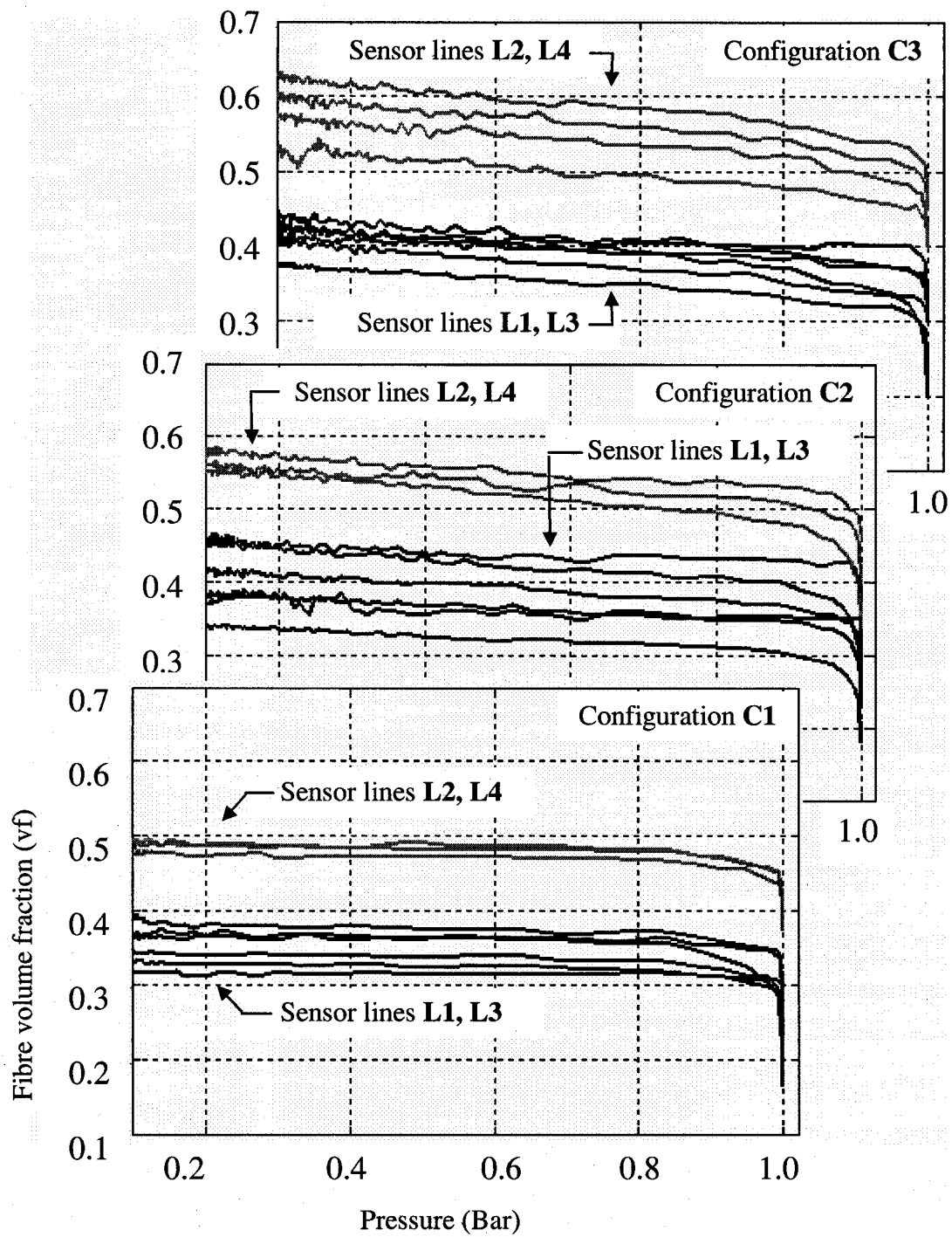


Figure 3.14 Results: reinforcement R2, configurations C1 to C3.

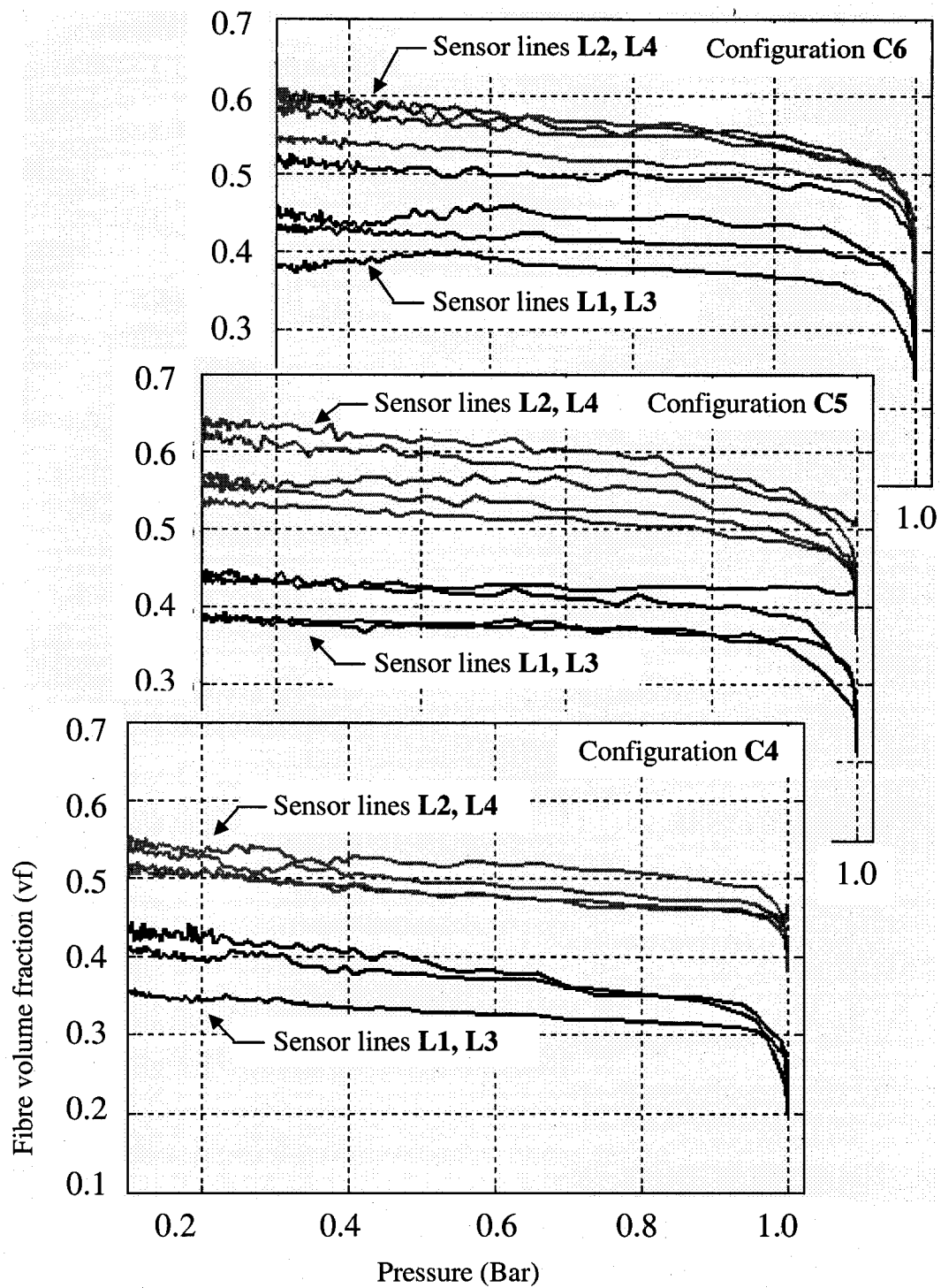


Figure 3.15 Results: reinforcement R2, configurations C4 to C6.

As previously observed v_f values away from joints tend to be weaker, indicating that the increased thickness at the joints affects the preform over some distance. Maximum v_f

values are seen to decrease from C7 to C9, indicating reduced compaction; this trend was observed before. Results for configuration C10 (no joints) appear in Figure 3.17.

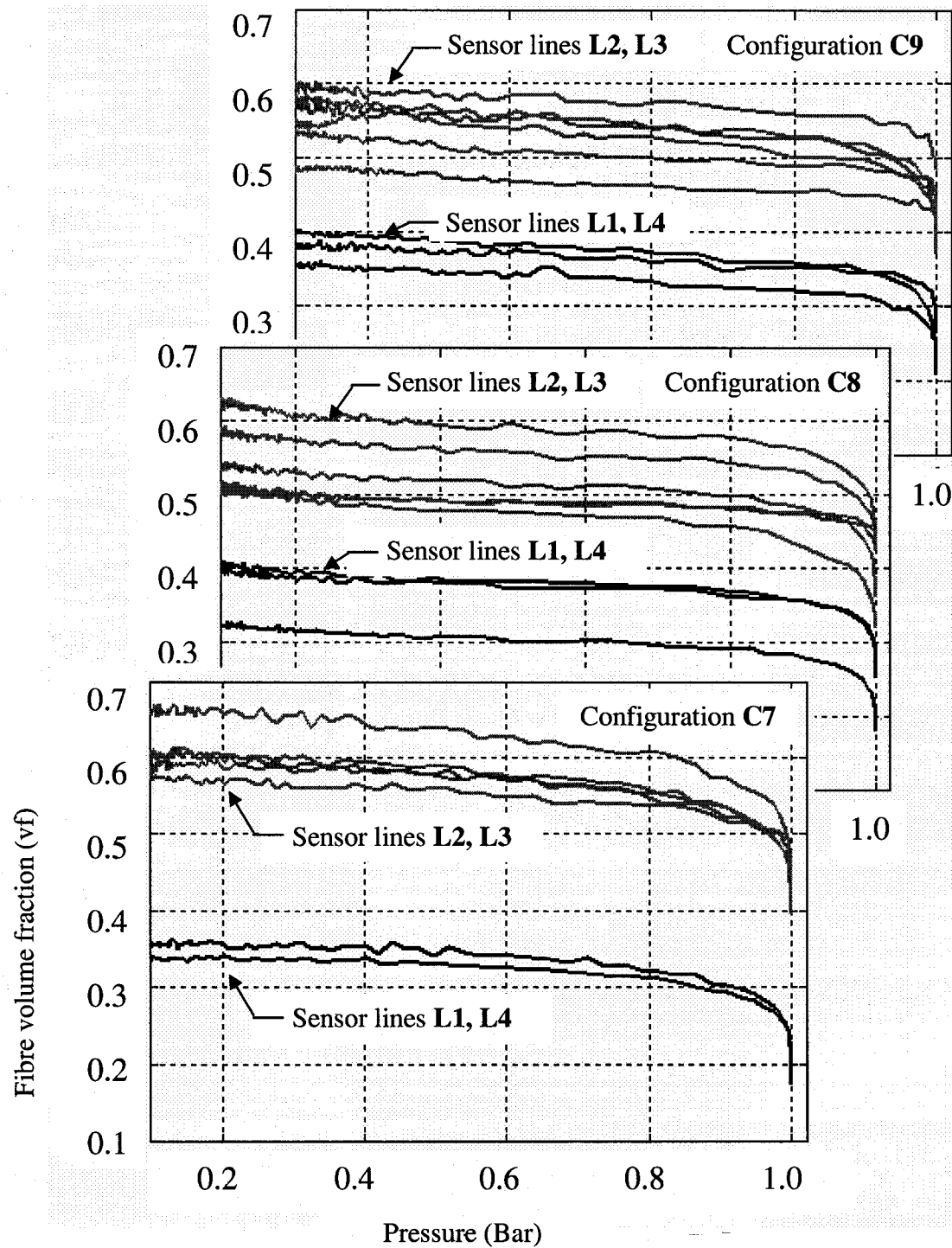


Figure 3.16 Results: reinforcement R2, configurations C7 to C9.

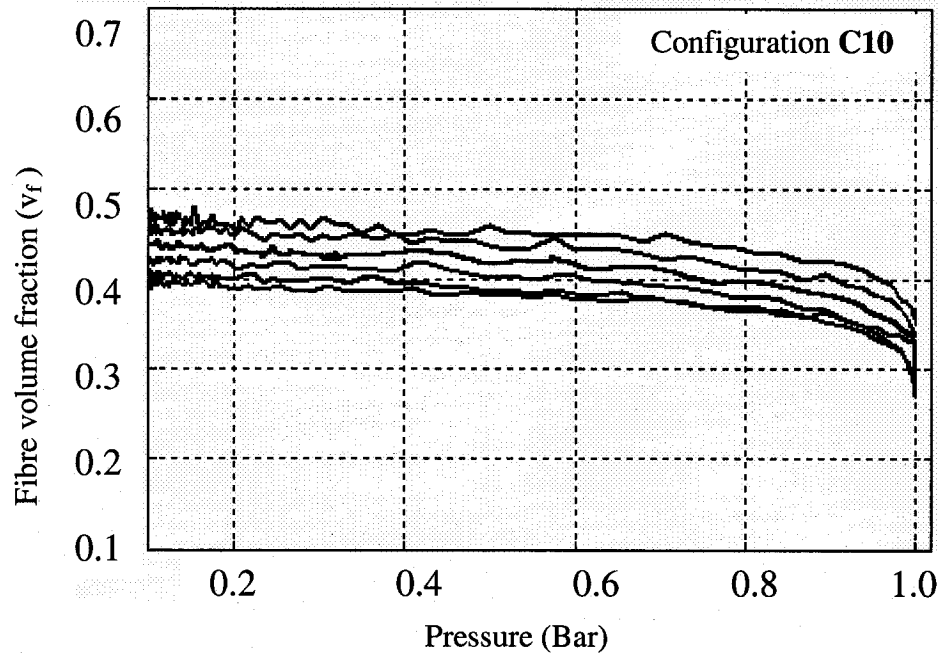


Figure 3.17 Results: reinforcement R2, configuration C10.

3.5.4 Analysis of results using the Power law model

All experimental compaction results were analysed using the power law model, Equation (3.29). The quantities reported are the initial fibre volume fraction under 1 Pa pressure, parameter A, and the stiffening index, parameter B as discussed in section 3.4.4. The basic Power law equation can be rewritten as follows:

$$v_f = A \cdot P_{comp}^B \quad (3.29)$$

The equation can also be expressed under a logarithmic form as follows:

$$\ln(v_f) = \ln(A) + B \cdot \ln(P_{comp}) \quad (3.30)$$

Using the following data conversion scheme:

$$\ln(v_f) \rightarrow y$$

$$\ln(P_{comp}) \rightarrow x$$

the equation becomes:

$$y = \ln(A) + B \cdot x \quad (3.31)$$

The above equation expresses the fibre volume fraction as a function of the mechanical compaction pressure applied on the preform. In order to get appropriate values of pressure in the power law equation, the following conversion was applied to change the absolute pressure p in the experiments into a compaction pressure P_{comp} expressed in Pascal:

$$P_{comp} = [(1 - p) \times 100000] \quad (3.32)$$

Simply put, the absolute pressure p which varied from one bar (no vacuum) to zero bar (complete vacuum) was transformed into a compaction pressure P_{comp} which varied from 0 Pa (no pressure) to 100 000 Pa (maximum pressure). The quantities $\ln(P)$ and $\ln(v_f)$ were reported as curves the of x as of function of y . By performing a linear regression parameters A and B were found. As mentioned earlier, 12 sensors were installed on each preform, laid along four lines. For each line, the sensor which best represented the compaction behaviour was selected for further analysis.

The adequacy of the power law model for representing the experimental results is demonstrated in Figure 3.18. The graph shows good agreement between experimental results and the line drawn using coefficients A and B derived from the liner regression and Power law model, Table 3.3.

Table 3.3 Parameters A and B , reinforcement R1, configuration C10.

Material	Number of layers	Initial fibre volume fraction A	Stiffening index B
Random Matt	12	0.11344	0.968

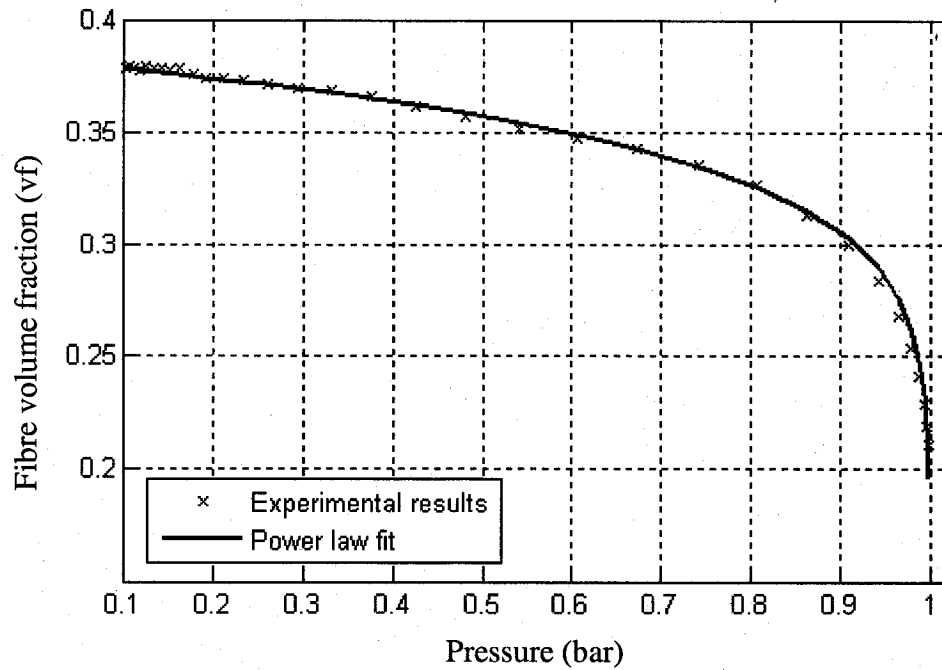


Figure 3.18 Comparing experimental results with the Power law model, random matt reinforcement R1, configuration C10.

Parameter A and B were calculated for different test panels based on the procedure described above. Values appear in Tables 3.4, 3.5, 3.6, and 3.7. Tables provide values of A and B for random matt reinforcement R1 and woven reinforcement R2.

Table 3.4 Computed initial fibre volume fraction (A) for random matt R1.

Parameter A		Random matt reinforcement			
Configuration	L1	L2	L3	L4	
C1	0.1002	0.1814	0.0713	0.1987	
C2	0.1001	0.1829	0.0746	0.2108	
C3	0.0998	0.1831	0.0814	0.1807	
C4	0.0827	0.1713	0.0575	0.1293	
C5	0.0901	0.1811	0.0966	0.1426	
C6	0.0842	0.1827	0.0753	0.1566	
C7	0.0982	0.1846	0.1149	0.1082	
C8	0.1084	0.1796	0.1855	0.1181	
C9	0.1050	0.1921	0.1431	0.1123	
C10	0.1087	0.1108	0.1132	0.1134	

Table 3.5 Computed stiffening index (B) for random matt R1.

Parameter B		Random matt reinforcement			
Configuration	L1	L2	L3	L4	
C1	0.1021	0.0821	0.1255	0.0783	
C2	0.1033	0.0751	0.1253	0.0684	
C3	0.1019	0.0841	0.1277	0.0812	
C4	0.1108	0.0753	0.1223	0.0792	
C5	0.1214	0.0825	0.1165	0.0977	
C6	0.1145	0.0706	0.1406	0.1061	
C7	0.1014	0.0891	0.0718	0.0976	
C8	0.1013	0.0813	0.0842	0.0989	
C9	0.1016	0.0873	0.0831	0.0903	
C10	0.1011	0.1022	0.1008	0.0968	

Table 3.6 Computed initial fibre volume fraction (A) for woven reinforcement R2.

Parameter A		Woven reinforcement			
Configuration	L1	L2	L3	L4	
C1	0.2515	0.3642	0.1394	0.3534	
C2	0.2231	0.3042	0.1998	0.2515	
C3	0.1737	0.3134	0.2465	0.3134	
C4	0.1541	0.3328	0.1164	0.4013	
C5	0.1686	0.3328	0.1755	0.4299	
C6	0.2865	0.3011	0.2018	0.2345	
C7	0.1480	0.3166	0.4037	0.1300	
C8	0.2018	0.2369	0.3726	0.2209	
C9	0.1422	0.3011	0.3295	0.2143	
C10	0.2122	0.2952	0.2393	0.2080	

Table 3.7 Computed stiffening index (B) for woven reinforcement R2.

Parameter B	woven reinforcement			
Configuration	L1	L2	L3	L4
C1	0.0277	0.0201	0.0735	0.0241
C2	0.0448	0.0444	0.0461	0.0565
C3	0.0553	0.0434	0.0361	0.0434
C4	0.0595	0.0330	0.0951	0.0176
C5	0.0612	0.0368	0.0667	0.0260
C6	0.0431	0.0460	0.0541	0.0681
C7	0.0601	0.0473	0.2520	0.0735
C8	0.0491	0.0543	0.0227	0.0417
C9	0.0752	0.0542	0.0346	0.0412
C10	0.0471	0.0334	0.0467	0.0511

Once the values of parameters A and B presented in Tables 3.4 to 3.5 were obtained the effect of the number of layers NS, overlap length OL and horizontal distance HD on A and B were formally quantified for reinforcements R1 and R2. This was done as follows: explanation is provided for the effect of overlap length OL on parameter A, and reinforcement R1 which is the random matt.

Two overlap lengths, 20 mm and 40 mm were used in preforms. To find the effect of overlap length on the initial fibre volume fraction (parameter A) two average values of parameter A were calculated from Table 3.4 and 3.6. One average was calculated for all random matt preforms with OL=20 mm, and one for all random matt preforms with OL=40 mm. The percentage of deviation ($Pr_{A_{OL}} \%$) between these averages was found comparing of these two values with overall average A_r .

The calculation procedure is presented as follows. For random matt, R1 values of parameter A were extracted from Table 3.4.

$$A_{OL=20} = \frac{A_{C1} + A_{C2} + A_{C3} + A_{C7} + A_{C8} + A_{C9}}{6} \quad (3.33)$$

$$A_{OL=40} = \frac{A_{C4} + A_{C5} + A_{C6}}{3} \quad (3.34)$$

$$A_T = \frac{A_{OL=20} + A_{OL=40}}{2} \quad (3.35)$$

$$Pr_{A_{OL}} \% = 100 \left[\frac{A_{OL=20} - A_{OL=40}}{A_T} \right] \quad (3.36)$$

where $A_{OL=20}$ is the average initial fibre volume fraction with overlap length of 20 mm and $A_{OL=40}$ is the average initial fibre volume fraction with overlap length of 40 mm. A_T represents the overall average initial fibre volume fraction.

The same procedure was applied to quantify the effect of OL, NS and HD on parameters A and B for reinforcements R1 and R2. Results are presented in Figure 3.19. It can be noted that the effect of length, distance and sequences is weak. Changes in reinforcement have a stronger effect on compaction. Changing random matt reinforcement R1 to woven reinforcement R2 increases initial fibre volume fraction by 64.35%. Also, an effect of the number of layers has been experienced; going from 24 layers to 36 layers increases parameter A by 56%. The stiffening index parameter B, of random matt preforms R1 is 68.66% higher than for woven preform R2. The number of layers also has a strong effect on the stiffening index as upon changing from 24 to 36 layers of reinforcement, parameter B decreases by 34.74%. It was also observed that overlaps length OL affects the stiffing index more than the initial fibre volume fraction.

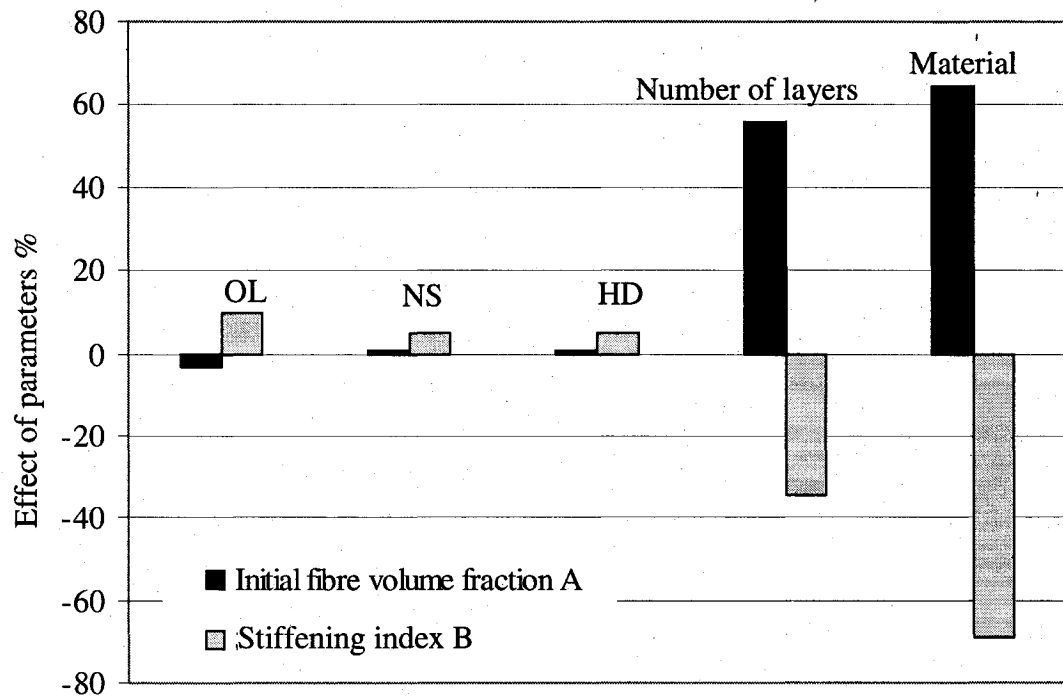


Figure 3.19 Effect of joint configuration and reinforcement on initial fibre volume fraction A and stiffening index B.

3.5.5 Compaction master curve

The relation between Power law parameters A and B is plotted in Figure 3.20. Points associated with each reinforcement R1 and R2 are identified. It is seen that points associated with each reinforcement from two clearly separated groups. Such findings confirm trends reported in Corriea's work [55].

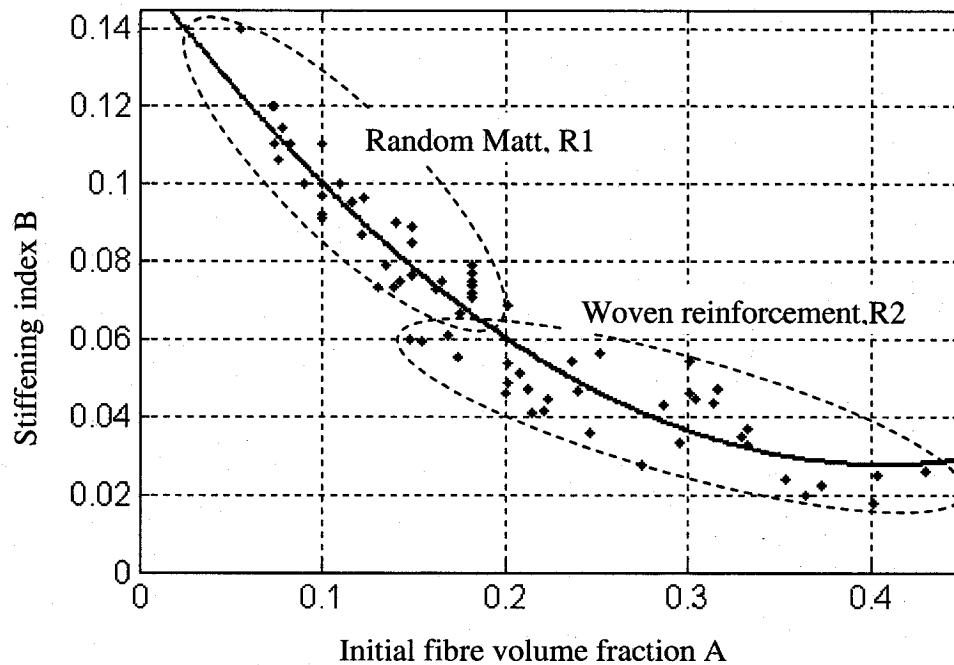


Figure 3.20 Compaction master curve for both random matt R1 and woven reinforcement R2.

All points originating from random matt reinforcement R1 are located on the left side of the curve, whereas points associated with woven reinforcement R2 are located to the right. It can be concluded that the initial fibre volume fraction for woven reinforcement R2 is higher than for matt reinforcement R1 and the stiffening index for R2 is lower than it is for R1. The physical implication is that the woven reinforcement stiffens more quickly from initially higher fibre volume fractions.

Following the above results, it was also shown that the number of layers N_L affects compaction characteristics. The more detailed Figure 3.21 shows that when the number of layers is increased, the initial fibre volume fraction increases and the stiffening index decreases. This interesting characteristic has not been reported before, in terms of groups of points on the compaction master curve.

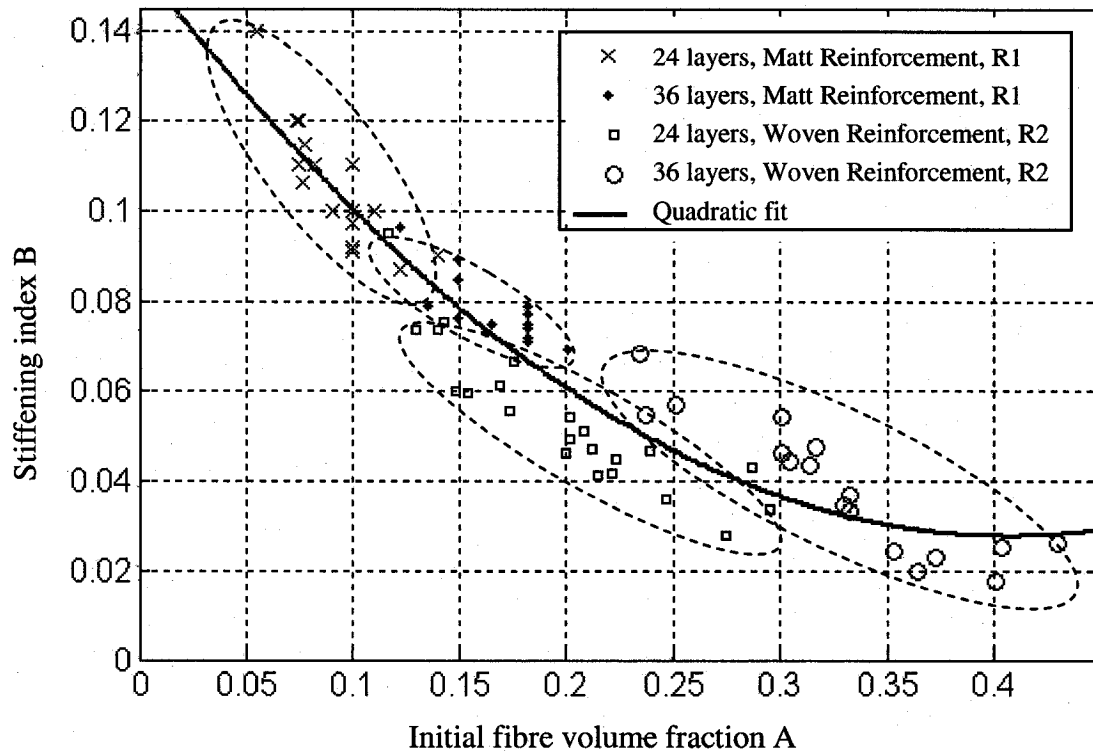


Figure 3.21 Compaction master curve showing the effect of reinforcement and number of layers.

3.5.6 Microscopic observation

Figure 3.22 shows micrographs for reinforcement R2, configuration C7. The figure shows more compaction and higher v_f in the joint, confirming earlier results. Changes in both v_f and part thickness are generally progressive with more empty space between the yarns in the transition zone.

Figure 3.23 shows similar micrographs for reinforcement R1, configuration C1. Whilst the change in thickness is progressive, for this thicker reinforcement clear triangular channels similar to those represented schematically in Figure 3.23 are visible. Such channels will likely alter resin flow locally, amongst other properties.

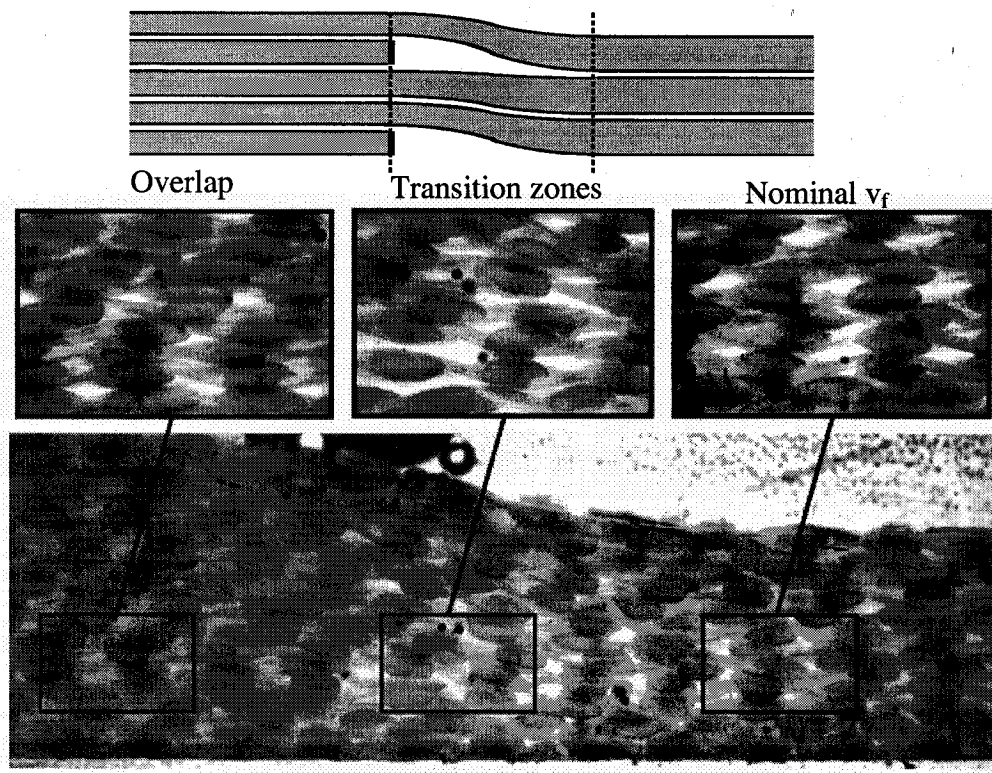


Figure 3.22 Micrograph : reinforcement R2, configuration C7.

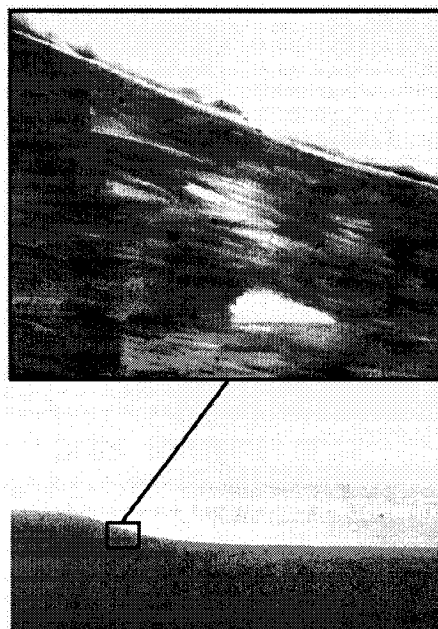


Figure 3.23 Micrograph: random matt reinforcement R1, configuration C1.

Figure 3.24 shows the difference in thickness observed away from the joints and between them, for reinforcement R1 and configuration C5. This confirms that compaction curves can be segregated into 3 groups with different behaviour in this case, and points to a distinct compaction behaviour between the two joints.

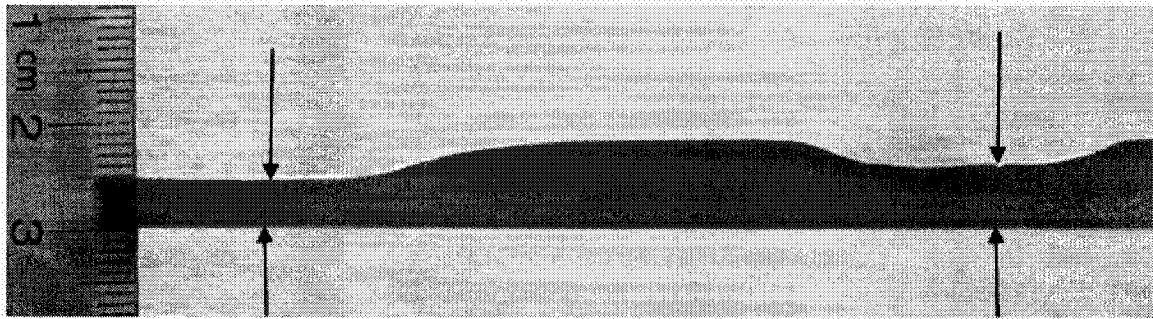


Figure 3.24 Micrograph: random matt reinforcement R1, configuration C5.

3.6 Discussion

The different trends mentioned above can be summed up as follows:

- Whilst joints are thicker, v_f is consistently higher in superimposed plies associated with joints;
- Lower v_f values away from the joints are generally close to those of joint-free preforms;
- Preforms with interlaid continuous plies ($NS = 1$) generally show less variability in v_f ;
- Close joints generally affect v_f over a larger zone away from the joints;
- Hall effect data was generally well validated with LVDT data but some curves had to be discarded;
- General trends are similar for both reinforcements, with effects of parameters OL, HD and NS having different amplitudes in both cases.

The occurrence of different v_f values in joints is not trivial. The same vacuum level should lead to similar fibre volume fractions; previous work [15,16,24] indicates that preforms containing more reinforcement layers compact somewhat less, albeit at higher pressures. In this work average differences were 15% to 20%. The behaviour can be explained by a number of factors. Differences in thickness at the joint and next to it can tension the film, in turn compacting the preform, Figure 3.25.

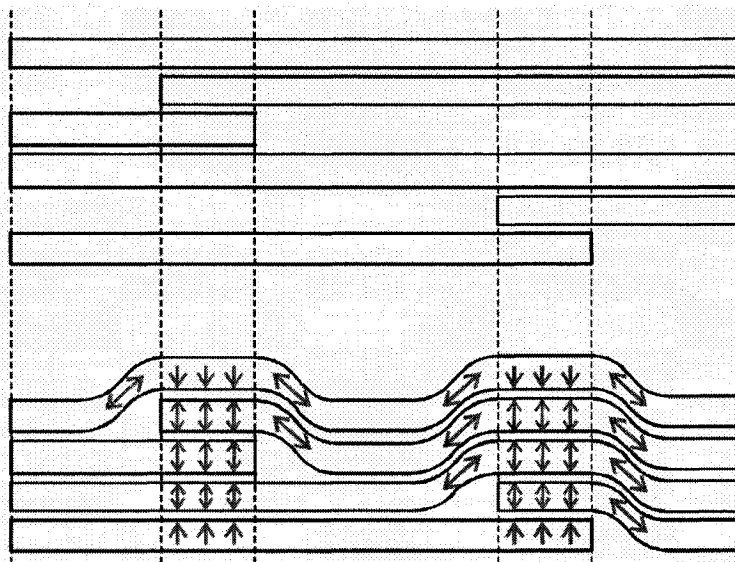


Figure 3.25 Local force build-up in compacted plies.

Whilst the strength of this effect may vary depending on the way in which the film and sealant tape are prepared, similar tension will also appear in the individual reinforcement layers which have high in-plane stiffness and can not slip relatively over long distance to each other whilst compacted. This effect is unrelated to potential folds or the actual configuration of the film; stiffness of one reinforcement layer is substantially greater than stiffness of the film. It should be noted that in a preform where a given number of reinforcement layers are superimposed locally, the increase in length in the top layer occurring upon compaction is significant, resulting in significant tension in that layer. The above is confirmed when considering that zones away from the joints in configurations C1-C9 compact to v_f values that are generally very similar to those reached in preforms devoid of joints, C10. For a set vacuum level, columns of superimposed plies compact more, whilst

other zones show the same behaviour other zones of the preform generally do not compact less.

High repeatability levels exhibited by preforms where one continuous ply was interlaid between all joints ($NS = 1$) result from local deformations in the continuous layers which adapt to any imperfection in geometry due to cutting or misalignment. Sudden reductions in v_f are present at discontinuities in the plies. Reinforcements have finite thickness and bending stiffness, hence v_f drops suddenly from higher values in the superimposed layers to lower values at the precise location where superimposed layers end, and increases again in the transition zone away from the joints as plies compact in a similar way to configuration C10 (Figure 3.13). The extent of the lower v_f transition zone is likely to depend on tension and bending in the layers, and on joint configuration. In this work, configurations C7-C9 featuring lower in-plane distance HD showed somewhat lower v_f values away from the joints. A stronger effect was observed with reinforcement R1, where configurations C4-C6 featuring higher overlap length OL showed reduced v_f values between the joints. The difference in behaviour between the two reinforcements in these cases likely results from larger thickness and bending stiffness of reinforcement R1.

CHAPTER 4

Flow behaviour of lap joints in preforms for VARTM

4.1 Introduction

Efficient flow of resin through VARTM preforms prior to gelling with complete and predictable mould fill is a major concern in polymer composites manufacturing. Incomplete impregnation results in the discarding of high-cost materials such as glass, carbon and aramid reinforcement and waste of consumables. Associated labour costs are similarly inflated.

To control these costs, it is important to predict and control a number of process parameters. These include the mould filling time to minimize the manufacturing cycle time, the viscosity of the injected material to predict the fluid pressure required to impregnate the preform, and the permeability of the preform to determine flow paths and overall success of the process.

To assist manufacturers in controlling these parameters, a number of software programs have been developed such as LIMS [56], PAM-RTM [57] and Polyworx [58]. However, the available programs model the preform as a continuous, uncut sheet with constant layering throughout. Overlapping of preform sheets is not considered. In practice,

software limitations require that the manufacturer experiments with the setup and explores analytical models later.

It is important to know when the resin fills the mould such that all of the fibres in the preform are wetted; that is, no dry areas are permitted in the impregnated preform. These dry areas are known as voids and are undesirable for acting as discontinuities in the final product when loads are applied. Prior to impregnation, the whole of the mould excluding the fibres may be considered a void, with preform porosity ϕ of calculated as $1-v_f$.

A higher fibre volume fraction v_f means that less space is available for resin in the final product. This can produce a higher strength product; however during manufacturing resin is restricted to flowing through smaller spaces and gaps. Therefore, the less space available, the more difficult it is for the resin to fill the mould for a fixed viscosity. In areas of overlapping sheets, the volume fraction can be higher than it is in the rest of the preform. This would result in more difficult flow through these regions than in regions without overlapping sheets. On the other hand overlaps form channels in the reinforcement which serve as distribution lines for resin in these areas.

The objective of this chapter is to assess perturbations to flow resulting from the presence of joints in VARTM preforms.

In this chapter, various flow and impregnation models are discussed. The main factors affecting resin infusion in a preform are explained and experimental results are presented.

4.2 Background and literature review

Predictions of flow thorough porous media and the progression of the flow front are usually based on Darcy's law [59]. Darcy's law expresses the proportional relationship between the pressure drop of an infusing fluid over a length of porous media, the viscosity of the fluid and the flow rate. Experiments and calculations generally show good agreement for 1D flow as the permeability is an empirical parameter. For 2D and 3D flow found in composites manufacturing the situation is usually more complex. The development of Darcy's law is discussed in detail in a latter section.

Permeability is a measure of the ease with which a fluid passes through a porous preform. Permeability is independent of the viscosity and density of the fluid. Viscosity is defined as internal resistance to flow.

Darcy's law forms the basis of a number of liquid moulding simulation software packages for predicting the flow front of the infusing resin. Before the product cycle reaches the manufacturing state, the pressure, placement and sizing of resin injection lines may be optimized. Software packages such as Polyworx™ can predict and simulate preform impregnation in composite manufacturing processes such as RTM, VARTM and Seeman Composites Resin Infusion Moulding Process, SCRIMP [60]. One of the main input parameter to such programs is permeability of the preform at each point. Therefore, reinforcements need to be characterized in terms of their permeability.

Much work was conducted to improve mould filling simulation software over recent years. For instance, Shojaei et al. [61] investigated 3D mould filling in the RTM process using numerical approaches. The numerical scheme used in their study was based on the formulation of nodal partial saturation at the flow front. The authors found that the approach enabled the inclusion of a transient term in the working equation, removing the need for calculation of a time step to track the flow front as in prior conventional schemes. In order to compare the results of the nodal partial saturation concept with conventional methods, a numerical scheme based on the quasi-steady state formulation was also introduced. The resulting computer codes based on both numerical formulations allowed the prediction of flow fronts and pressure fields in 3-D moulds with complex geometry.

Simulation software requires permeability data, which can be difficult to measure. In the work of Parnas et al. [62] a three-dimensional woven fabric was proposed as a standard reference material for the characterization of permeability. The material used in the study was characterized for permeability in radial and 1D, unsaturated and saturated flow, and also in through-thickness flow. The permeability of the 3-D woven fabric was repeatedly measured within 15% in either radial or 1-D saturated flow. The results indicated the importance of structural heterogeneity on the unsaturated flow behaviour and showed qualitatively agreement with a simple model of flow in heterogeneous unsaturated porous media.

Industrial preforms are often made of variable numbers of different reinforcement, Bruschke et al. [63] developed numerical approaches to calculate the effective in-plane permeability of multi-layer preforms in RTM. Transverse flow was modelled without requiring a computationally intensive three-dimensional solution. This numerical method was validated with preforms made of random matt and woven reinforcements.

Calado et al. [64] also disclosed a numerical method for predicting the average effective permeability of multi-layer preforms for RTM. The effective permeability is a function of the in-plane and transverse permeabilities of the constituent reinforcements, the thickness of each layer and the total length of the mould. Results of the study demonstrated that in-plane permeability is very high compared to transverse permeability, but there is significant transverse flow between the layers. For calculating an average effective permeability through the thickness, only the transverse permeability between the layers need to be considered.

A number of researchers studied the effect of reinforcement type and configuration on permeability. Phelan et al. [65] investigated flow in unidirectional fibre porous media. The effect of tow shape, packing, and intra-tow permeability on the overall bed permeability was studied. It was shown that the influence of the intra-tow permeability on the overall bed permeability increases with inter-tow packing and increasing degree of tow ellipticity. Experiments were performed using a commercially available unidirectional material, Knytex D155, and results were compared with available numerical calculations. The results showed that reducing the number of warp threads holding the tows in place has a substantial effect on the permeability, whereas removal increases it by as much as a factor of six.

Woven reinforcements typically exhibit orthotropic flow behaviour because of their architecture and fibre layout. The principal directions for woven preforms are often assumed to be parallel to the warp and weft. Matt with random fibre orientation demonstrate isotropic flow behaviour. Matt preforms have little geometric complexity and may be assimilated to isotropic porous media having a constant and known fibre volume fraction. Most multilayer preforms have a clear set of flow or permeability axes, usually along and across some fibre directions. This permits the application of Darcy's law, explained in section 4.3.1, in its isotropic form for determining permeability and flow characteristics using 1D tests. Woven fibers have more complexity but they are regularly used in reinforced composite material

manufacturing hence some extension to the isotropic Darcy's law is necessary to simulate such flows.

Slade et al. [66] investigated fluid permeability in deformed preforms due to the double curvature of RTM moulds. Deformation of the preform changes the permeability tensor locally in the deformed regions and the flow front is less uniform. The study used two different types of preforms sheared to specific angles. A relationship between the deformation angle and permeability was noted. Through both experimentation and numerical modelling, it was found that the anisotropy ratio increases with the shearing angle.

For such cases, the permeability of the preform may be estimated by modifying Darcy's law using a generalized three-by-three tensor in place of a scalar value. Equations appear in the section 4.3.1. In determining the permeability of the structure, one must determine the principal directions of the preform and then individual terms of this tensor.

Permeability measurements feature another complication. Fibre tows are densely packed regions of bundled fibres. These regions have a much lower permeability than the channels between the fibre tows. As resin begins to enter the preform it fills these channels at a much higher rate than it impregnates the inner tows. Stated otherwise, the inside of fibre tows are saturated at a much slower rate than the channels due to their lower permeability. A region of the preform which includes both filled channels and impregnated fibre tows is known as a fully saturated region. A region where the channels are completely filled with resin but the fibre tows are not fully saturated is known as a partially saturated region. This phenomenon is illustrated in Figure 4.1.

Sadiq et al. [67] investigated experimental flow of viscous fluids across an array of solid and porous circular cylinders together representing a porous medium. By packing 50 to 100 nylon fibres into 6.35 mm diameter holes and measuring the flow rate and pressure drop across the cylinders, the transverse permeability of the model porous media was characterized. The volume fraction of bundles inside the cylinders ranged from 60 to 75%. Both Newtonian and shear thinning fluids were used as infusion liquid. These fluids were pumped through the medium such that the flow was perpendicular to the fibre axes. Once the porous bed was fully saturated, the permeability was determined from Darcy's law. Also investigated in this study was the flow through a heterogeneous fibre bundle, consisting of fibre bundles in a regular array. During the filling stage, the progress of the flow front

through the heterogeneous fibre beds was observed and flow-induced void formation inside the fibre bundles was monitored. A series model was suggested to estimate permeabilities of such heterogeneous media.

Parnas et al. [68] investigated the interaction between microscopic and macroscopic flow in dual scale RTM preforms. Void formation was observed. Differences between experimental measurements of the saturated and the unsaturated permeabilities were explained. The study shows that the heterogeneous reinforcement structure may also contribute to differences observed in permeability measurements carried out using the radial and the one-dimensional flow methods.

De Parseval et al. [69] mathematically modelled the variation of permeability due to partial saturation in dual scale porous media made of fibre bundles where a Newtonian viscous fluid was impregnating the media. Pillai et al. [70] also introduced a sink function in their model, which affects permeability of the unsaturated preform. De Parseval et al. [69] explained the discrepancies between experimental pressure results and analytical predictions based on Darcy's Law. The permeability was determined from a linear interpolation between the lower permeability of the forward region (where flow is only present in inter-tow channels) to higher permeability in the fully saturated region, and interpolated values applied in the intermediate region where the medium is gradually approaching full saturation. This linear change in permeability for the flow of resin near the flow front are illustrated in Figure 4.1. At the extreme left, fibre bundles are almost completely saturated. The surrounding area is also saturated. Between this region and the flow front, fibre bundles having substantial dry fibre areas and the adjacent channels form a partially saturated region.

The excellent agreement between the predictive model and the experimental results of inlet pressure profile with respect to time suggests that the model can be used to describe the variation of permeability behind a moving front. It can also be used to characterize the fibrous medium by determining two different permeabilities, and quantify the relative importance of the unsaturated portion of the flow domain for a given preform architecture.

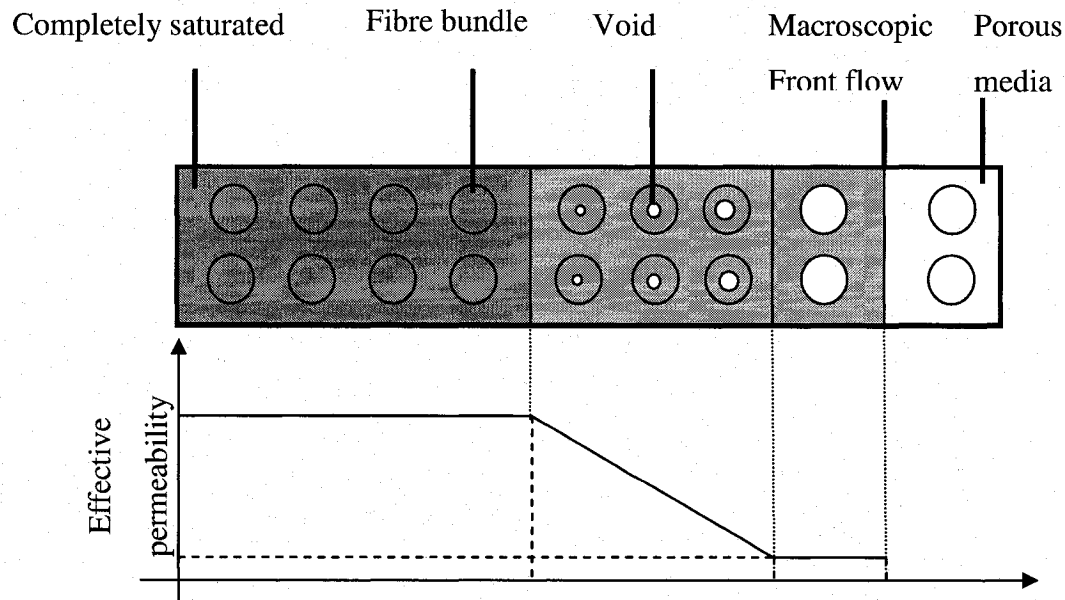


Figure 4.1 Permeability characterization for dual scale preforms and front flow progression in the yarn.

The partial saturation is typically neglected, but its effect is prominent in dual-scale porous media. Its relative importance depends on the fibre density within tows and on the spacing between adjacent tows. As the fibre density increases, or as the spacing increases, the contribution of the partially saturated region likewise increases. It is also understood that variations in permeability measurements are caused by measurement errors, partial mould deflection and different preform stacking arrangements for each experiment.

Different experimental and modelling procedures were proposed for obtaining saturated and unsaturated permeability values of a preform. Lekakou et al. [71] proposed such a method for 2D woven reinforcements. A viscoelastic model in which the pressure acts on the fibres in an elastic manner and on the liquid matrix in a viscous manner was described. The authors derived an analytical model for the nonlinear elastic compression of two-dimensional, orthotropic, plain woven fibre cloths. The model was validated by experimental data and empirical constants were determined through compression of wet plain woven glass fibre reinforcement. The effects of the compression of woven cloths on the permeability during processing were demonstrated.

Historically, many authors have generated permeability data for preforms and reinforcements using various techniques, Lai et al. [72] characterized the permeability of carbon and glass preforms for 1D and 2D radial flow using silicone oil and motor oil. Results indicate that reliable permeability data for fibre preforms with varying architectural complexity can be obtained. The results obtained from the radial flow experiments were in excellent agreement with 1D flow experiments. The largest difference observed between various measurement techniques was 10%. Gauvin et al. [73] conducted permeability measurements for simple mould geometries to find in-plane permeability values. Luce et al. [74] characterized the flow behaviour of multi-layer preforms and also considered permeability measurements through the thickness of the preform. Ahn et al. [75] embedded fibre optic sensors in the preform to measure three-dimensional permeability of 3D preforms. Ballata and Walsh [76] proposed improvements on transverse permeability measurement by utilizing SMARTweave sensor technology. Nedanov et al. [77] also proposed a method for determining the principal values of the 3D permeability tensor for preforms by using SMARTweave.

None of the above studies have provided means for characterizing the permeability in areas of overlapping preforms, or information about flow in lap joints. Lap joints represent a unique preform configuration that has not been studied where a higher fibre volume fraction exists in the overlap and flow channels at its edge accelerate flow. The present work addresses this by querying the relationship between lap joint characteristics and permeability via a series of experiments.

4.3 Permeability

The ability of resin to flow through a preform can be quantified by the preform permeability. This characteristic of a preform affects the impregnation and is therefore an important processing parameter in composite manufacturing. A preform is considered to have high permeability when resin flows quickly and easily through it.

4.3.1 Darcy's law

Permeability is identified by the variable K in Darcy's law, which relates the pressure P , viscosity μ and rate of flow v_x through a porous media. Darcy's law is expressed as:

$$v_x = -\frac{K}{\mu} \cdot \frac{dP}{dx} \quad (4.1)$$

where v is the velocity of the resin through the preform for 1D flow (m/s), μ is the viscosity of the impregnating liquid or resin (Pa/s) and dP/dx is the pressure drop of the resin over a known distance during impregnation (Pa/m). Permeability has m^2 units. The negative sign indicates that fluid flows from zones of high pressure to zones of low pressure; pressure decreases from the inlet to the outlet. The lower pressure is generated by a pump in VARTM. Permeability K may be isolated in Darcy's law as follows:

$$K = -v_x \mu \left(\frac{dx}{dP} \right) \quad (4.2)$$

In thick preform processes, the three-dimensional form of Darcy's law may be used where permeability is a tensorial property:

$$v_x = -\frac{1}{\mu} \left(K_{xx} \frac{\partial P}{\partial x} + K_{xy} \frac{\partial P}{\partial y} + K_{xz} \frac{\partial P}{\partial z} \right) \quad (4.3)$$

$$v_y = -\frac{1}{\mu} \left(K_{yx} \frac{\partial P}{\partial x} + K_{yy} \frac{\partial P}{\partial y} + K_{yz} \frac{\partial P}{\partial z} \right) \quad (4.4)$$

$$v_z = -\frac{1}{\mu} \left(K_{zx} \frac{\partial P}{\partial x} + K_{zy} \frac{\partial P}{\partial y} + K_{zz} \frac{\partial P}{\partial z} \right) \quad (4.5)$$

The above is equivalent to the matrix expression:

$$\bar{v} = -\frac{1}{\mu} K_{ij} \nabla P = \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = -\frac{1}{\mu} \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \begin{Bmatrix} \partial P / \partial x \\ \partial P / \partial y \\ \partial P / \partial z \end{Bmatrix} \quad (4.6)$$

Preforms in the present study are modelled as two-dimensional structures which are thin with respect to the length and width of the components. Flow through the thickness usually the z direction, may be neglected. Darcy's law may be written as follows:

$$\bar{v} = -\frac{1}{\mu} K_{ij} \nabla P = \begin{Bmatrix} v_x \\ v_y \end{Bmatrix} = -\frac{1}{\mu} \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} \partial P / \partial x \\ \partial P / \partial y \end{Bmatrix} \quad (4.7)$$

Permeability tensor components K_{xy} and K_{yx} are assumed equivalent, the permeability tensor being symmetric. If orthogonal axes 1 and 2 correspond to the main flow orientations, permeability can be characterized using two scalar components:

$$K_{11} = -v_1 \mu \left(\frac{dx}{dP} \right) \quad (4.8)$$

$$K_{22} = -v_2 \mu \left(\frac{dy}{dP} \right) \quad (4.9)$$

where K_{11} is the principal maximum permeability in principal direction of flow 1 and K_{22} is the permeability perpendicular to K_{11} . In zones where the flow is mostly linear, a preform may practically be characterized using a single permeability value.

4.3.2 Flow rate

The section above discussed permeability in terms of Darcy's seepage velocity. Two fluid velocities are defined from Darcy's law: the seepage velocity and the particle velocity

as expressed below. The seepage velocity v (equation 4.1) of the resin is calculated by dividing the volumetric flow rate Q by the total cross sectional area of the mould, A :

$$v = \frac{Q}{A} \quad (4.10)$$

The particle velocity v_p is determined by dividing the volumetric flow rate Q by the free cross sectional area A_p of the preform:

$$v_p = \frac{Q}{A_p} \quad (4.11)$$

The difference between the total cross sectional area A and the free area A_p is shown in Figure 4.2, where A_{fibres} is the total fibres cross section:

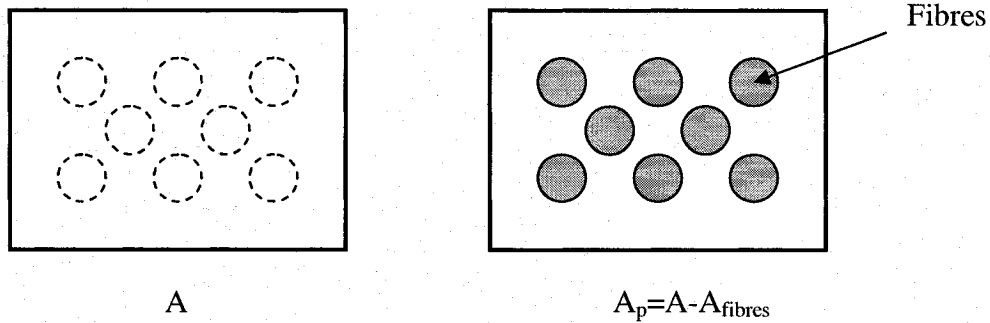


Figure 4.2 Total cross sectional area A and free area A_p .

It is evident from the figures that the total cross sectional area of the mould is determined by the thickness and width of the preform where as the free area A_p is determined by subtracting the area of the cross section fibres from the total cross sectional area.

If porosity $\phi = (1 - v_f)$, Darcy's velocity and the free velocity are related as follows:

$$v = v_p \cdot \phi \quad (4.12)$$

In theory, Darcy's velocity and the free velocity can both be used in Darcy's Law, but these two velocities result in two different measures of permeability. In practice, permeability is defined based on the seepage velocity v .

$$K = -v \cdot \mu \cdot \left(\frac{dx}{dP} \right) = -v_p \cdot \phi \cdot \mu \cdot \left(\frac{dx}{dP} \right) \quad (4.13)$$

In a porous medium, several factors affect the permeability. These factors include the pore shape, their specific surface area, porosity and others. In VARTM permeability changes with in plane shear, orientation of the fibres and with the fibre volume fraction. However, if the materials are the same throughout the preform, and porosity is constant, the permeability tensor does not change in time, and is also constant throughout the preform.

4.3.3 The Kozeny-Carman equation

An industrial preform comprises a wide distribution of capillary sizes. The manner in which these capillaries are interconnected varies widely and irregularly throughout the preform. If the pore size distribution and irregular interconnections are ignored the flow of resin through the preform can be modelled by geometric permeability models like that developed by Kozeny and Carman [78].

The Kozeny-Carman model predicts the average velocity of a liquid flowing through a porous medium under a set pressure difference. This approach is also known as the hydraulic radius theory and relies on a set of assumptions about the structure of pores within the preform. In the Kozeny-Carman model the porous medium is assumed to be equivalent to a channel with a complex cross section which has, on average, a constant area along the channel. The channel diameter is quantified by dividing the cross sectional area by the wetted perimeter. The flow rate is calculated using the nominal length of the preform or the channels length. Small spacing between fibres and limited flow rates results in laminar flow.

The Kozeny-Carman model is based on Poiseuille's equation for flow in a circular tube:

$$Q = \frac{\pi R_{ch}^4 \Delta p}{8 \mu L_{ch}} \quad (4.14)$$

where Δp is the pressure drop over the tube length L_{ch} , Q is the volumetric flow rate and R_{ch} is radius of the tube. The average velocity $\bar{v}_{ave}$ of the fluid in the tube can be expressed in terms of the flow rate:

$$\bar{v}_{ave} = \frac{Q_{ch}}{\pi R_{ch}^2} \quad (4.15)$$

$$\bar{v}_{ave} = \frac{R_{ch}^2 \Delta p}{8 \mu L_{ch}} \quad (4.16)$$

Kozeny modelled the porous material as many small capillary tubes of diameter D_{ch} laid in parallel over a cross sectional area A . The cross sectional area of the flow path is A_p .

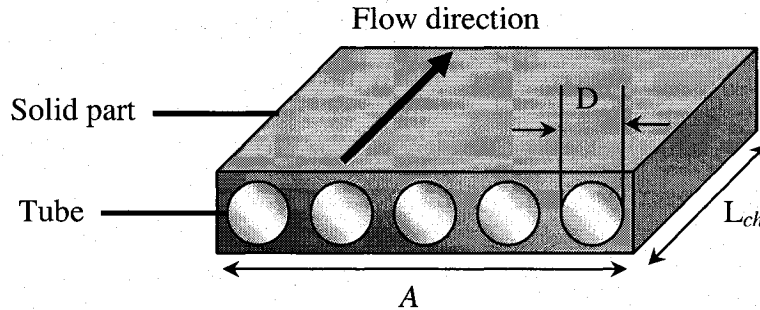


Figure 4.3 Schematic figure for Kozeny-Carman model.

The time required to flow a liquid particle along the length of the tube is t_{tim} and the velocity of the fluid through the tube is $\bar{v}_{ch}$:

$$t_{tim} = \frac{L_{ch}}{\bar{v}_{ch}} \quad (4.17)$$

In a true preform flow channels are not straight but may be approximated by representative channel length and velocity L_{rep} and $\bar{v}_{rep}$:

$$t_{im} = \frac{L_{ch}}{\bar{v}_{ch}} = \frac{L_{rep}}{\bar{v}_{rep}} \quad (4.18)$$

Where $\bar{v} = \frac{Q}{A\phi}$

The above relationships may be combined with Darcy's law as follows:

$$\frac{L_{ch}}{\bar{v}_{ch}} = \frac{8\mu L_{ch}^2}{R_{ch}^2 \Delta p} \quad \frac{L_{rep}}{\bar{v}_{rep}} = \frac{\phi \mu L_{rep}^2}{K \Delta p} \quad (4.19)$$

Permeability along the flow direction is obtained as:

$$K = \frac{\phi R_{ch}^2 L_{rep}^2}{8 L_{ch}^2} \quad (4.20)$$

$$\left(\frac{L_{rep}}{L_{ch}} \right)^2 = S_s \quad (4.21)$$

where $\frac{L_{rep}}{L_{ch}} = 1$ for straight channels and $2 \leq \frac{L_{rep}}{L_{ch}} \leq 5$ for common porous materials.

Therefore:

$$K = \frac{\phi R^2}{8 S_s} \quad (4.22)$$

Due to their nature, the radii of channels in preforms are not uniform. It is thus necessary to define a hydraulic radius R_h :

$$R_h = \frac{A_{flow}}{P_{wetted}} \quad (4.23)$$

where A_p is the cross section area of flow and P_{wetted} is wetted parameter, a well known parameter in the fluid mechanics.

The hydraulic radius for porous media is defined mathematically as follows:

$$R_h = 2 \frac{\phi}{S_{ssa} (1 - \phi)} \quad (4.24)$$

where S_{ssa} is the specific surface area of the porous media.

Substituting, the Kozeny-Carman equation becomes:

$$K = \frac{\phi^3}{2S_s (1 - \phi)^2 S_{ssa}} \quad (4.25)$$

The Kozeny-Carman equation does not apply to all porous media:

-Dependence of permeability on porosity: The Kozeny-Carman model is based on conduit flow. Very high porosities the model breaks down and experimental results are better described by modelling the flow using a submerged objects approach.

-Parallel-type pore non-uniformities: Capillaries forming a porous medium are interconnected in a generally random fashion. As the fluid reaches a juncture between capillaries of different cross sectional areas, the fluid may enter either the narrower or larger pore. If the largest available pore is entered at every juncture, the fluid particle travels through a flow channel of largest possible hydraulic conductivity in the sample.

-Serial-type pore non-uniformities: The effective channel cross section in a porous medium usually varies in a quasi-periodical manner. Such sequential variation in cross section tends to result in a smaller permeability than the one calculated from the Kozeny-Carman equation.

Generally speaking, the Kozeny-Carman model is an interesting tool for understanding basic phenomena in flow through porous media; however, it is too simplistic to capture the

complex geometry of preforms; hence preforms permeability can not predicted using this equation.

4.4 Experimental work

To determine the flow characteristics of multilayer lap joints, a series of specimens were produced using the same reinforcements and configurations as described in chapter three.

4.4.1 Apparatus and set-up

Randomly oriented continuous filament glass matt M8610-450 was used as reinforcement R1. Glass plain weave 0154/139 was used as reinforcement R2. Both reinforcements were obtained from Saint-Gobain Technical Fabrics.

The apparatus used to manufacture the specimens is similar to that described in Chapter 3; it is illustrated in Figure 4.4. A 1000x1000 mm square PMMA plate with a thickness of 6.5 mm provided a base for the process. For the overlay, an Airtech WL5400 nylon vacuum infusion film was sealed to the PMMA plate with a perimeter strip of Airtech AT-199 vacuum infusion sealant tape. Vacuum was generated using a Welch 1399 pump and transparent flexible piping with 8.5 mm inner diameter. Typical preform size was 210 x 210 mm. A resin tank was connected to an inlet port under the film. At the exit of the VARTM setup, a resin trap fitted with a pressure transducer was added to prevent resin entering the vacuum pump. An on/off valve and a flow control valve were placed between the trap and pump. The flow control valve ensured controlled infusion. The Cole-Palmer 68073 high accuracy pressure transducer permitted control of the maximum vacuum level and of any leakage in the system. Two pinch clamps were installed on the line for rapid shutdown of resin flow through the system. In all trials resin was infused into the preform via a line inlet port positioned below the film.

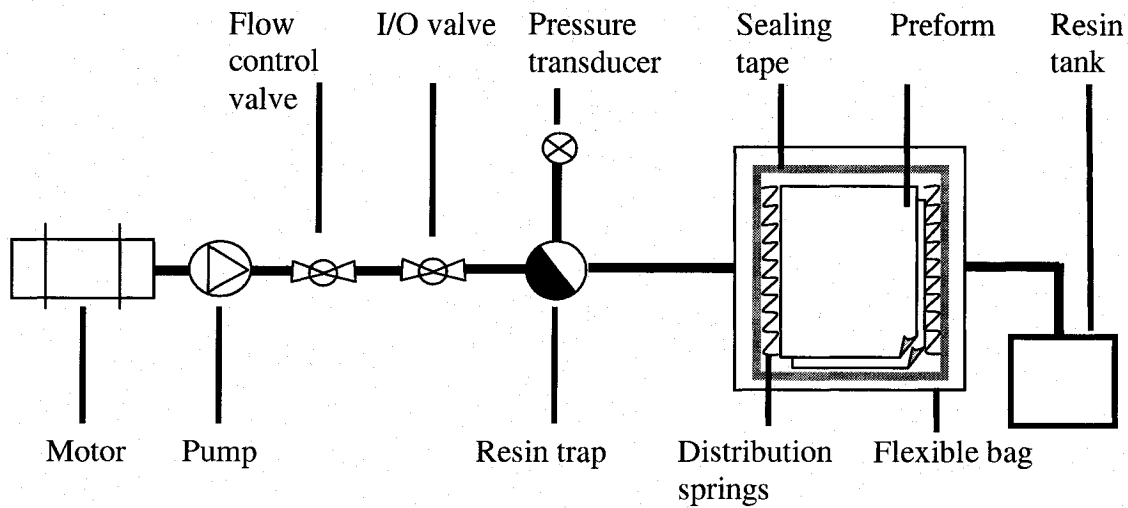


Figure 4.4 Schematic set-up for flow test.

Infusion epoxy resin MIA-POXY100 and hardener 95 from MIA were used in tests. Physical properties as provided by the manufacture are listed in Table 4.1.

Table 4.1 Characteristics of epoxy and hardener mix provided by MIA.

Property	Value
Ratio by weight	100R/24H
Ratio by volume	100R/25H
Gel time	38 minutes
Viscosity, resin	2500 cp
Viscosity, hardener	450 cp
Mixed viscosity	800 cp

The resin and hardener were weighted on a digital scale. Resin flow front in the panels was recorded at 1 second intervals via a Canon S2IS digital camera situated 500 mm above the preform. Image timing was controlled using the Canon Photo Record 2.2 software; images were stored on a PC linked to the camera. Reinforcements were infused from a line inlet that extended for the full length of one size of the preform. Infusion progressed in parallel with the lap joints and the front was generally perpendicular to the joints.

The variation of resin viscosity with temperature was measured by Brookfield Viscometer LV, Figure 4.5.

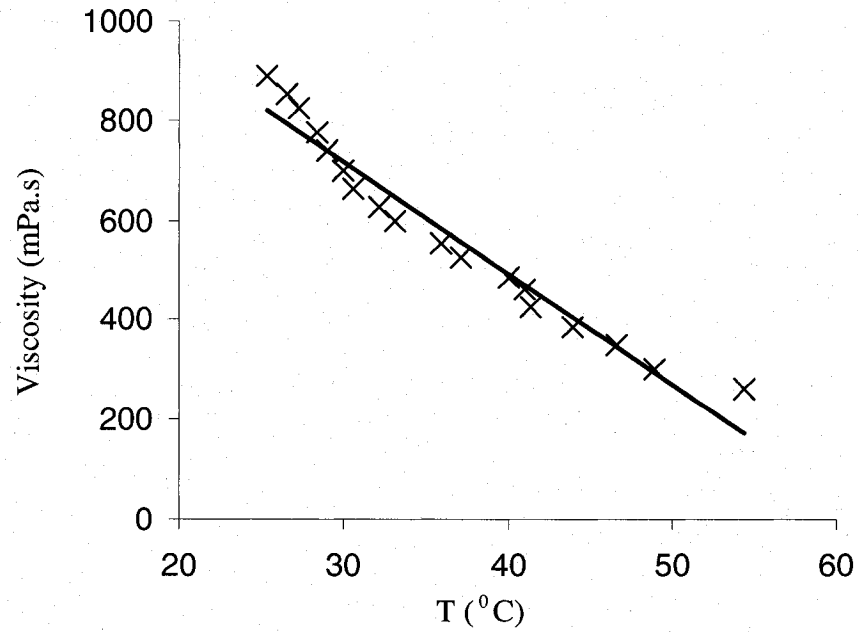


Figure 4.5 Viscosity of resin as a function of temperature.

The chemical reaction of the resin and hardener is exothermic. Therefore resin viscosity reduces with time as shown in Figure 4.6; resin temperature was not controlled for this experiment.

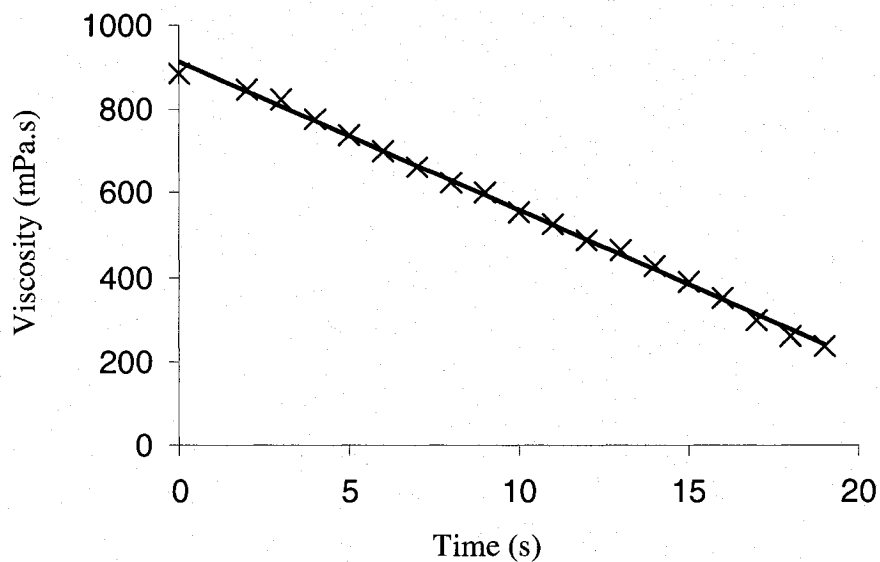


Figure 4.6 Viscosity of resin MIA-POXY 100 and hardener 95 as a function of time.

Another experiment was performed where resin viscosity was measured at a constant temperature of 26 °C every 4 min. Viscosity was measured at 850 mPa.s whilst the manufacturer supplied a value of 800 mPa.s. Gelation was observed to occur at 38 minutes, as mentioned in the manufacturer's data, Figure 4.7.

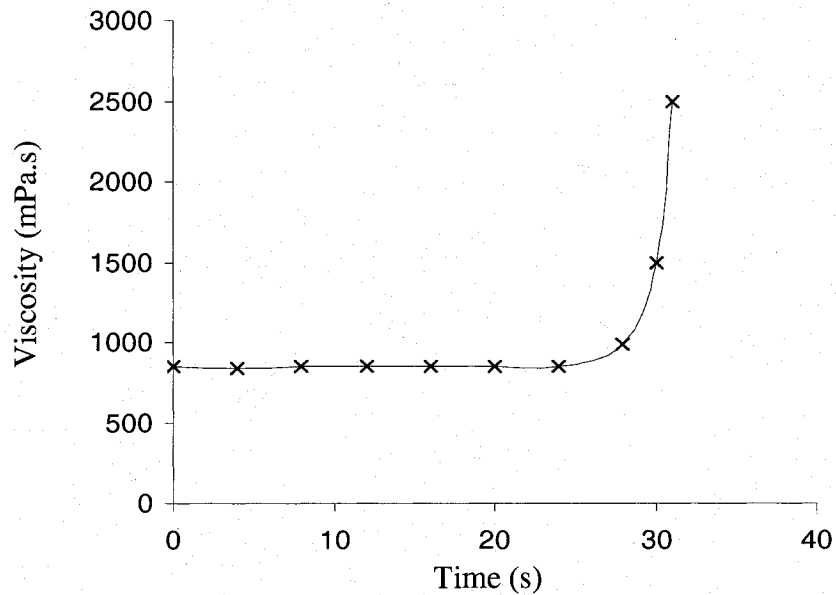


Figure 4.7 Viscosity of resin MIA_POXY 100 and hardener 95 as a function of time, at constant temperature.

4.4.2 Data analysis procedure

The analysis of resin flow images was performed using Microsoft Visio™. Standardized grids were aligned with a reference point and were superimposed over the images. The position of the front flow line was read at five points on lines L1 to L5 across the width of the preform as shown in Figure 4.8. The flow position along each line was evaluated for the fully saturated front.

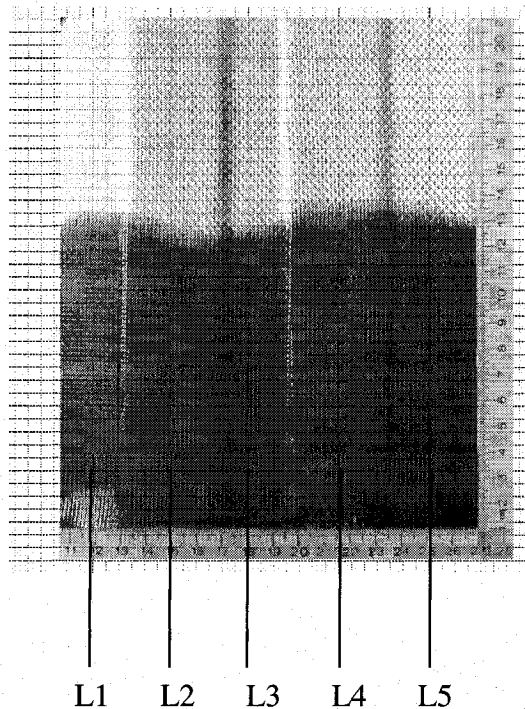


Figure 4.8 Reading of data using Microsoft Visio™.

For each time interval, the flow front position was recorded and entered into the mathematical software package Matlab™. The data was plotted as flow front position as a function of time, Figure 4.9. Similar plots were created for lines L1 through L5 for both reinforcements in all configurations.

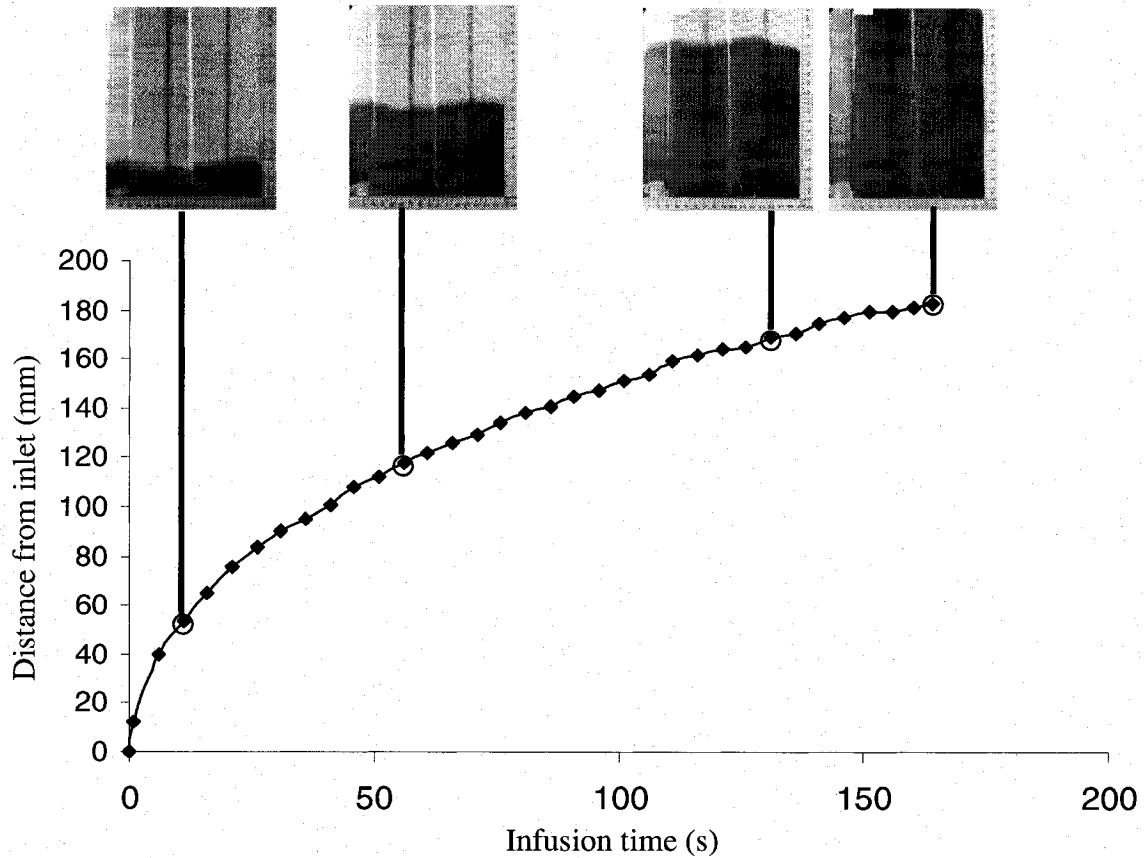


Figure 4.9 Flow front position as a function of time, random matt reinforcement R1, Configuration C1, Line L3.

4.4.3 Results, random matt reinforcement R1

Infusions through preforms in the 10 configuration described in previous chapters were performed to study the effect of the selected parameters on flow. In all, 20 preforms comprising two lap joints for random matt reinforcement R1 and woven reinforcement R2 were infused. Curves illustrating flow front progression as position versus time for preforms made from random matt reinforcement R1 laid in configurations C1, C5 and C10 are presented in Figures 4.10, 4.12 and 4.15; curves for random matt reinforcement R1 in all configurations are in Appendix B. The duration of infusion was between 200 s and 250 s for a flow length of approximately 200 mm.

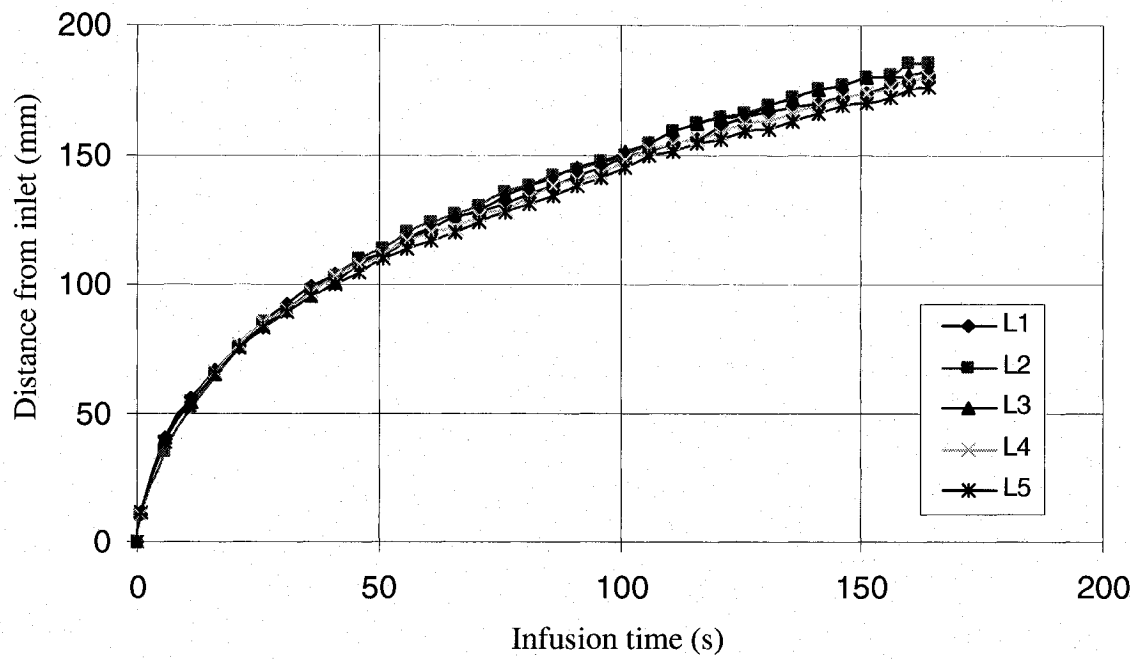


Figure 4.10 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C1.

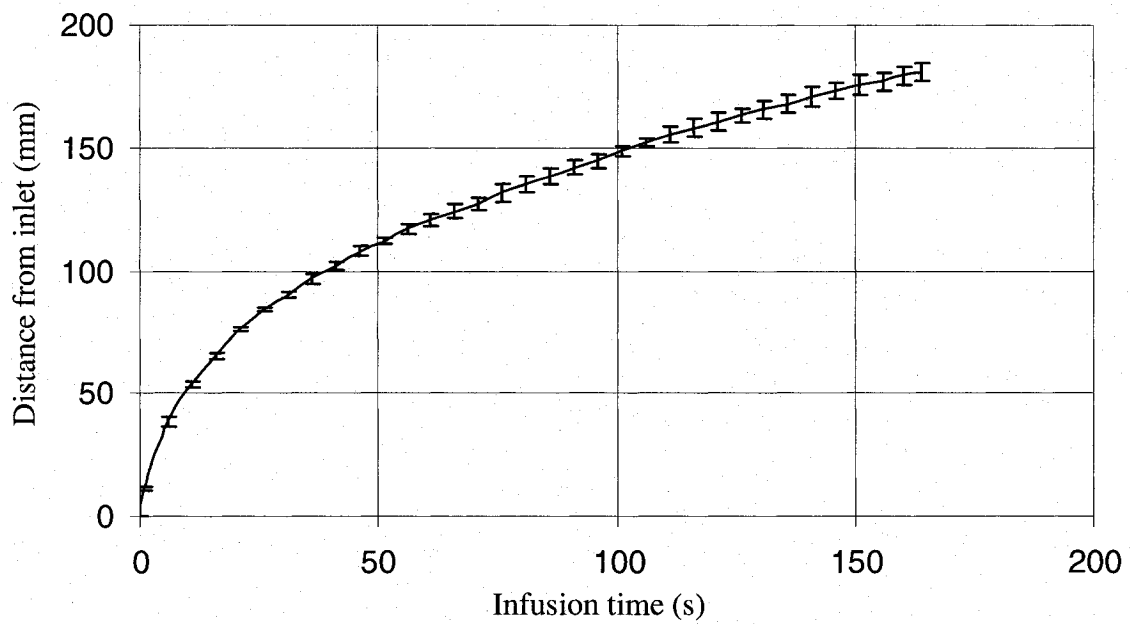


Figure 4.11 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C1.

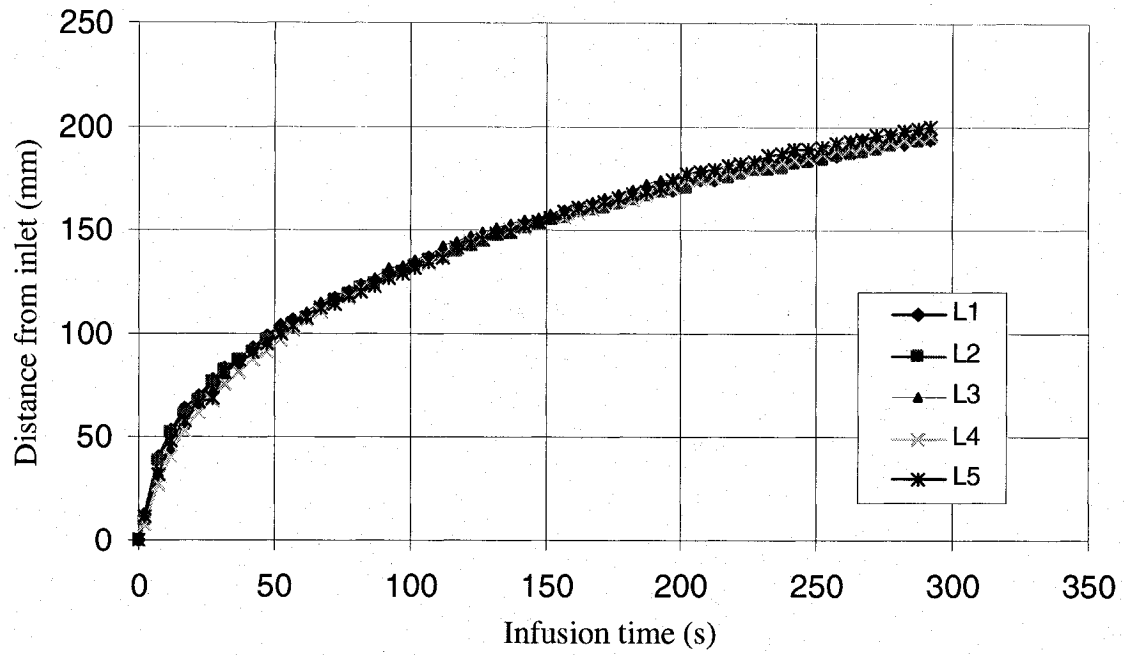


Figure 4.12 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C5.

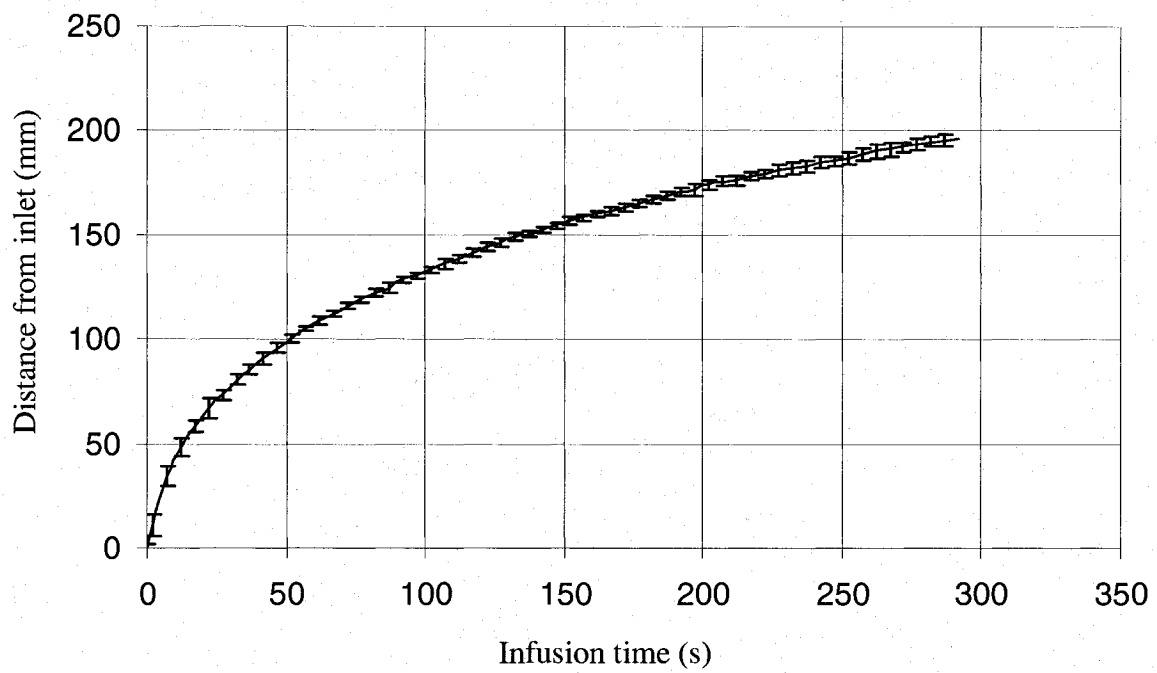


Figure 4.13 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C5.

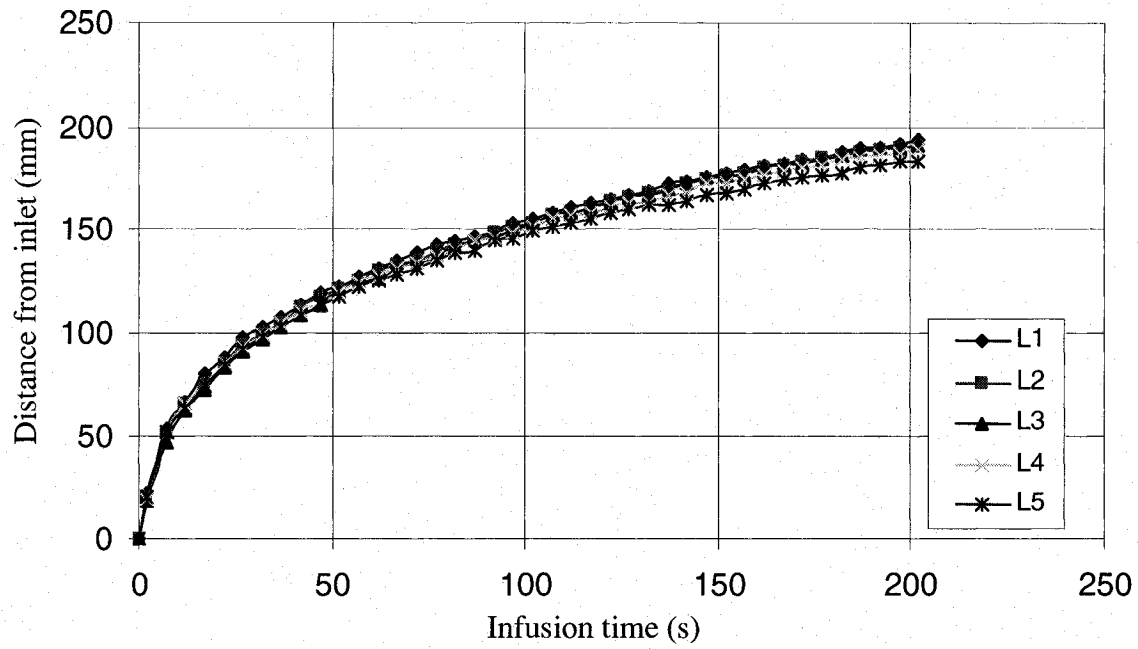


Figure 4.14 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C10.

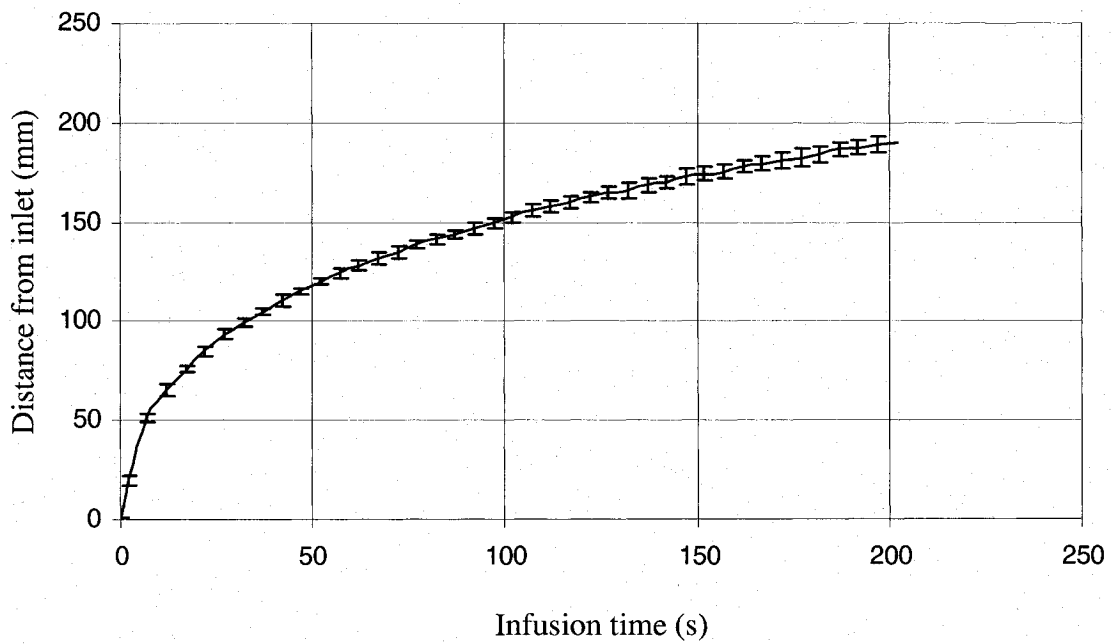


Figure 4.15 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C10.

As expected, each curve shows that infusion progresses smoothly with no sudden fluctuations in flow front speed. As resin progresses through a preform, flow front velocity decreases. One important observation to be made is that along lines L1 to L5, the macroscopic flow rate progressed at a generally equal rate, independently of variations in local v_f . That is, there appears to be no discernable lag of the flow front through regions with a higher v_f .

Figure 4.16 presents curves for configurations C1 to C10 for random matt reinforcement R1. Each curve represents the average flow front position as a function of infusion time for all path lines. Configurations C4 to C6 exhibited slower infusion while C7 to C9 showed faster flow front progression. For configurations C1 to C3, flow front progression was between groups C4 to C6 and C7 to C9. For configuration C10 which was free of joints, the preform filled slightly faster than for the other configurations. It should be noted that major differences can be seen in the times needed for flow front to reach a given distance from the inlet as a result of the different configurations.

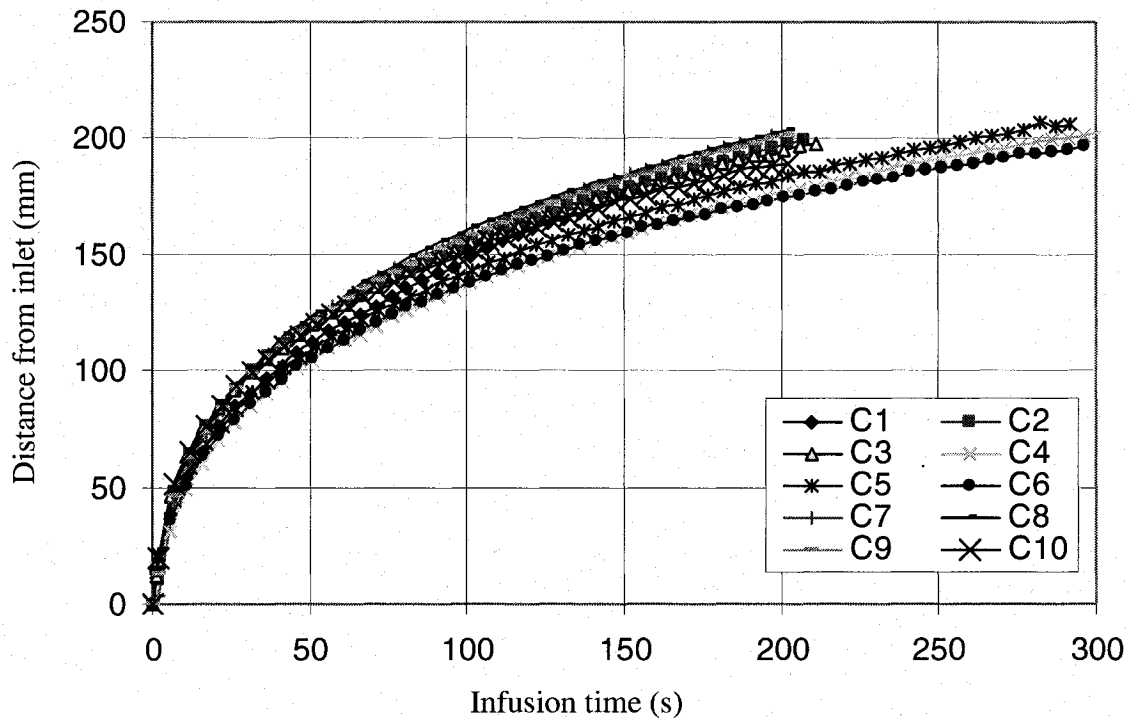


Figure 4.16 Average flow front position as function of time, random matt reinforcement R1, configurations C1-C10.

Figure 4.17 shows the standard deviation of position along the five path lines for configurations C1 to C10, reinforcement R1. The range of standard deviations extends between 1 mm and 6 mm with a generally slow increase during infusion. No clear patterns can be identified, meaning that there is no systematic distortion of the flow front. For joint-free configuration C10, the standard deviation lies at the middle of the range and cannot be clearly differentiated from other configurations.

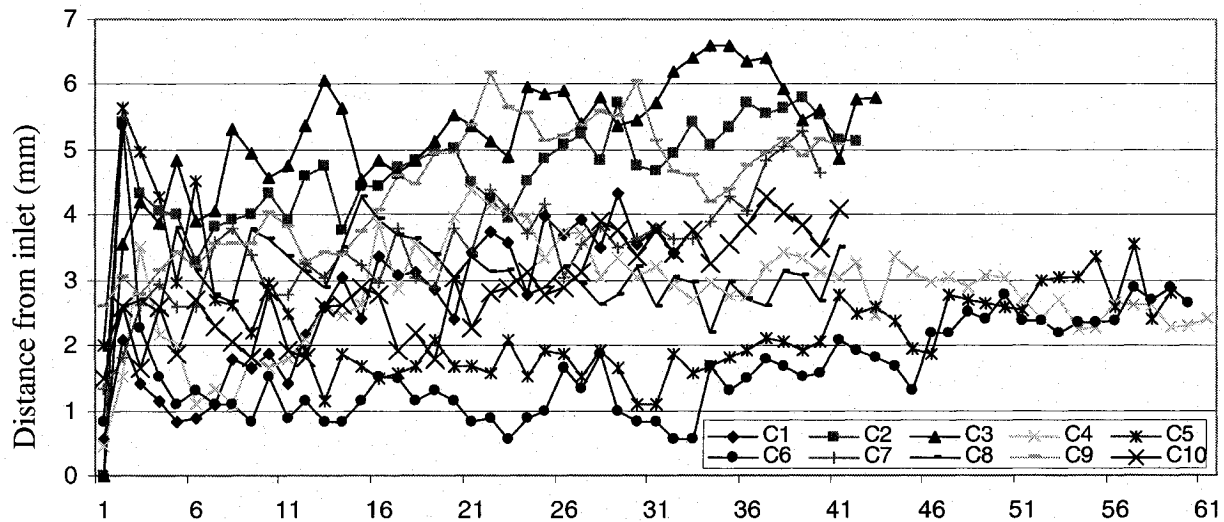


Figure 4.17 Standard deviation of position, random matt reinforcement R1, configurations C1-C10.

4.4.4 Results, woven reinforcement R2

Figures 4.18, 4.20 and 4.22 show flow front progression data for preforms made of woven reinforcement R2 laid in joint configurations C1, C5 and C10 respectively. These curves are generally similar to those obtained for other joint configurations. Curves for woven reinforcement R2 laid in other configurations appear in Appendix C. Infusion times range from 60 s to 150 s for a flow length of approximately 200 mm.

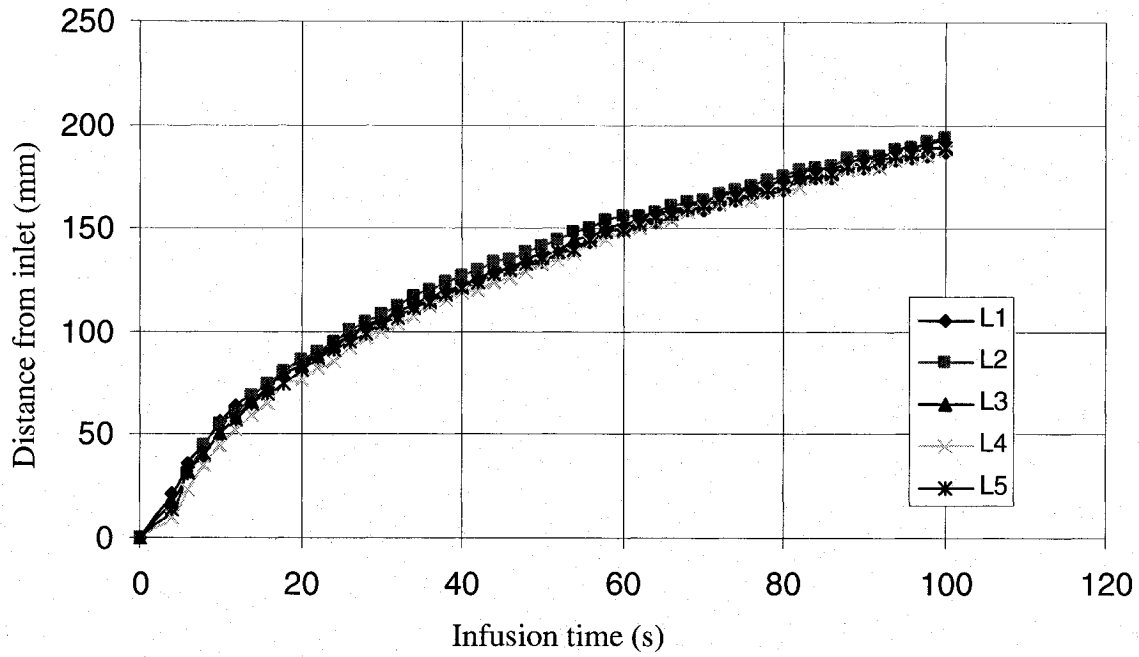


Figure 4.18 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C1.

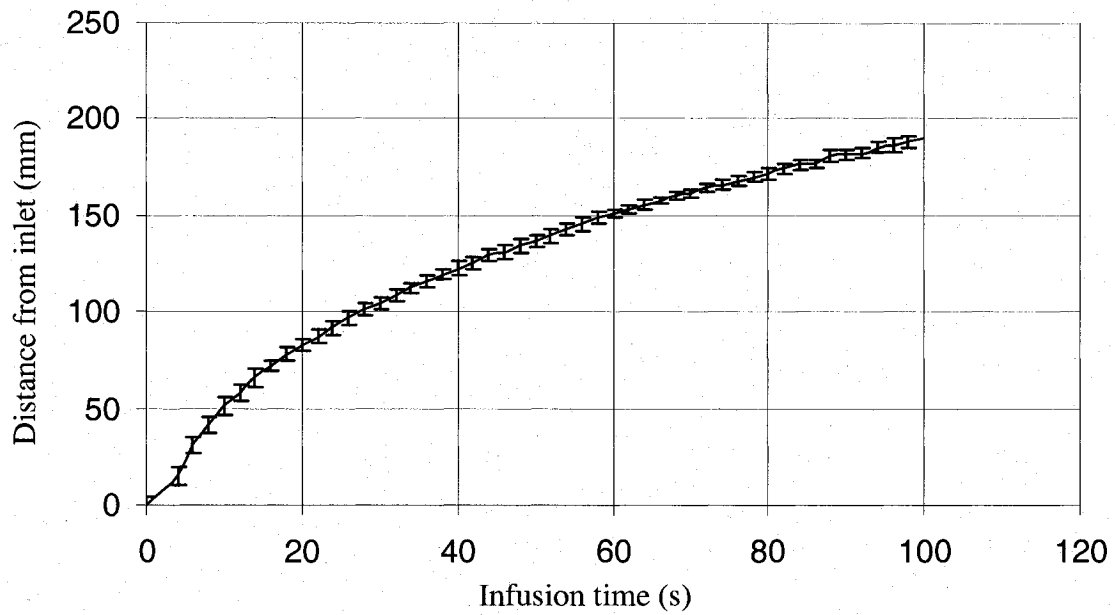


Figure 4.19 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C1.

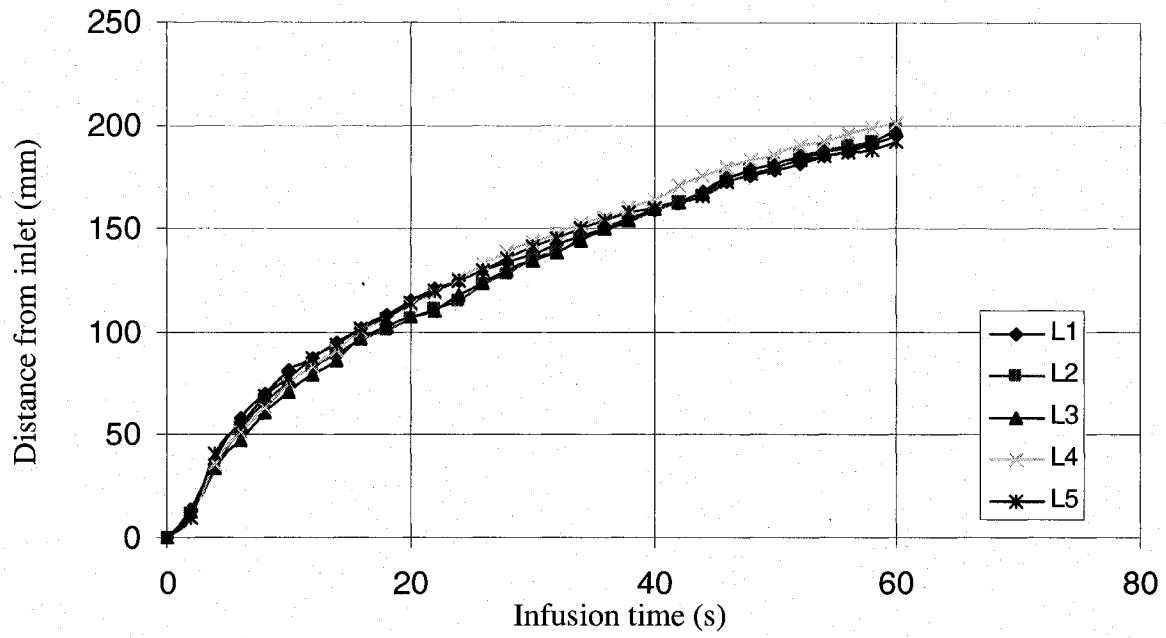


Figure 4.20 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C5.

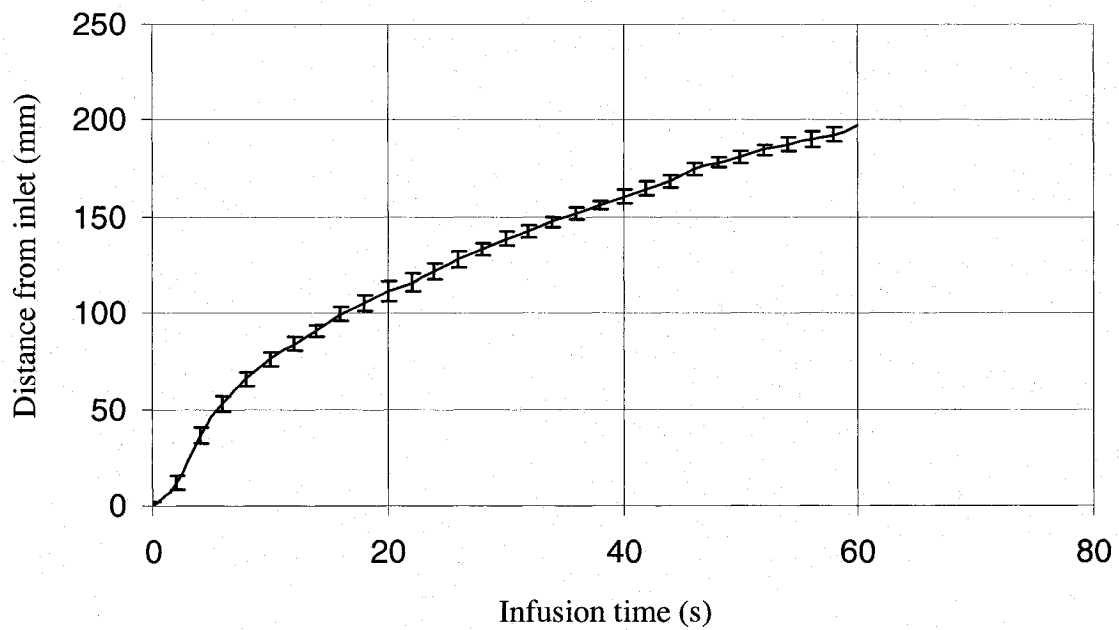


Figure 4.21 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C5.

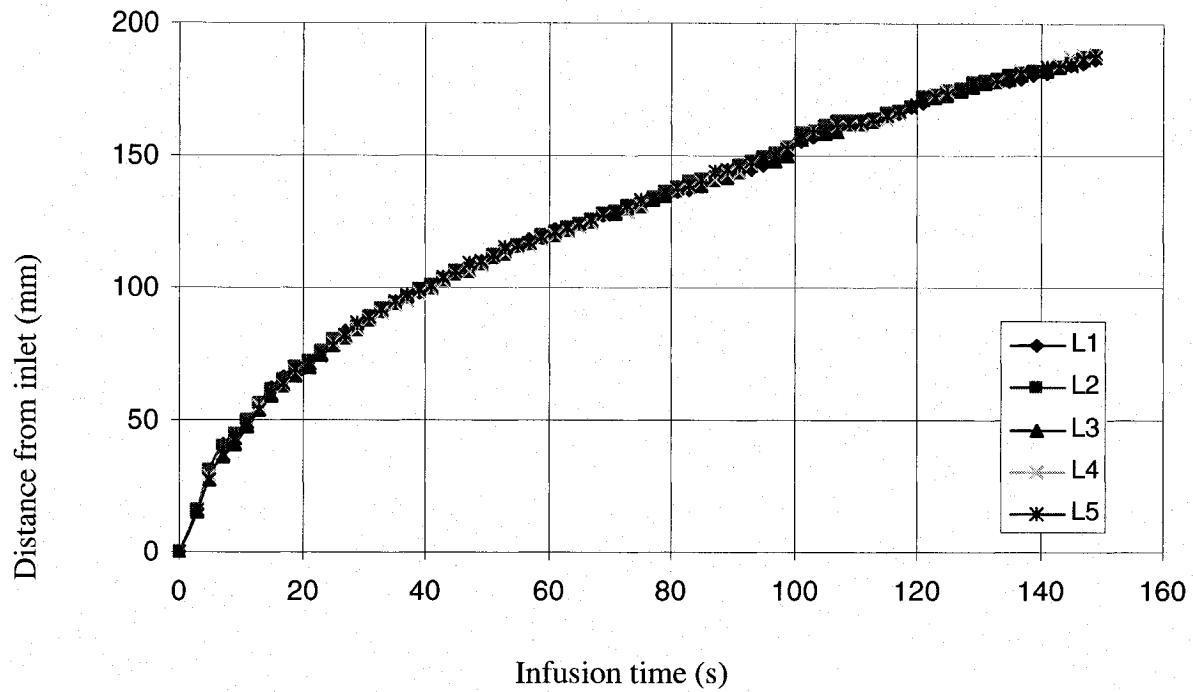


Figure 4.22 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C10.

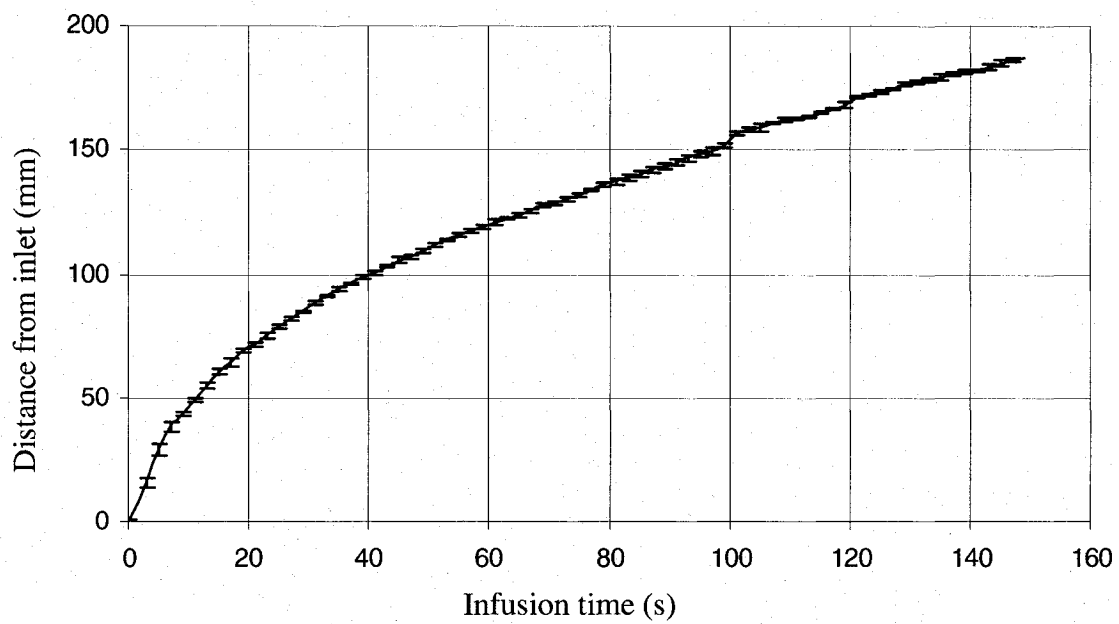


Figure 4.23 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C10.

Whilst the general trend is similar for all curves for woven reinforcement R2, the fill times and scatter show identifiable differences and trends. Figure 4.24 shows 10 curves of average positions associated with configurations C1 to C10; the data presented for reinforcement R2 is similar to that shown in Figure 4.16 for reinforcement R1. It is seen that the curves are more widely spread some configurations show faster fill and other configurations show slower fill, but the configurations that result in faster or slower fill with woven reinforcement R2 are not the same as they were for random matt reinforcement R1. In this case, fill is faster for configuration C2, followed by C3 and then C1. Similarly, fill is faster for configuration C5 followed by C6 and C4, and it is also faster for C8 followed by C9 and C7. Within each group of preforms with the same overall length OL and horizontal distance HD, preforms with 3 immediately superimposed joints NS fill faster than those featuring 6 immediately superimposed joints, followed by preforms with 1 superimposed joint. This pattern can not be readily explained, and it is not very strong. Generally it can be said that preforms with $NS = 1$ tend to fill more slowly than other preforms. The clearest difference seen in these curves as compared with curves in Figure 4.16 is that for woven reinforcement R2, fill in the preform devoid of joint, configuration C10, is significantly slower than it is for other preforms.

Another marked difference between configuration C10 and other configurations for woven reinforcement R2 can be seen in Figure 4.25, which shows 10 curves of standard deviations of position associated with configurations C1 to C10; the data is similar to that shown in Figure 4.17 for random matt reinforcement R1. Whilst most standard deviations are around 4 mm for configurations C1-C9, with no clearly identified pattern, they fluctuate around 1 mm for configuration C10. For woven reinforcement R2 the introduction of joints results in a marked increase in standard deviation between positions recorded at a given time along lines L1, L2, L3, L4 and L5; the shape of the flow front is less regular as a result.

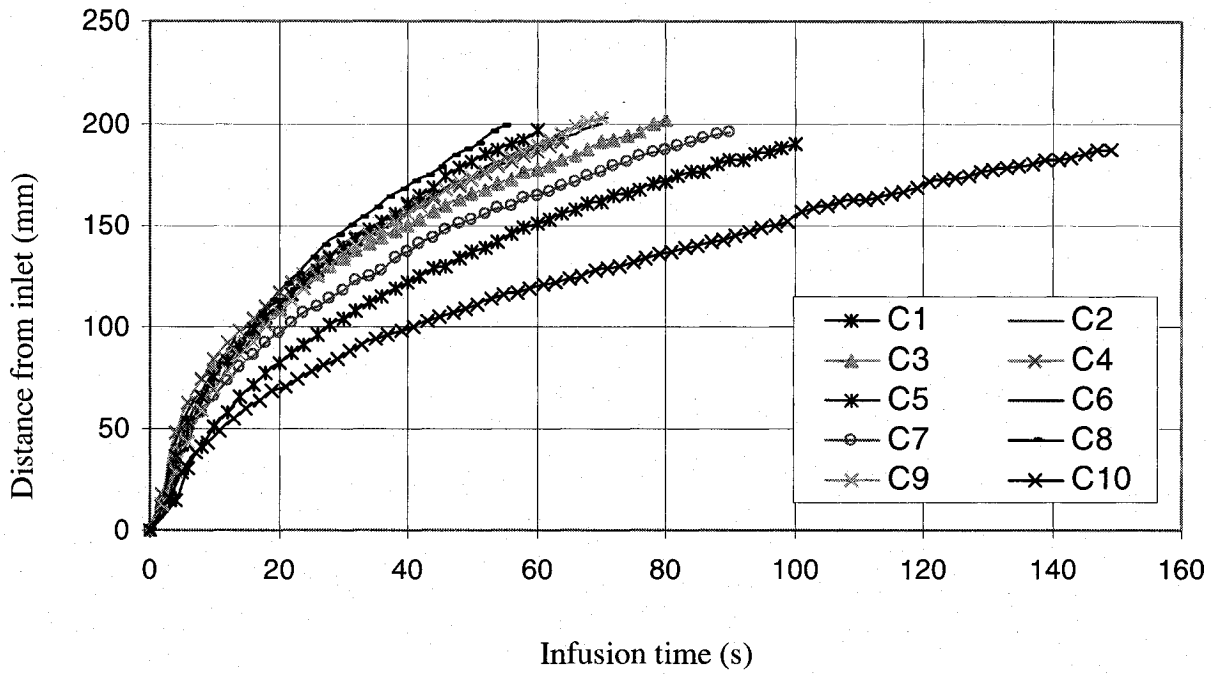


Figure 4.24 Average flow front position as function of time, woven reinforcement R2, configurations C1-C10

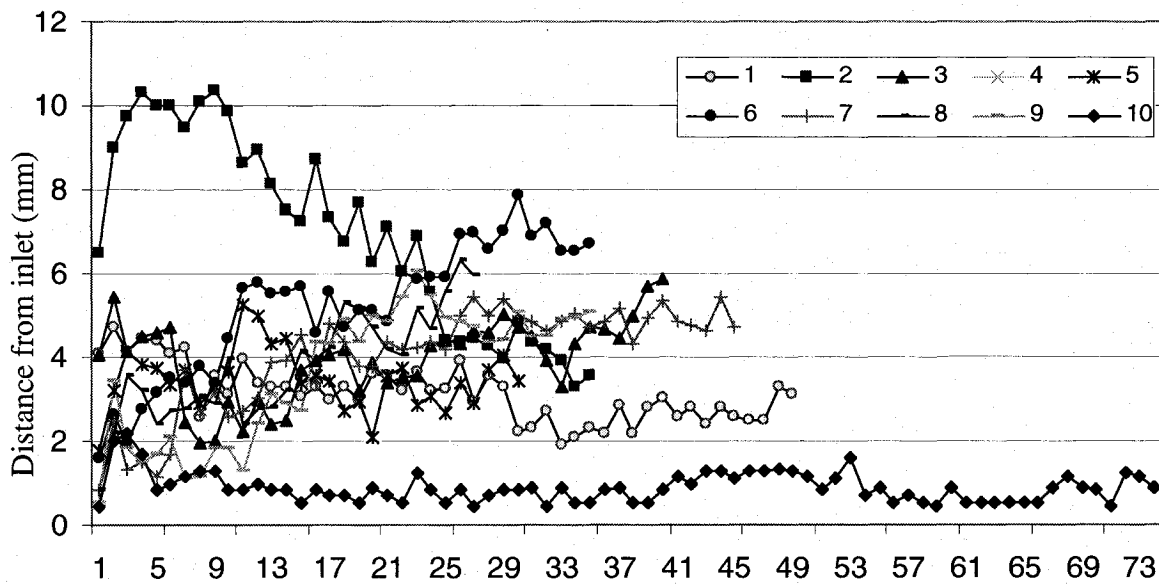


Figure 4.25 Standard deviation of position, woven reinforcement R2, configurations C1-C10.

4.5 Discussion

The effect on flow of zones characterized by different values of v_f in jointed preforms was investigated. It can be demonstrated that in the case of infusion under an imposed pressure difference, the permeability of a preform has a direct relation with the slope of the linear fit of the square of position x^2 to time. Limited variation in that slope was observed with random matt reinforcement R1. Figure 4.26 shows results for configuration C1, for which the most important different in slope was observed. Figure 4.27 shows similar results for C5; here, the two lines corresponding to low v_f and high v_f virtually superimpose. Results indicate that the variation in effective permeability as a function of v_f is smaller than it is for cases where uncut sheets are used as a preform. The reason for this limited variation is believed to lie with the presence of channels in the overlapped preform; such channels promote the infusion of resin.

Figure 4.28 and 4.29 show similar results for woven reinforcement R2, illustrated using configurations C4 and C1. Here again, the difference in effective permeability along lines L1 and L2 is much less than the difference in permeability that would be observed from preforms devoid of joints, featuring similar v_f values.

The effect on the average flow front position of the different configurations C1 to C10 was studied for both random matt reinforcement R1 and woven reinforcement R2, Figure 4.30 and 4.31. It was observed that the configuration of the lap joint has a stronger effect on effective permeability for woven reinforcement R2 than for random matt reinforcement R1, as reflected by the higher variation in the slope of the fitted lines. The reinforcement R2 is more sensitive to the configuration of the set-up, and any change can lead to considerable difference in the overall permeability.

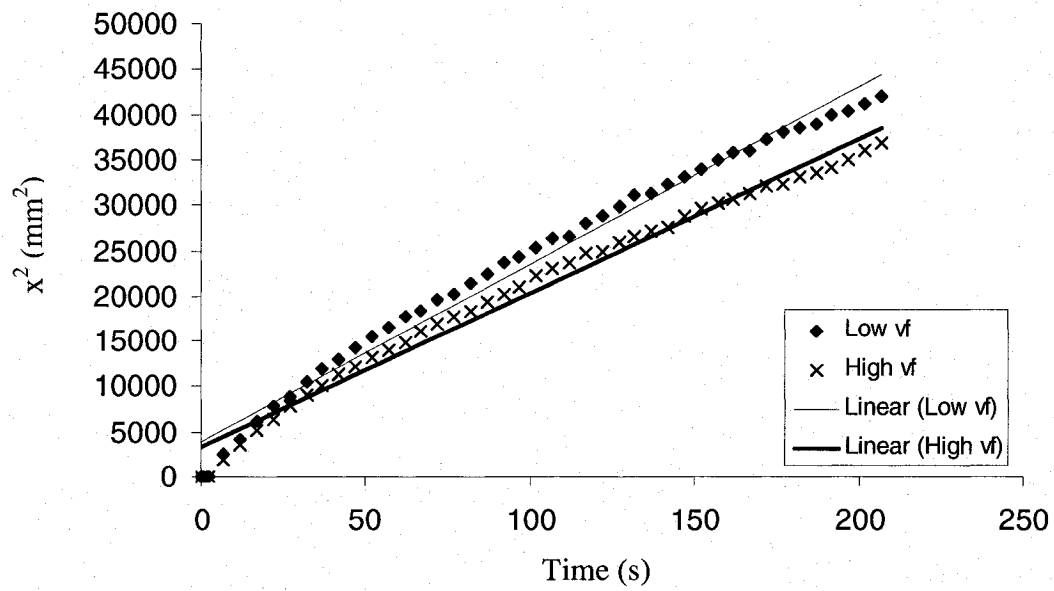


Figure 4.26 Effect of fibre volume fraction on one test panel with lap joints, random matt reinforcement R1, configuration C1.

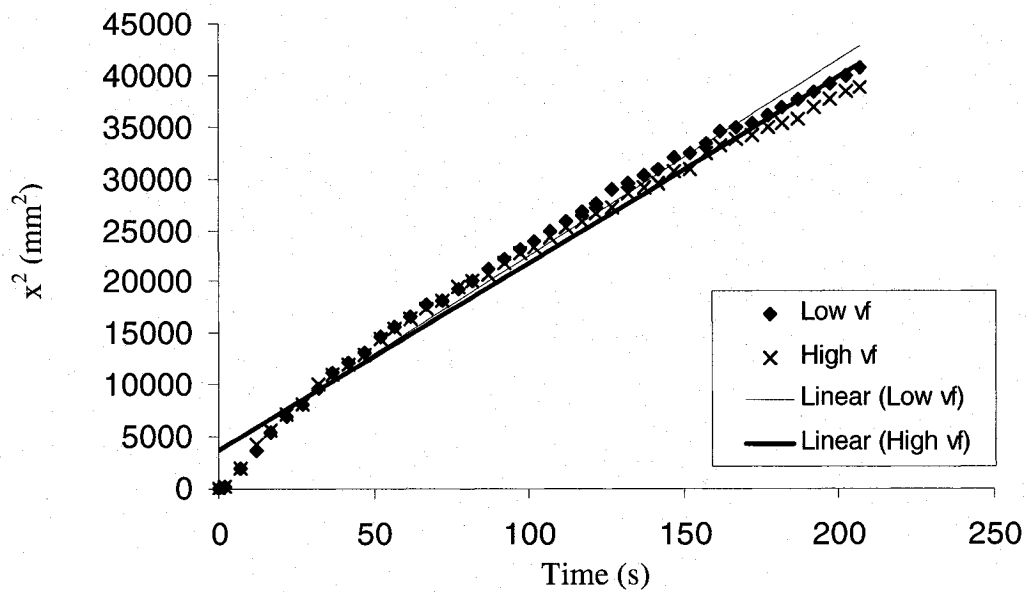


Figure 4.27 Effect of fibre volume fraction on one test panel with lap joints, random matt reinforcement R1, configuration C5.

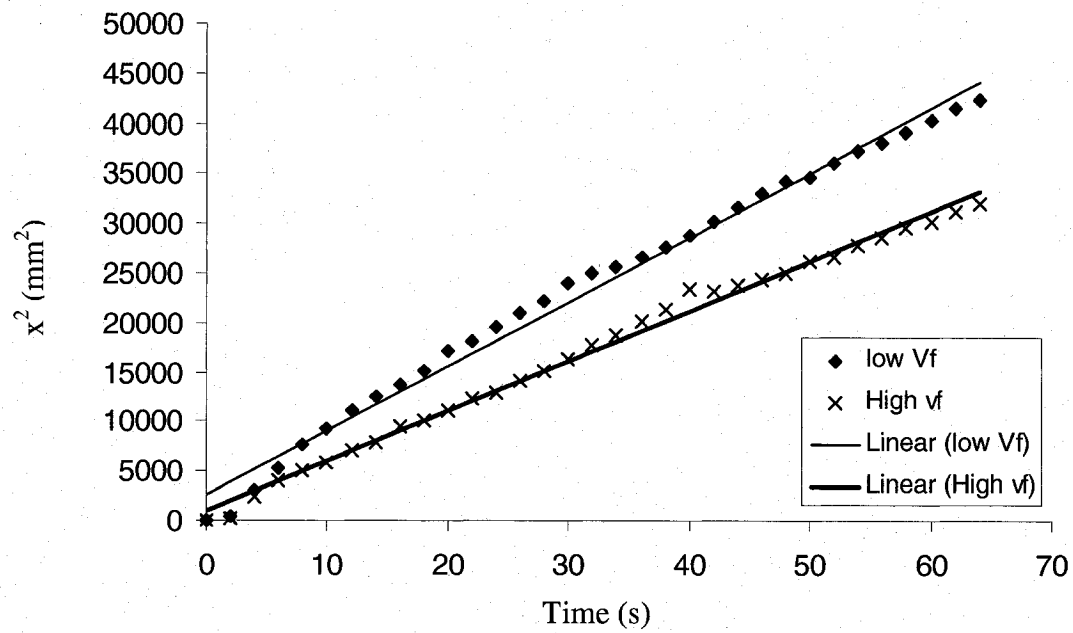


Figure 4.28 Effect of fibre volume fraction on one test panel with lap joints, woven reinforcement R2, configuration C4.

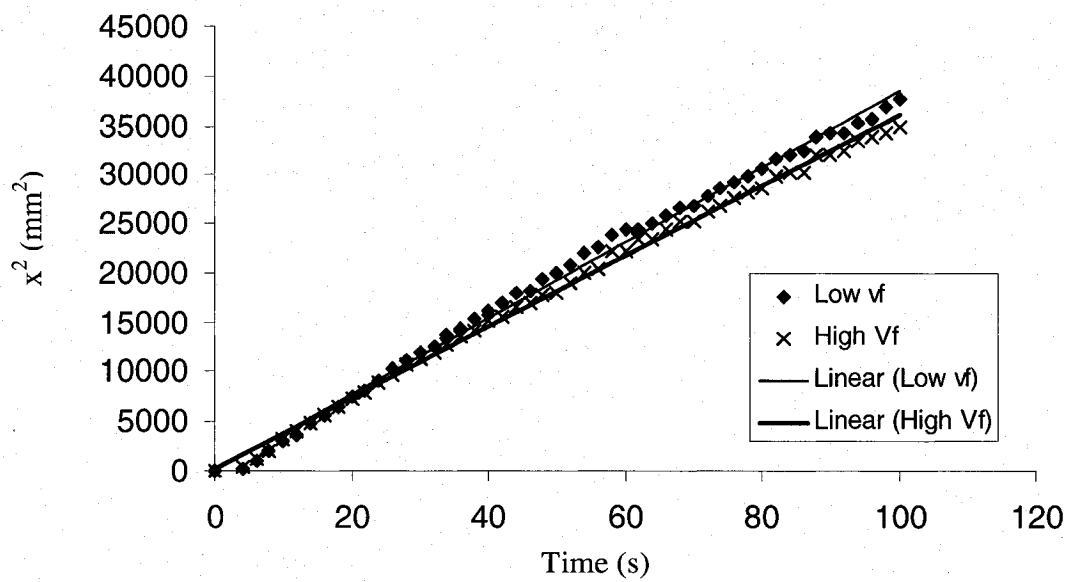


Figure 4.29 Effect of fibre volume fraction on one test panel with lap joints, woven reinforcement R2, configuration C1.

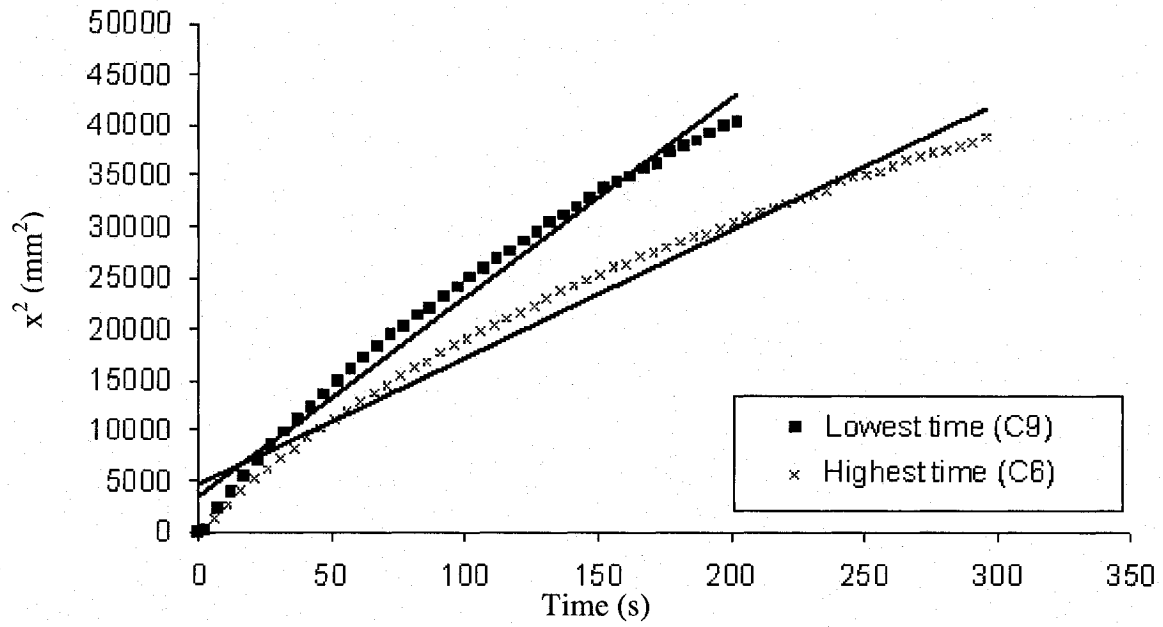


Figure 4.30 Effect of configuration on flow through random matt reinforcement R1, configurations C6 and C9.

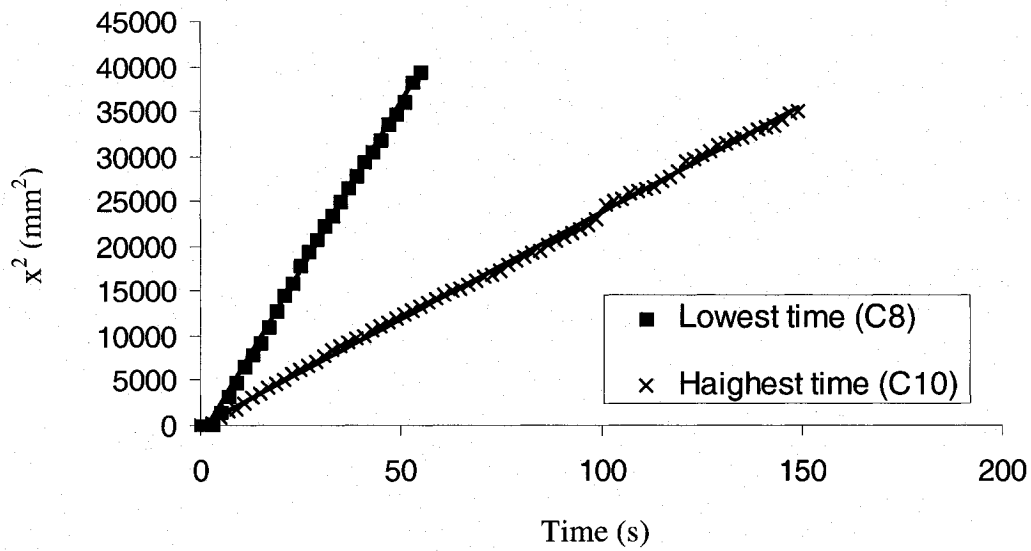


Figure 4.31 Effect of configuration on flow through woven reinforcement R2, configurations C10 and C8.

The averaged front flow positions and their linear fit for random matt reinforcement R1 in configurations C1 to C10 appear in Figure 4.32. It is observed that configurations C4, C5 and C6 which feature an overlap length OL=40 mm were more difficult to infuse when compared to other configurations. Configurations C1, C2 and C3 with OL=20 mm were similar to configuration C10 in terms of effective permeability. Also, a relatively easy resin infusion was observed with configurations C7, C8 and C9. It was concluded that the presence of joints does not necessarily result in faster or slower flow; different configurations have more or less effect on flow rates.

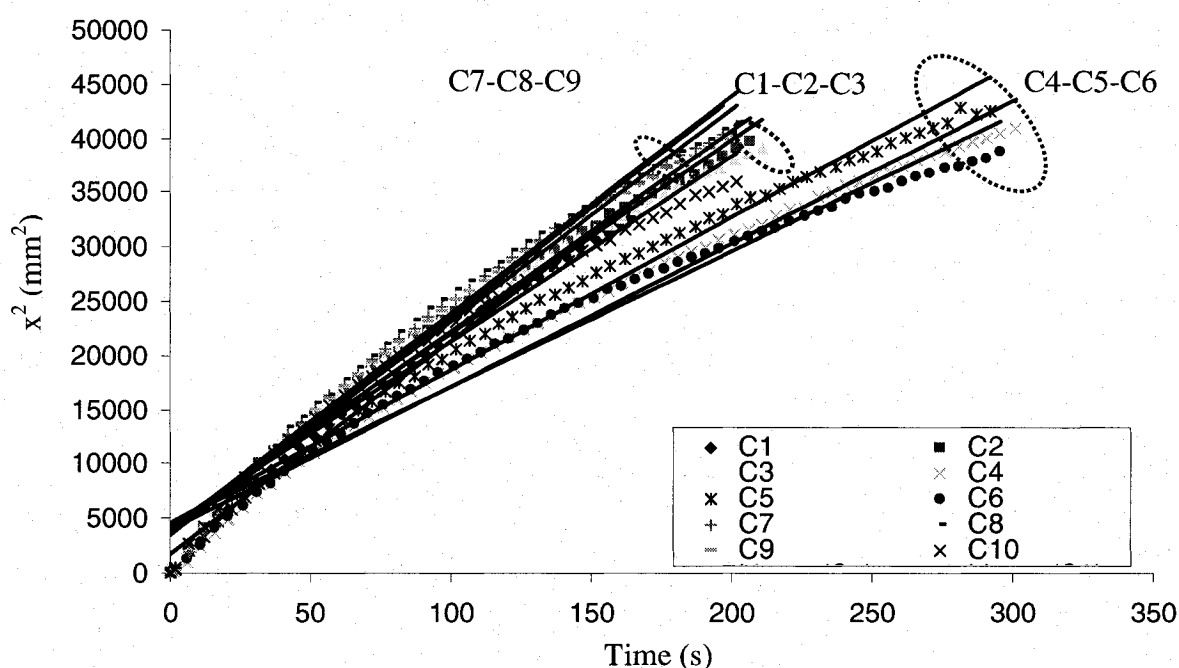


Figure 4.32 Effect of different configurations on flow through random matt reinforcement R1, configurations C1 to C10.

The averaged front flow positions and linear fit in all configurations C1 to C10 for woven reinforcement R2 appear in Figure 4.33. It is observed that configurations C2, C5 and C8 which feature joints with NS=3 were easy to infuse when compared to other configurations. Configurations C1 and C7 were similar to configuration C10 in terms of effective permeability. Configurations with NS=6, C3, C6 and C9 showed average effective

permeability compare to other configurations. Joints accelerated resin flow. It was interesting to note that different configurations do not affect flow in the same way for two reinforcements.

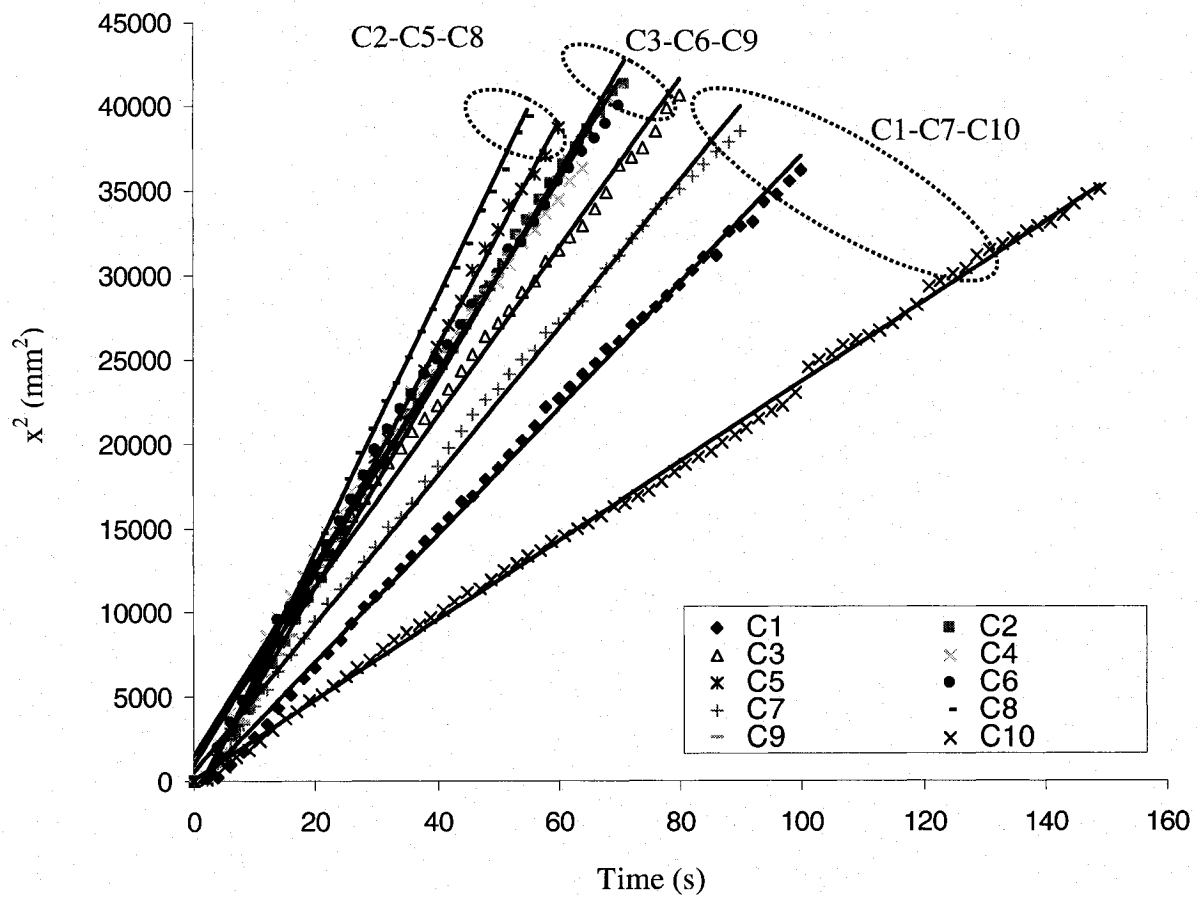


Figure 4.33 Effect of different configurations on flow through woven reinforcement R2, configurations C1 to C10.

CHAPTER 5

Mechanical performance of lap joints in preform for VARTM

5.1 Introduction

A series of tests were conducted to determine the mechanical performance of reinforced composite plates with lap joints. Reinforcements, the resin and configurations used are identical to those described in previous chapters. Specimens with variable thickness were cut out of cured composite panels. The panels were manufactured using VARTM. Each panel featured two joints as described in earlier chapters. Resin flow was parallel to the joints, and the resin flow front was perpendicular to the joints. Specimens were cut perpendicular to joints. Because of resin pressure distribution during filling, composite parts produced by VARTM tend to be thicker at the inlet and thinner at the outlet. Therefore, whilst the thickness of specimens away from the joints was generally constant for a given specimen, it decreased from one specimen to the next. Thorough thickness data was recorded as described below. Precise knowledge of the specimen geometry and material properties enabled the analysis of the structural performance of the jointed samples. A series of four-point bending tests were performed to assess the structural performance, determine the weakest flexural point in the loading span and identify the failure mode. The overlap length

OL, distance between overlaps HD and the sequence of overlaps NS were changed as described in previous chapters and the effect of these parameters were investigated thoroughly for random matt reinforcement R1 and woven reinforcement R2. Tests were based on standard ASTM D-790–92 that was modified as appropriate. Details of modifications are presented in this chapter.

The general objective is not to seek improvement of the mechanical behaviour of the jointed structure when compared with regular plates featuring no joins. Instead, the objective is to see if the joints induce any reduction in structural performance, either through the introduction of discontinuities in the reinforcement layer or through some stress concentration effect. Also, the work aims at quantifying the effect of joint configuration in the structural performance.

5.2 Background and literature review

In composite materials manufacturing, a joint is generally described as preregs or cured parts attached with adhesive, following different procedures, Figure 5.1.

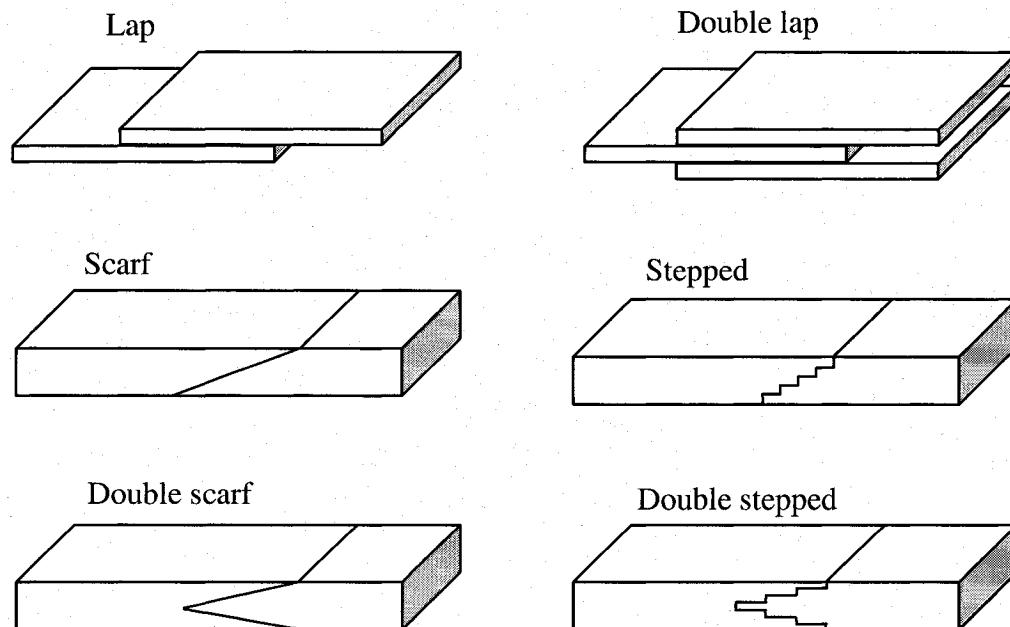


Figure 5.1 Common used joints in composite engineering.

Borsellino et al. [79] studied the strength of two adhesive systems for composite joints. Two adhesive resins in a single lap joint configuration were studied with static and impact tests. The effect of cure time on the mechanical properties of the joint was investigated. A relationship between the different failure mechanisms observed for the two resins and the curing reaction was observed. A numerical model of the single lap joint test was developed. Such model should be suitable for designing and/or verifying the mechanical performance of composites joints, and for evaluating trends in the shear, axial and peel stress.

Lucas et al. [80] investigated the design of joints suitable for low to high temperatures realised by the combination of two adhesives. Finite element models were used to predict the stress distribution in a mixed adhesive joint, so as to find the best possible design of double lap joints. It has been showed, for the temperatures studied, that the use of two adhesives provides better performance in terms of load capacity as opposed to using a single high temperature adhesive.

Gunnion and Herszberg [81] conducted a parametric study of scarf joints in composite structures. Scarf or stepped joints were used in composite structures where high strength is required. A finite element (FE) model was developed to study the performance of a scarf joint. Stress distribution along the bond line was investigated. The sensitivity of peak stresses to changes in scarf angle, adhesive thickness, ply thickness, laminate thickness, over-laminate thickness and lay-up sequence was quantified. Harman and Wong [82] presented an analytical method to optimise the performance of scarf joints between dissimilar parts. The optimised scarf joints were expected to improve joint strength and reduce the amount of material removal in the repair of aircraft structures.

Campilho et al. [83] studied the performance of single and double-lap joints on composite materials during repair. They evaluated the stress distribution and the residual strength under tensile loading of a repaired composite plate. The main parameters concerning the good performance of a repair were highlighted as the specimen geometry, the stacking sequence and the patch thickness. The main findings were related to the important influence of adhesive strength on the failure mode.

Delamination in composite is one of the disadvantages in joint performance and durability. Qin et al. [84] analyzed joints with unidirectional and cross-ply adherends. Variations in the strain rates with crack location and size were calculated.

Lap joints in the reinforcement layers prior to infusion were not investigated for mechanical performance, but study of failure and behaviour under tension and bending are common for cured composite materials.

Yang [85] studied the failure modes, failure strength, and failure criteria of laminated composite plates with stress concentration, subjected to bending. A series of bending tests were conducted for laminated, graphite/epoxy composite plates with and without a hole to investigate their failure mode and strength. Finite element analyses were performed to study stress distributions around holes of the composite plates subjected to bending.

Kumosa et al. [86] studied factors including fibre and resin types, surface fibre exposure, polymer fracture toughness, moisture absorption, interfacial properties and sandblasting, affecting the resistance of composites to brittle fracture. They eliminated brittle fracture in composites for insulators by selecting the proper resin chemistry by eliminating stress corrosion cracking.

Gupta and Woldeesenbet [87] carried out three- and four-point bending and short beam shear strength tests to characterize the flexural behaviour of foam core sandwich composites. Khashaba and Seif [88] studied the effect of different loading conditions on the mechanical behaviour of woven composites. The behaviour of woven FRP composites under tension, bending, and combined bending/tension loading conditions was investigated. Bending properties were determined using three-point and four-point bending tests. Results showed that the woven composites performed better under bending than under tension. Failure occurred at the centre of the specimens under pure bending as a result of high levels of delamination on the compression.

Daniel et al. [89] studied experimentally the flexural behaviour of composite sandwich beams, and compared the results with predictions of theoretical models. Sandwich beams were tested under four-point and three-point bending. Strains to failure in the face sheets were recorded with strain gages; beam deflection, and strains in the honeycomb core were also recorded. Softening and stiffening on compressive and tensile sides respectively occurred on the face sheets. Values obtained from simple models agreed with experimental

results. The simple models assumed that the face sheets can be represented as membranes; this allows neglecting the contribution of the honeycomb core and allows for non-linear behaviour of the face.

Research at the National Renewable Energy Laboratory [90] conducted Four-Point Bending strength testing of pultruded fibreglass for wind turbine blade sections. Blade segments were individually tested to determine their maximum moment carrying capability.

Qian et al. [91] studied the fracture behaviour of high-temperature polymer composites. These composites are vulnerable to brittle failure with relatively low resistance to crack propagation (fracture toughness). In order to increase their load-carrying capability and improve their fracture toughness, these materials are commonly reinforced with graphite fibres in the form of woven fabric.

Lagunegrand et al. [92] designed an improved four-point bending tests on a sandwich beam for free edge delamination, to allow interface loading under a uniform stress field. Loading an interface in tension or in compression gives rise to, respectively, compressive or tensile normal stresses superimposed to the inter-laminar shear stresses. In their work, a four-point bending test was designed in order to load the interface of the composite skin either with a tensile or a compressive uniform stress field.

The performance of composite I-beams under axial compression and bending loads was investigated by Khalid et al [93]. In their research a glass/epoxy composite was analyzed using finite element techniques. Then, specimens with different numbers of layers were tested in the laboratory.

Yu et al. [94] studied shear characteristics of textile composites using four-point bending tests. Measuring the shear properties of 3D textile composites is complex, due to the lack of planes of weak shear strength and the high structural heterogeneity of the materials. Experimental study of shear strength and shear modulus carried out for three types of 3D textile composites from different reinforcements were made using various technologies.

Cortes et al. [95] used four-point bending tests to investigate the mechanical properties of carbon-fibre reinforced silicate matrix composites. In their research, they compared the mechanical properties of their specimens, i.e. Young's modulus and fracture toughness, with cortical bone.

Yurgartis and Sternstein [96] studied micrographs of bending failure in five thermoplastic-carbon fibre composite laminates. The local deformation and failure sequences were studied by performing four-point bending tests of five thermoplastic matrix composites with typical span to thickness ratio of 39:1. It was found that all thermoplastic composites failed by abrupt longitudinal compression buckling of the outer ply. The delamination that did occur was found to be the result of compression buckling, rather than vice versa.

Huang [97] performed failure analysis of laminated structures by FEM. The influence of different load increments, mesh scales, and stiffness discount schemes on the results was studied. Strength envelopes and stress-strain or load-deflection curves of several laminates subjected to in-plane as well as bending loads were obtained. It was shown that FE results agree well with experimental data.

Borri et al. [98] proposed an experimental programme based on a four-point bending test to characterize the stiffness, ductility and strength response of FRP-wood beams. Mechanical tests on the composite material showed that external bonding of FRP materials may produce increases in flexural stiffness and loading capacity.

Predicting patterns of behaviour for these materials becomes feasible after performing mechanical tests. Serizawa et al. [99] performed four-point bending tests on SiC/SiC composites (Silicon carbide-based fibre reinforced silicon carbide composite) specimens. The test results were used to evaluate the strength of SiC/SiC joints.

Shih and Ebert [100] investigated the flexural/shear failure mode transition of composites subjected to four-point bending. They showed that changes in external parameters such as the span to thickness ratio and the fibre volume fraction cause variation in bending test results. Choi and Sankar [101] studied the fracture toughness of transverse cracks in graphite/epoxy laminates. Four-point bending tests were performed to determine the fracture load at different temperatures. Fractural test for sandwich panels was performed by Smith [102]. In his research, he performed both three-point loading and four-point loading for sandwich panels with different cores.

Cattell and Kibble [103] determined a relationship between strength and test method for glass fibre epoxy composites, using Weibull analysis. The three common test standards were tensile, three-point flexure and four-point flexure. It is generally accepted that tensile tests result in lower strength than flexural tests. After carrying tests on woven E-glass epoxy

composites data from each test were fitted to a two-parameter Weibull distribution and strength variability dependence was examined.

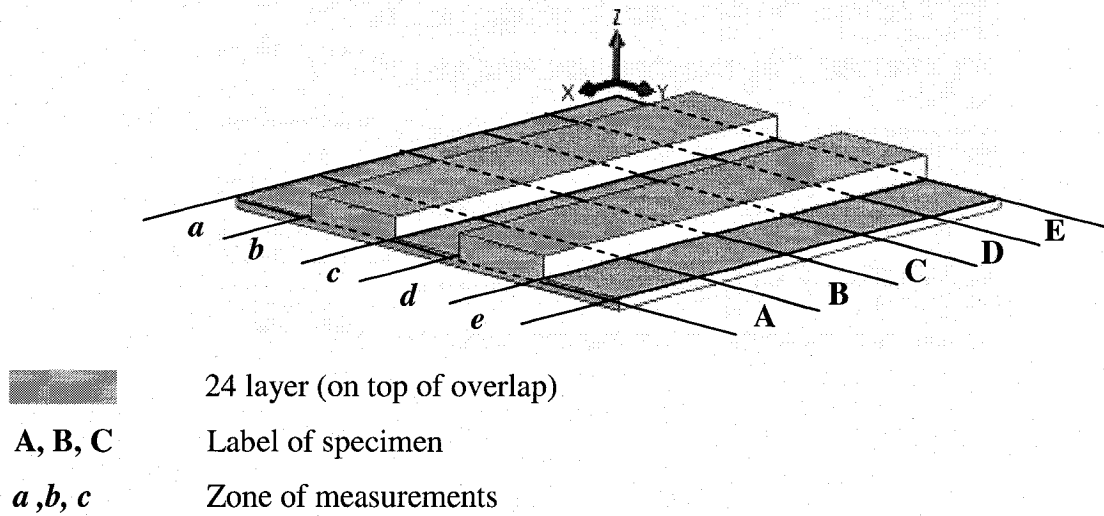
Juntikka and Hallstro [104] studied shear characterization of sandwich core materials using four-point bending tests. Sandwich beams were loaded in four-point bending, and the shear deformation was measured with two sensors. The stress–strain responses for two polymer foam core materials, one relatively brittle and one relatively ductile, were extracted and compared with results from single-block shear tests of the same material batch. For the ductile material, large deformations during the test resulting in bending failure of the face sheet instead of shear failure of the core observed.

Experimental and numerical analyses of the short term loading performance up to failure of cellular box beams under four-point loading configuration were proposed by Lee et al. [105].

5.3 Experimental procedure

Specimens cut from composite panels made by VARTM were measured and tested in four-point bending. The panels were made using epoxy resin MIA-POXY100 and MIA hardener 95, as described in section 4.4.1. The preform was made from reinforcements random matt R1 and woven R2 as described in section 3.5.1. Most preforms featured joints; the joints were realised in 10 different configurations C1-C10 described in section 3.5.2. The plates were moulded using a process similar to that described in section 4.4.1. Samples were cut perpendicular to the joints as described in the beginning of this chapter.

The cured reinforced composite panels were tested to establish the mechanical performance of the composite material. The thickness of each specimen and joints were accurately measured at 25 different locations using a micrometer. Measurements on the cured panels indicated a variation in the thickness. It was observed that the thickness decreases from the inlet to the outlet. This is due to the fact that the preform material is compacted to higher pressures near the outlet as explained in chapter three, and could be observed visually during the infusion. A sample of thickness measurements is presented in Figure 5.2. Numbers in the table represent the average of five measurements for each zone. Measurements for all specimens and panels are reported in Appendix D.



	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.11	7.42	5.13	7.49	5.19
B	5.17	7.69	5.13	7.92	5.35
C	5.34	8.01	5.17	8.27	5.53
D	5.47	8.46	5.27	8.51	5.79
E	5.76	8.82	6.01	8.72	5.95

Figure 5.2 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C1.

The thickness data was used for the following purposes:

- Document the variation in thickness of the specimens.
- Calculate the average thickness for evaluating the structural performance.
- Model representative panels using structural finite element software ADINA as discussed in a following section.

As a general rule, it was observed that the thickness of the cured composite panels varied significantly over zones where it should theoretically be constant, that is, excluding the effect of the number layers (overlap vs. away from overlaps) and any change of thickness between the inlet and the outlet. Such variation is to be expected in panels produced using VARTM. However, it is useful to put the fluctuations in v_f that were recorded using the Hall effect sensors as reported in chapter three in perspective of the variations in thickness

described here. While one can not verify that fluctuation in the preform under vacuum before resin infusion corresponds exactly to changes in thickness, the latter make the variability of the former perfectly acceptable, at least in terms of amplitude.

5.4 Four-point bending

A four-point bending test consists in applying two symmetrical point loads on a simply supported beam as shown in Figure 5.3-(a). This configuration produces a constant bending moment in the beam section located between the two concentrated loads. This middle span is known as loading span. Loads, shear forces and bending moments are shown in Figure 5.3-(a), 5.3-(b) and 5.3-(c) respectively. As shown in Figure 5.3-(b), unlike in the three point bending where the maximum axial fibre stress and internal shear are located exactly at the middle of the beam, the shear force magnitude in the middle span of a four-point bending beam is equal to zero. This characteristic of the test set-up can be used to determine the weakest point in the middle span under flexural load; also it can be used to determine the modulus of elasticity of the specimens.

In the experiments presented in this chapter, the setup was customized in such way that point loads were always placed on the centre of the over-lap joints. By doing this, two parts of the specimens are subjected to the same moment simultaneously. These two parts are the transition zone at the joints (chapter 1, section 1.3) and the thin section in the middle of the specimen.

The American Society for Testing of Materials (ASTM) offers two standards regarding four-point bending tests on unreinforced and reinforced plastics, including high modulus composites. These two standards are ASTM D 790-92 [106] and ASTM D 6272-02 [107]. It should be noted that these tests are only applicable for rigid and semi-rigid materials that break or fail under flexure. The reinforced fibreglass composite material used in this research complies with all the necessary pre-requisites of these test procedures. ASTM D 6272-02 is a complementary test procedure that is more suitable for materials that do not fail within the strain limits specified in ASTM D 790-92. In this thesis, standard ASTM D 790-92 was used. Details of this standard are presented in the next section.

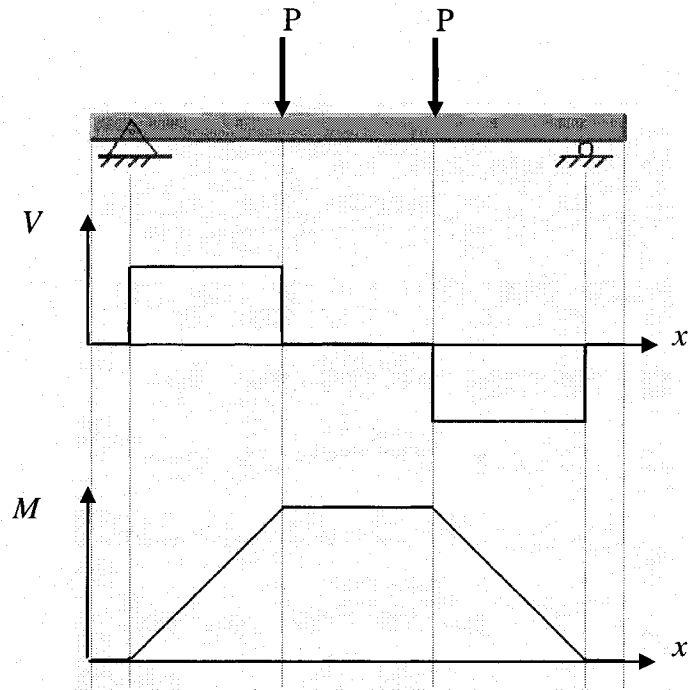


Figure 5.3 (a) Simply supported beam with two symmetric concentrated loads.
 (b) Shear force diagram in the specimen.
 (c) Bending moment diagram in the specimen.

5.4.1 The ASTM D-790 standard test for flexural properties of materials

Standard ASTM D 790-92 covers three-point and four-point bending tests. The proposed set-up can be used to determine the flexural behaviour of unreinforced and reinforced plastics and composite materials of moderate to high stiffness. The machinery for this test set-up has to meet the following conditions. The load-cell must be able to measure load with $\pm 1\%$ from the maximum expected load. In addition, the loading machine should have the capability to be programmed to move at a constant crosshead motion rate chosen from ASTM tables. The deflection has to be accurately measured. A camera or LVDT may be used for deformation measurement if it provides sufficient accuracy. In these tests the displacements were directly obtained from the crosshead position.

Based on specimen dimensions and thickness ratio, tables in standard ASTM D-790 were used to determine the suggested support span length and crosshead motion rate. Total

specimen length was either 170 or 190 mm with an average thickness of approximately 5 mm. From the tables, a support span length of 140 mm was selected. The cross-head motion rate R was calculated based on the following equation, taken directly from ASTM D-790 [106]:

$$R = Zl^2/6d \quad (5.1)$$

where R is the crosshead motion rate (mm/min), l is the support span length (mm), d is the thickness of the specimen (mm) and Z is the rate of straining of outer fibres (mm/mm), equal to 0.01. Acceptable tolerance on cross-head motion rate is 50%. In the configurations reported here, R is calculated as:

$$R = (0.01) \times (140)^2 / 6 \times 5 = 6.5 \text{ (mm/min)}$$

In the experiments reported in this chapter, R was set at 5 mm/min.

5.4.2 Apparatus

To perform the bending tests, an Instron 4482 universal testing machine equipped with a ± 100 kN static load cell was used. This testing machine was calibrated prior to testing. Load-cell calibration performed by the Instron technician in December 2005 guarantees that the error in measured load shall not exceed $\pm 1\%$ of the maximum expected load during experiments. The Instron Blue-Hill software was used to control and program the machine. The same program was used to record all measurements in computer files. Recorded information in these files includes displacement of the crosshead and measured forces. The data was further processed after completion of experiments as explained below. A Canon S2IS digital camera was used to photograph all experiments every second. The pictures can be used to determine the exact location of rupture initiation.

In the experiments, the loading noses were positioned exactly at the centre of the overlap joints. Since the distance between the overlap joints was one of the experimental

parameters, two different loading noses were manufactured in the workshop to match exactly the loading points with the centre of the lap joints. The loading set-up for four-point bending tests is shown in Figure 5.4.

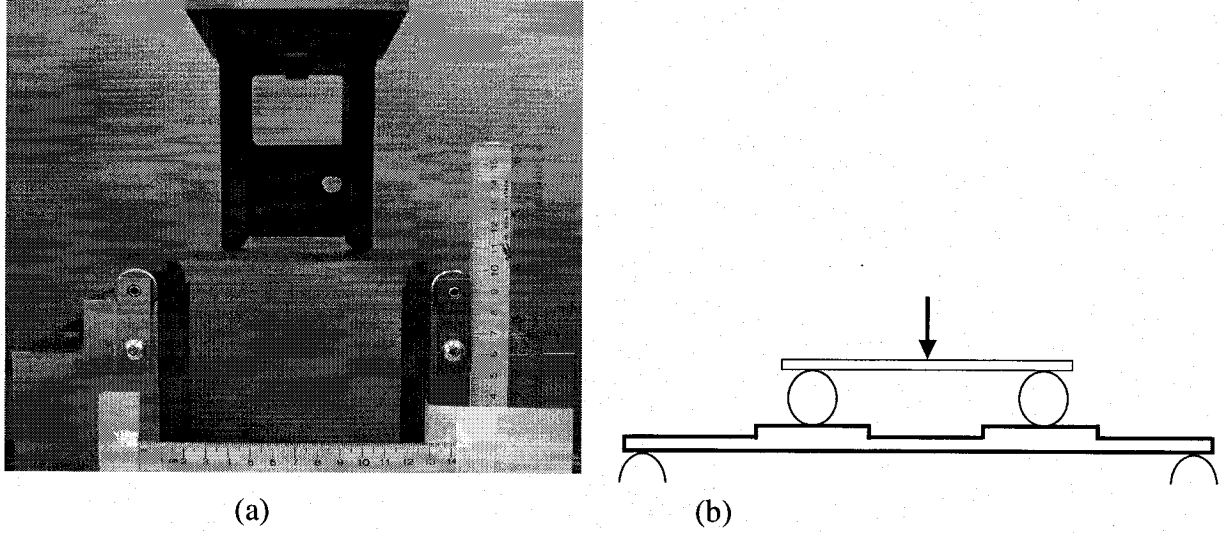


Figure 5.4 Loading set-up of a four-point bending test.

After the completion of tests, the deflection under the loading noses, which is equal to the displacement of the crosshead, was used to find the stiffness of each specimen and the flexural stress at failure. From the method of elastic weights [108], one can modify the beam bending moment diagram in Figure 5.3 to the following diagram, Figure 5.5:

The following equations are obtained for R_A and R_B as a function of the applied force F :

$$\frac{1}{EI} \left[\frac{Fa^2}{2} + Fa \left(\frac{L}{2} - a \right) \right] = R_A \quad (5.2)$$

$$\frac{1}{EI} \left[Fa \frac{L}{2} - \frac{Fa^2}{2} \right] = R_A = R_B \quad (5.3)$$

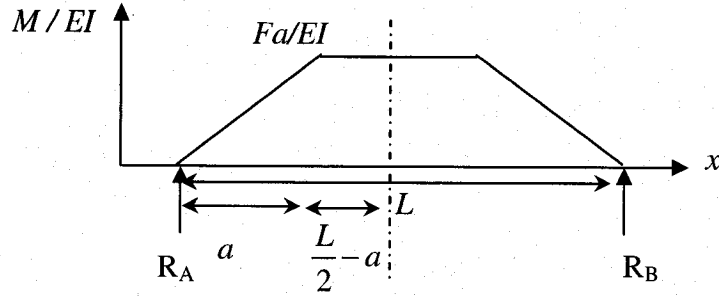


Figure 5.5 Curvature of loads from elastic weights method

where E is the modulus of elasticity in bending and I is the moment inertia obtained from the following equation:

$$I = \frac{bh^3}{12}$$

where b is the length of specimen and h is the thickness of specimen. The deflection of the beam at the loading points is:

$$D_L = \frac{1}{EI} \left[\left[Fa \frac{L}{2} - \frac{Fa^2}{2} \right] \times a - \left[\frac{Fa^2}{2} \times \frac{a}{3} \right] \right] \quad (5.4)$$

$$D_L = \frac{3Fa^2L - 3Fa^3 - Fa^3}{6EI} = \frac{Fa^2}{6EI} [3L - 4a] \quad (5.5)$$

The following formula for E is obtained, where E can be calculated from the force-deflection graph if I is known:

$$E = \frac{Fa^2}{6D_L I} (3L - 4a) \quad (5.6)$$

This can be further simplified into:

$$E = \frac{F}{ID_L} \cdot C \quad (5.7)$$

Or

$$E \cdot I = \frac{F}{D_L} \cdot C \quad (5.8)$$

where C is constant for given loading conditions, and changes with the position of applied loads. For the tests reported in this chapter, constants a and C are given in table 5.1:

Table 5. 1 Constants a and C for four-point bending tests.

	L (mm)	a(mm)	C(mm³)
C1-C6 and C10	140	38.250	6.511
C7-C9	140	54.125	9.935

One can find the slope of the load-deflection curve as F/D_L ; for example, Figure 5.6 for woven reinforcement R2 in configuration C1. The slope was mostly constant up to the initiation of damage for all tests reported in this chapter.

5.4.3 Modulus of elasticity of composite materials in bending

The bending moduli of the materials used in this work were obtained from the above procedure using specimens from configuration C10 where thickness is constant and known; Table 5.2.

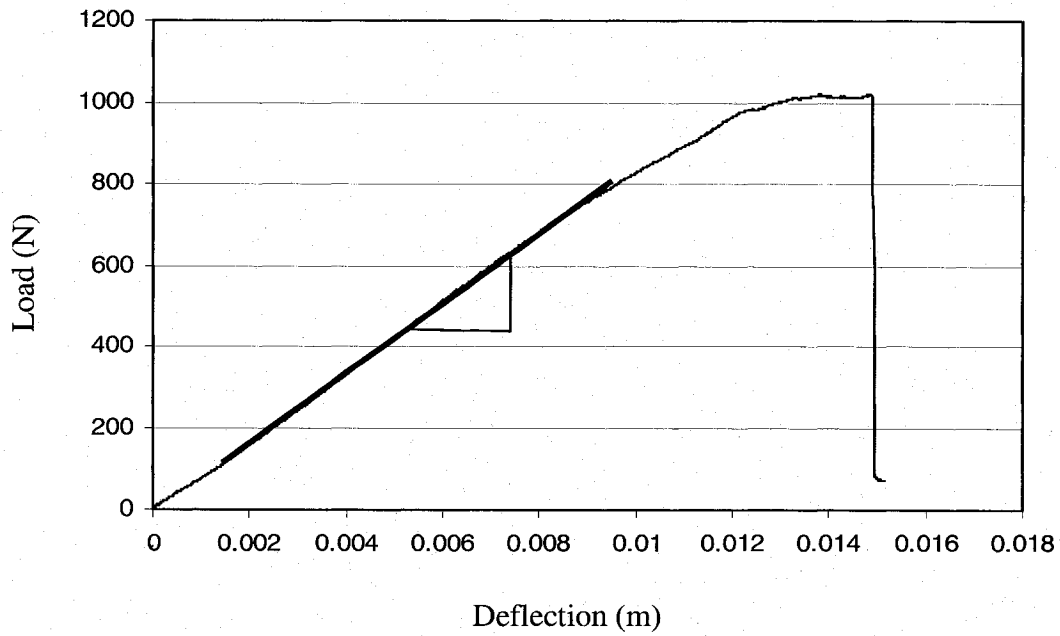


Figure 5.6 Load as a function of deflection, woven reinforcement R2, configuration C1.

Table 5.2 Calculation of bending modulus for random matt and woven reinforcement, C10.

<i>Specimen #</i>	<i>t (mm)</i>	<i>I (mm⁴)</i>	<i>E.I (GPa.mm⁴)</i>	<i>E (GPa)</i>	<i>E_{ave} (GPa)</i>	<i>S* (GPa)</i>
Matt						
S1	4.86	239.1	4.35	18.1	22.83	4.85
S2	5.02	263.5	4.58	17.3		
S3	5.15	285.8	8.17	28.5		
S4	5.47	342.4	8.69	25.3		
S5	5.79	404.8	9.99	24.6		
Woven						
S1	3.45	85.698	3.31	38.6	38.75	0.46
S2	3.50	89.476	3.44	38.4		
S3	3.51	89.937	3.53	39.2		
S4	3.60	97.362	3.81	39.1		
S5	3.73	108.115	4.13	38.1		

*S**: Standard deviation on modulus

5.5 Results

The structural stiffness of all specimens was evaluated by calculating the product EI for each specimen. The product reflects the effect of the material properties through E and the section properties through I . Elasticity modulus E in bending could not be evaluated on its own as v_f is known to vary in and between the joints, chapter 3. Similarly, the effect of changes in thickness, overlap length OL and in plane distance between the joints HD on the distribution of I along the length of the beam were not assessed. Here, each specimen is evaluated as a structure, the stiffness of which is affected by both E and I . Whilst the curvature in the specimens differs from that of a beam of constant cross section, the equations presented above are based on the displacement of the points where the loads is applied. As the objective is to draw general comparisons between the structural stiffness of the composites and to assess how the presence of joints in different configurations affects it, the above equations can be used. It is understood the comparisons are only valid, in a quantitative sense, for beams with the specified distances between spans. Furthermore, because of varying distance between the points of load application, it is more prudent to make comparisons between each configuration and configuration C10, as apposed to comparing configurations between themselves.

5.5.1 Structural stiffness EI

Structural stiffness EI results appear in Figure 5.7 for random reinforcement R1 and in Figure 5.8 for woven reinforcement R2.

For reinforcement R1, specimens from all jointed configurations C1-C9 are stiffer than those from configuration C10 which is devoid of joints. It is also observed that specimens made from reinforcement R1 are stiffer than those made from reinforcement R2, despite the fact that the material was shown to have a lower elasticity modulus. The observation is explained by the thickness of the specimens, which was larger for reinforcement R1. Standard deviation of EI is substantially larger for the random matt. This

is explained by higher variation in thickness between specimen S1 (outlet) and specimen S5 (inlet), which in turn is explained by the fact that reinforcement R2 stiffens much more rapidly than reinforcement R1 during compaction.

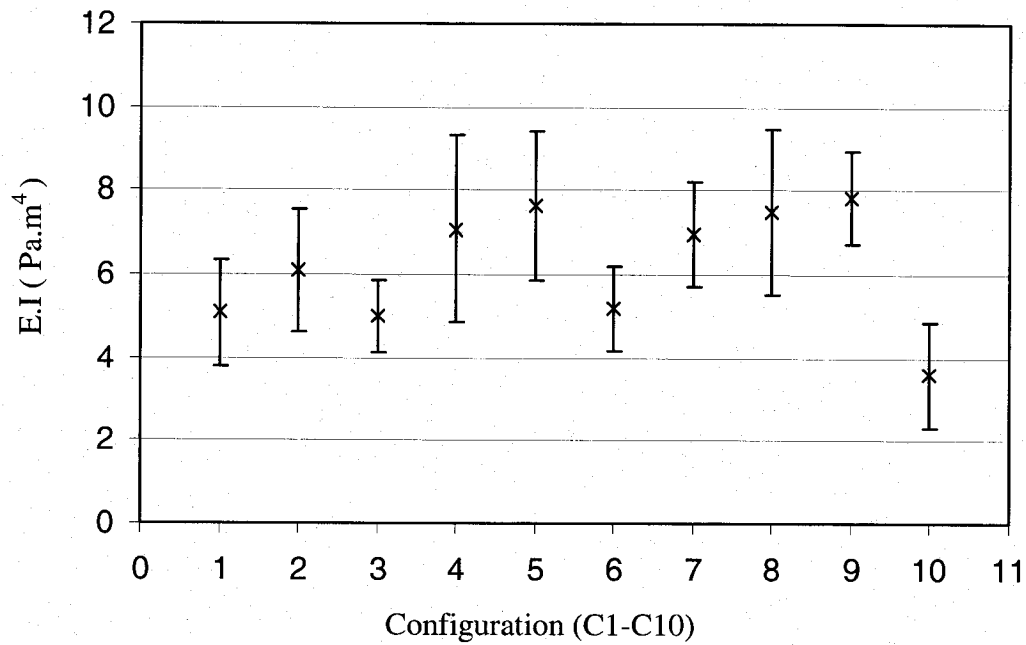


Figure 5.7 Stiffness results for random matt reinforcement R1, configurations C1-C10.

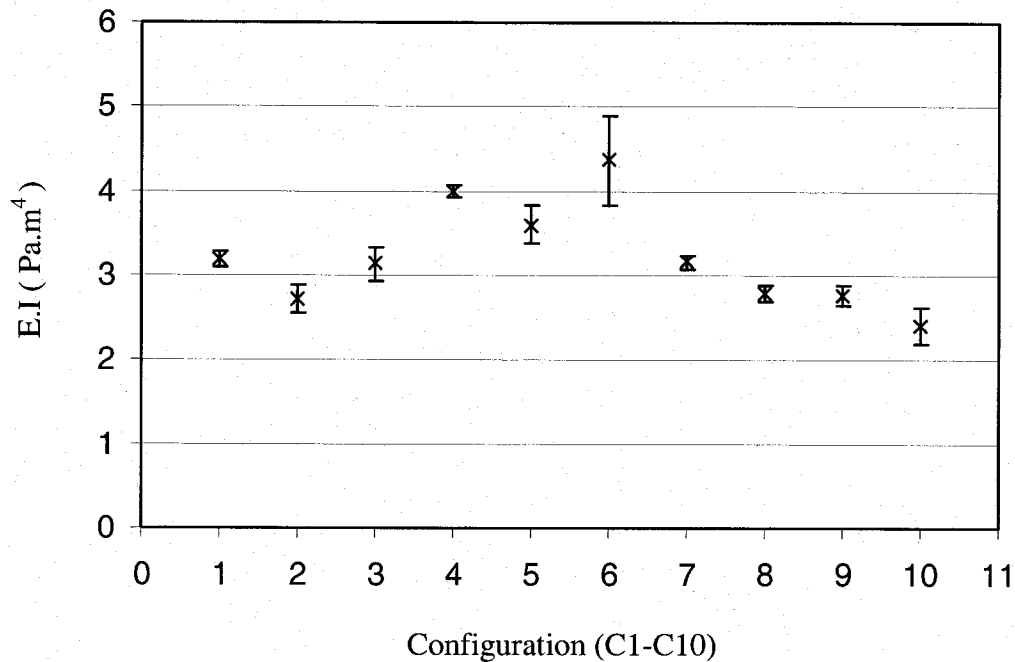


Figure 5.8 Stiffness results for woven reinforcement R2, configurations C1-C10

It was expected that specimens from configurations C4 to C6 would show higher structural stiffness; generally this was observed to be true. No general trends could be identified for the horizontal distance HD or number of superimposed joints NS.

5.5.2 Failure configurations

All specimens were loaded to failure. As discussed previously, the bending moment was constant between the loading noses. Between these points, sample thickness was maximum at the noses and minimum at the center of span. From a theoretical perspective it was expected that failure would occur in the zone of smaller thickness. In fact, for all configurations other than C10 catastrophic tensile failure occurred one of the two transition zones. In all cases, failure started on top face in compression, see Figure 5.9.

Catastrophic failure then took place on the lower face, in tension. Examples of these phenomena are presented in Figure 5.10 for matt reinforcement R1 and figure 5.11 for woven reinforcement R2; the figures show that a similar scenario was repeated for the different configurations.

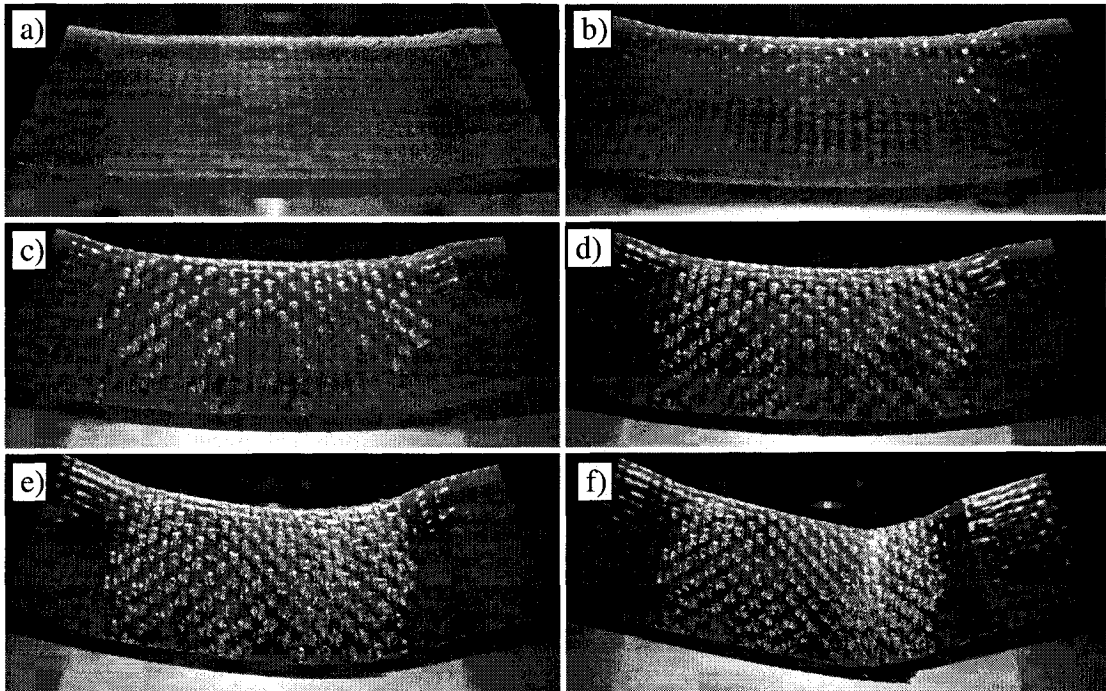
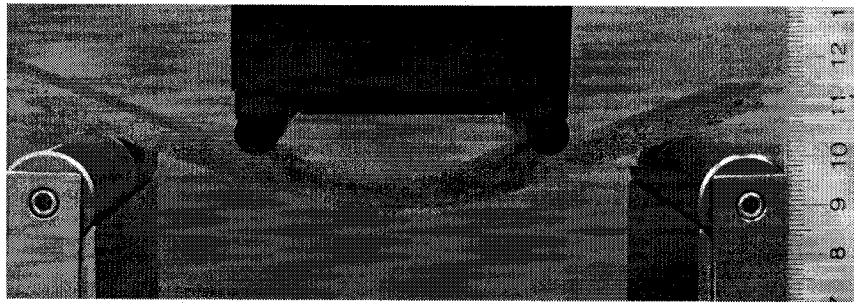
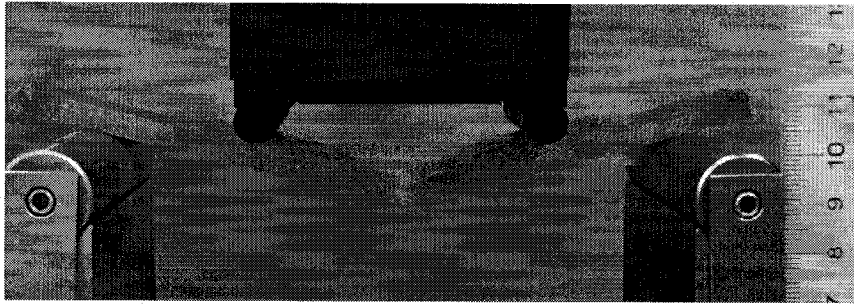


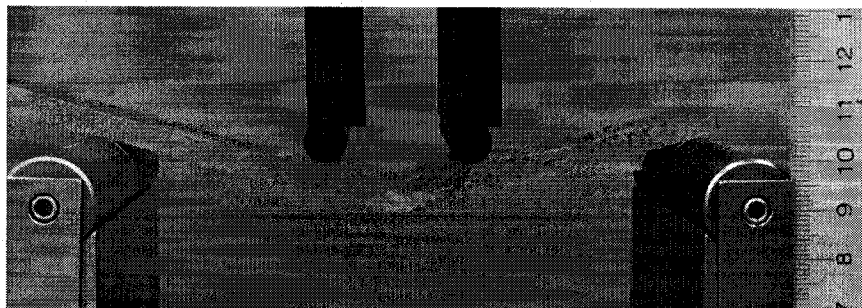
Figure 5.9 Failure of composite in compression and then in tension, woven reinforcement R2, configuration C3.



a)



b)

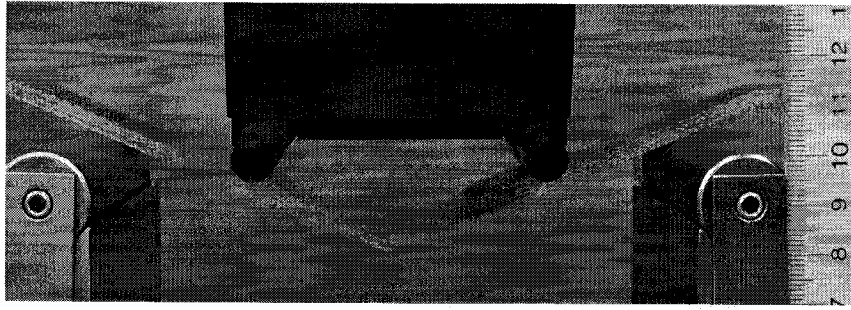


c)



d)

Figure 5.10 Failure near transition zones for lap joints in random matt reinforcement R1, configuration: a) C1-C3, b) C4-C6, c) C7-C9 and d) C10.



a)



b)



c)



d)

Figure 5.11 Failure near transition zones for lap joints in woven reinforcement R2, configuration: a) C1-C3, b) C4-C6, c) C7-C9 and d) C10.

In the case of reinforcement R1, configurations C4 to C6 delamination was observed after catastrophic failure as shown in Figure 5.12. Failure of other plies occurred progressively as indicated by the stepped failure curves, presented in Appendix F.

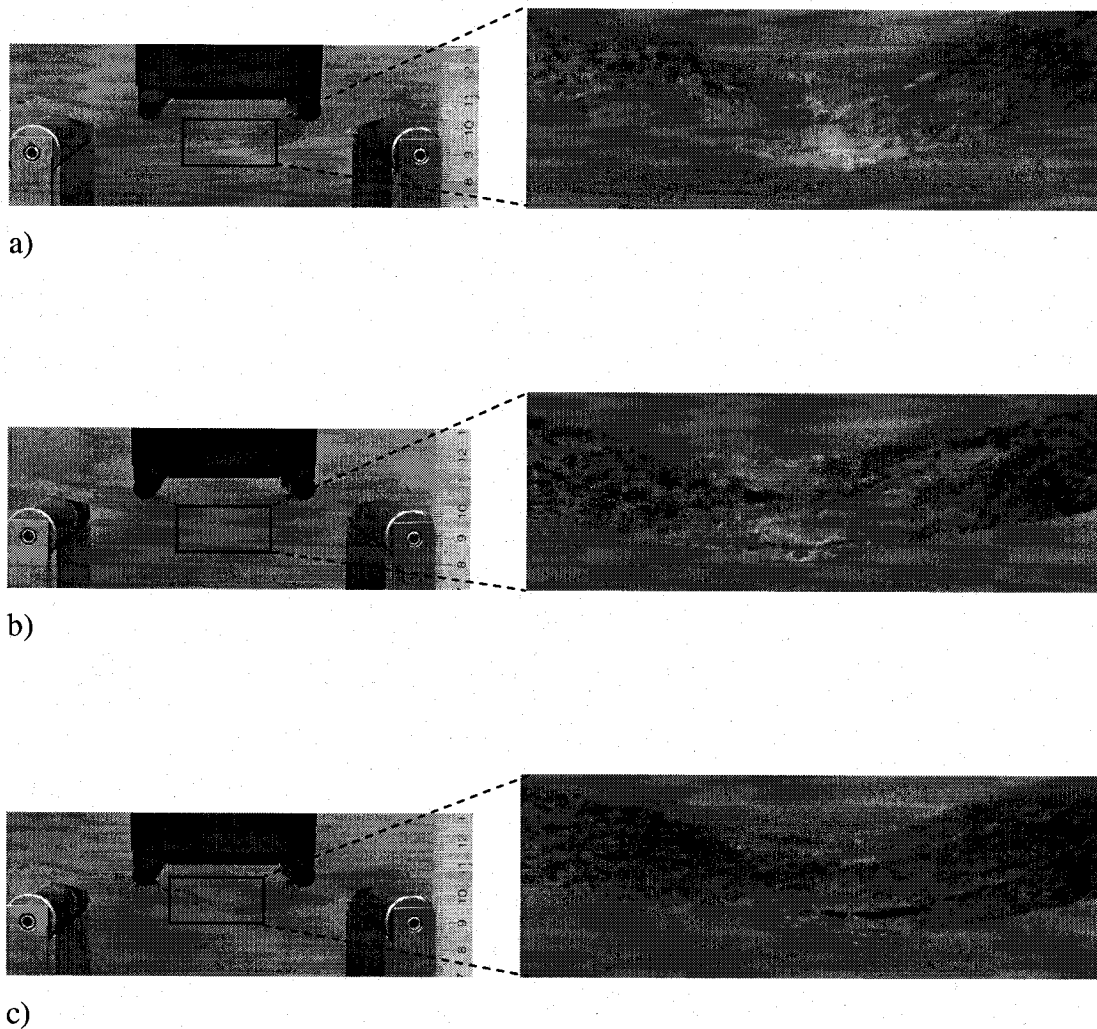


Figure 5.12 Failure in transition zones for lap joints in random matt reinforcement R1, configurations: a) C4, b) C5 and c) C6.

5.5.3 Flexural Strength ($\sigma_{\max}$)

Maximum stress along x at the outer faces in the central section of the specimens was evaluated using the following equation:

$$\sigma_{\max} = \frac{M \cdot y}{I} \quad (5.9)$$

where M is the bending moment and y is distance from the natural plane to the surface of the specimen; I was described previously.

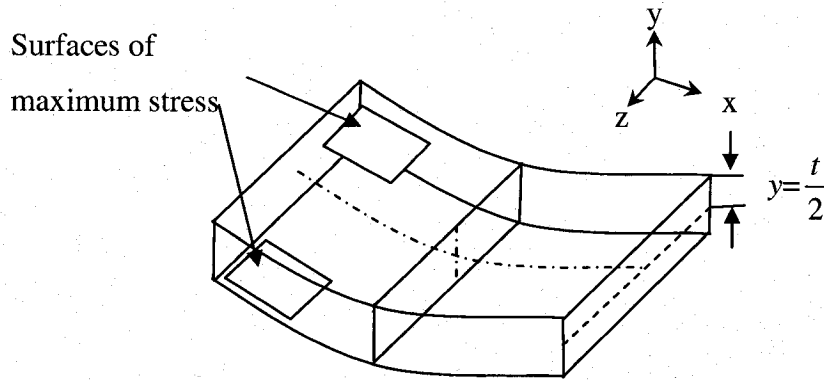


Figure 5.13 Schematic shape of zone under load.

Results for matt reinforcement R1 and woven reinforcement R2 appears in Figures 5.14 and Figure 5.15 respectively. In the case of reinforcement R1, jointed specimens generally support higher stress levels with configurations C4 to C6 taking the highest bending stress. The standard deviation on the maximum stress is essentially constant.

Woven reinforcement R2 showed a different behaviour; in this case most jointed specimens failed under stress levels that are lower than reached for configuration C10. Furthermore, significant fluctuations in the standard deviation were observed and no precise trends could be identified with parameters NS, HD, or OL. Whilst a precise explanation to the above results for maximum stress would require more extensive characterisation, it

should be noted that failure occurred in the thickness transition zone for all specimens. For sake of discussion, finite element simulations were conducted as follows.

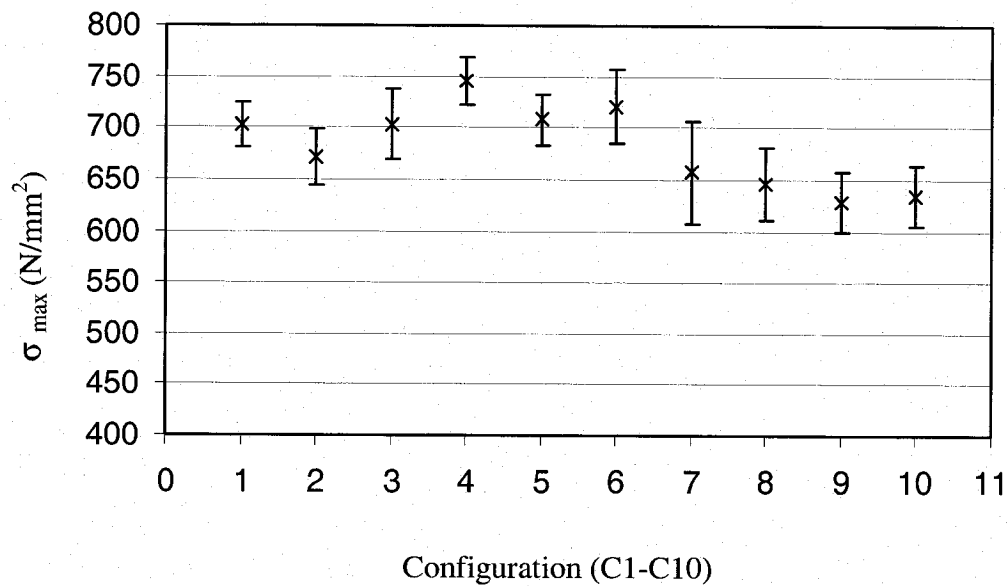


Figure 5.14 Maximum stress for random matt reinforcement R1, configurations C1-C10.

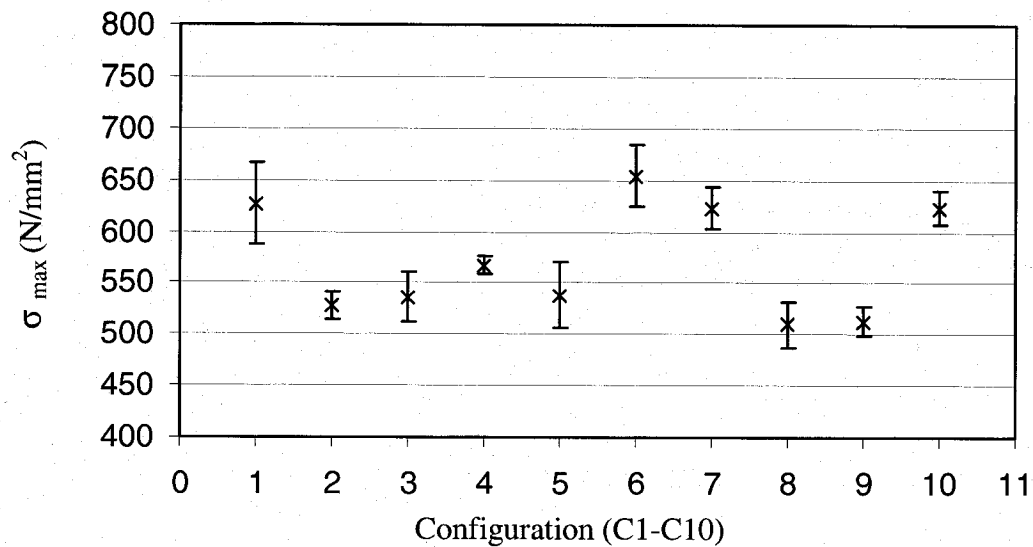


Figure 5.15 Maximum stress for woven reinforcement R2, configurations C1-C10.

5.5.4 Transition zone analysis, simulation with ADINA

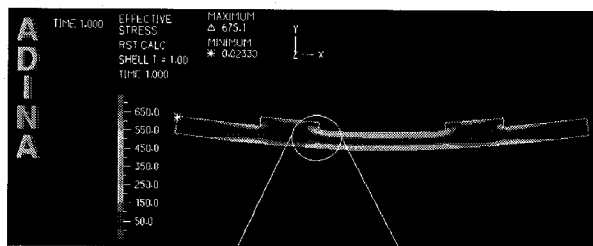
Simple structural simulations of four-point bending of specimens were performed using the ADINA™ (Automatic Dynamic Incremental Nonlinear Analysis) finite element software to illustrate the structural behaviour of selected lap joints under four-point bending. More specifically, the effect of the geometry at the transition zone was investigated. In order to perform finite element modelling, a geometric model of specimens must be created. Different 2D specimen outlines were created using commercial modeller SolidWorks™. The objective was to create three different models with similar thicknesses, nominal overlap length and horizontal distance between joints, but with different transition geometry, to document the effect of any stress concentration on lap joints and possibly relate this with some of the variation seen in experimental results. All 2D simulation featured the same simplified isotropic material properties and load conditions. Simulation results were the effective stress distributions throughout the specimens resulting from imposed forces. Dimension used for the three specimens were similar except for the radii of corners in transition zones.

Three cases with sharp lap joint edges, moderately rounded edges and smooth edges were created. Loads were imposed in the same positions for all three cases and boundary conditions were identical. Three node elements are used in simulations.

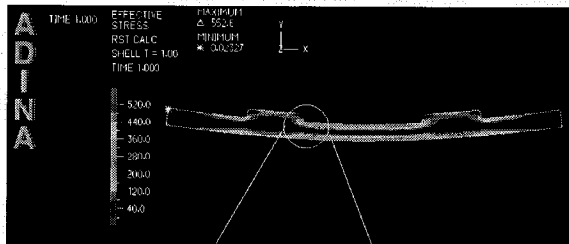
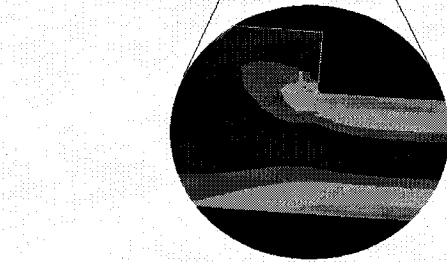
The simulations showed higher stress levels reached in the mid span for the three samples, as expected. Maximum stress levels were observed in the transition zones in the three cases, as shown in Figure 5.16 and Table 5.2. This verifies that the maximum stress and position of the rupture point depend on surface conditions.

Table 5.3 Finite element analysis results for different edge conditions.

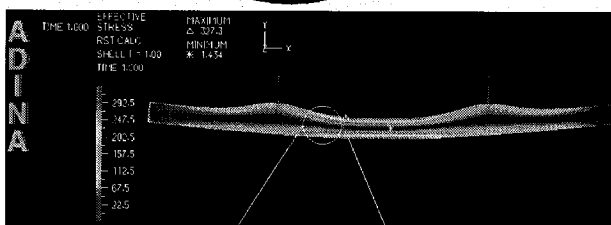
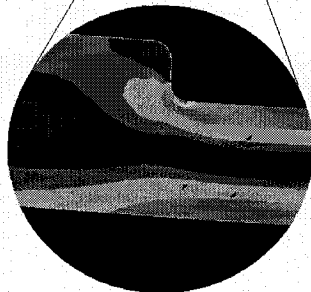
Case	Edge Condition	Location of Max Stress	Max Stress (MPa)
1	Sharp	On corner	675.1
2	Rounded	Displaced from corner	552.6
3	Smooth	Mid span	327.3



a) Sharp edge



b) Rounded edge



c) Smooth edge

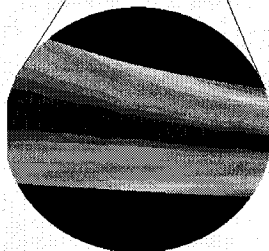


Figure 5.16 Finite element simulations for three lap joints with different edge conditions.

5.6 Discussion

Changes in thickness in the specimens made the evaluation of modulus E and second moment inertia I for cases tested. Therefore the mechanical performance was evaluated through product $E.I$. Structural stiffness results showed that jointed specimens are stiffer than specimens devoid of joints, as expected. Also, experiment showed that the specimens failed under compression first with flaking of the upper surface, followed by tensile failure of the plies.

It was more interesting to observe failure of all jointed specimens in transition zone under a constant bending moment in the mid span. Summary finite element analyses made on 2D models with different transition characteristics illustrated a dependency on the condition of the edge of the lap joins. Smoother edges resulted in failure at the mid span. Variability over the actual specimen shape makes it difficult predict the maximum flexural stresses that can be supported by the specimens.

CHAPTER 6

Conclusions and recommendations

An experimental procedure was conducted where the compaction, flow and mechanical behaviour of lap joints manufactured by VARTM were investigated. Joints in ten different configurations were fabricated from two different reinforcements. The thickness of different joints with varying overlap length OL, overlap horizontal distance HD and number of superimposed joints NS was measured using a dedicated thickness measurement system. This measurement system used a novel technique based on Hall effect sensors. The data was validated using LVDT measurements.

Preforms were infused with resin flowing parallel to the joints. Flow progression was recorded and compared for the different joint configurations. After resin cure the panels were cut and four-point bending tests were performed based on ASTM D790-03 standard to compare the mechanical behaviour of different configurations. The conclusions drawn from the test results are as follows:

- For the thickness measurement technique, the accuracy of Hall effect sensors for this application was tested. Results were compared with thickness data obtained from LVDTs during vacuuming. Good agreement was observed between Hall effect sensor data and LVDT measurements. In further Hall effect sensor use for this application, it should be considered that they are sensitive to a magnetic field in a precise orientation relative to the Hall effect sensor surface; possible lack of accuracy on orientation can be a major source of error in this application. Advantages of these sensors are that do not require contact and have

no theoretical limit to their life, and they provide absolute reading hence there is no need for recalibration after use. Hall effect sensors offer other appealing advantages such as good repeatability, limited size and low cost.

- For the compaction behaviour at and around lap joints in multilayer textile preforms, a number of trends were identified and quantified for different reinforcements and joint configurations. Some configurations lead to reduced variability in v_f , and the transition zone next to the joints can extend more or less into the preform depending on joint configuration. The occurrence of different v_f values in joints was not trivial.

- Analysis of compaction results based on the power law model was applied to quantify the effect of OL, NS and HD on the initial fibre volume fraction A and the stiffening index B . The effect of length, distance and sequences were weak while changes in reinforcement had a strong effect on compaction behaviour. Also, the relation between power law parameters A and B was plotted. It was seen that points associated with each reinforcement and different numbers of layers were clearly separated in groups.

- Variation in effective permeability as a function of v_f was smaller than it is for cases where uncut sheets are used as a preform. The reason for this limited variation was believed to originate from the presence of channels in the jointed preforms; such channels promote the infusion of resin.

- The effect on the average flow front position of the different configurations was studied. It was observed that the configuration of the lap joints has a stronger effect on effective permeability for woven reinforcement R2 than for random matt reinforcement R1. Also, any change in configurations could lead to considerable differences in overall permeability. It was concluded that the presence of joints does not necessarily result in faster or slower flow.

- For mechanical properties of lap jointed specimens, structural stiffness EI was calculated. Lap jointed specimens were stiffer compared to specimens devoid of joints. Failures occurred in transition zones for both reinforcements. Failure started in compression in the up face but catastrophic failure took place in tension in the lower face. Different maximum flexural stresses were obtained for different configurations with no clear trends. Results for the maximum flexural stress showed that stress concentration at the lap joints is an important factor in failure and should be considered in design and manufacturing.

The following recommendations are made for future work:

- More research is needed to investigate and improve the performance of Hall effect sensors for thickness measurement especially for reducing the noise.
- There is a need to develop a method where Hall effect sensors are used for controlling the infusion and flow parameters in VARTM manufacturing, automatically.
- Analytical models need to be developed to predict the effect of lap joints on the VARTM manufacturing.
- Further experimental and analytical work is needed to extend the results of the limited investigation conducted for this thesis to larger scale and to a wider array of joint configurations.

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Appendix A

Hall effect sensor calibration:

Co-ordinate z as a function of output voltage

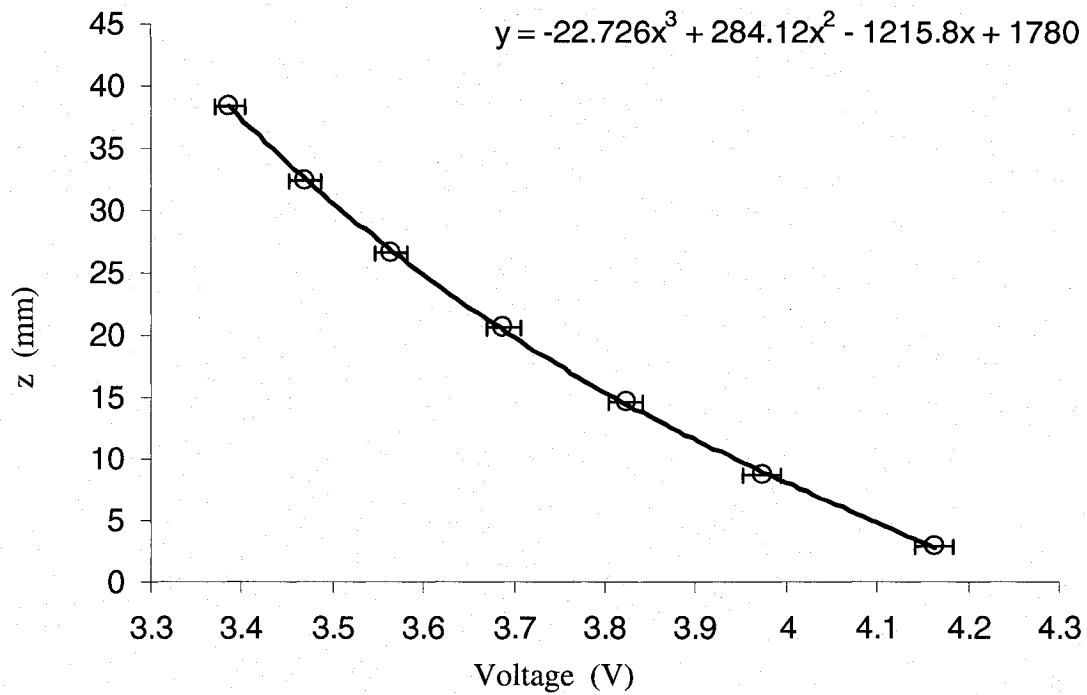


Figure A.1 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 1.

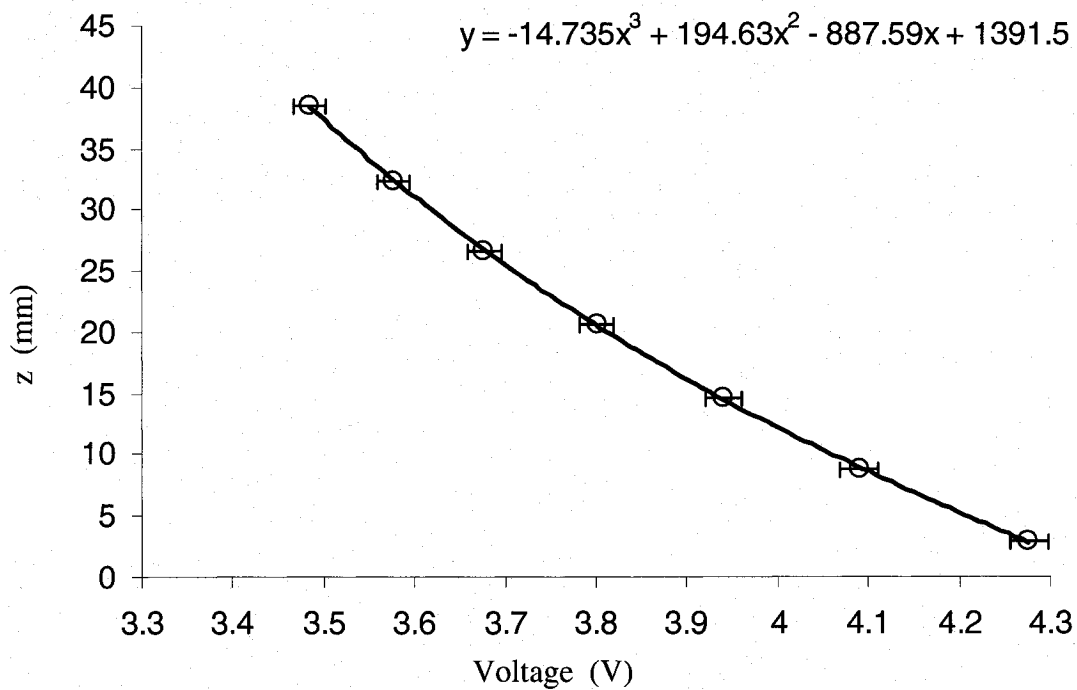


Figure A.2 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 2.

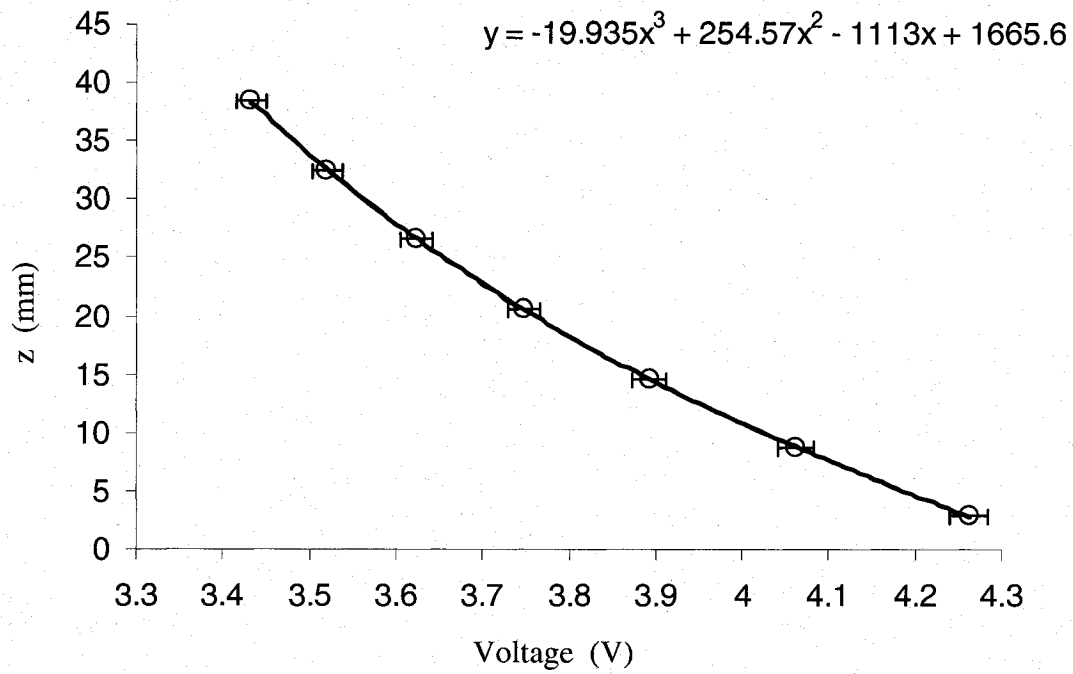


Figure A.3 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 3.

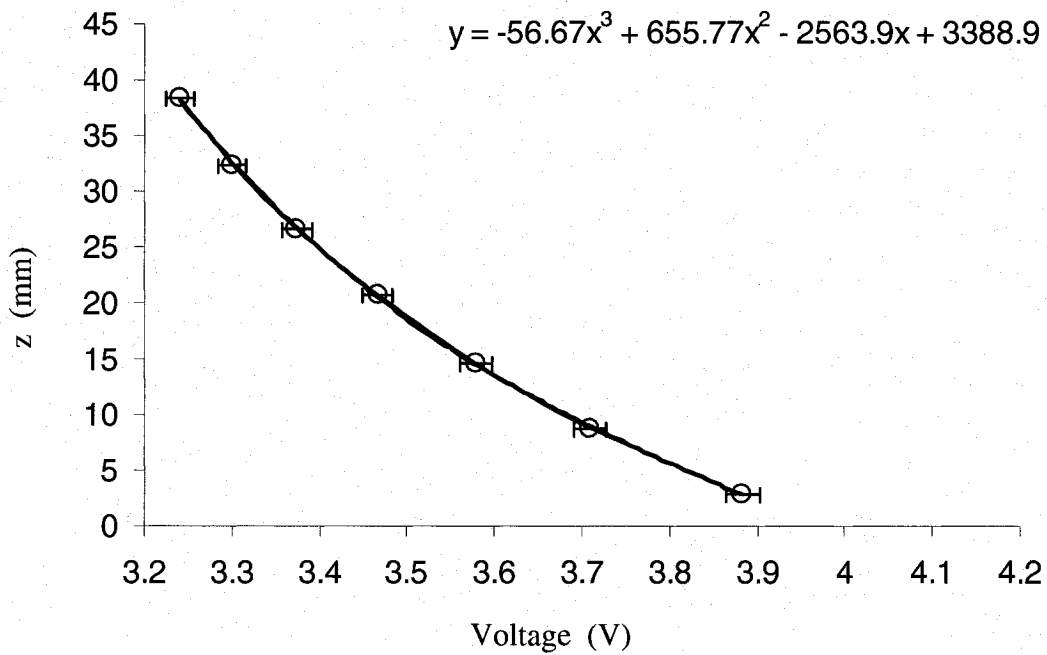


Figure A.4 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 4.

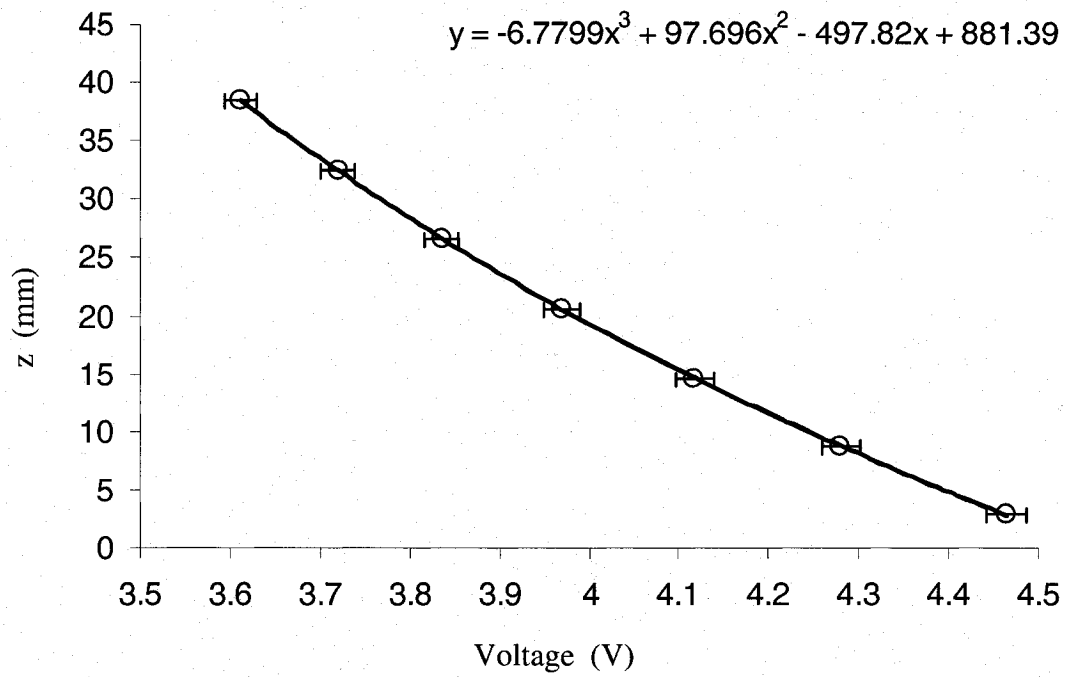


Figure A.5 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 5.

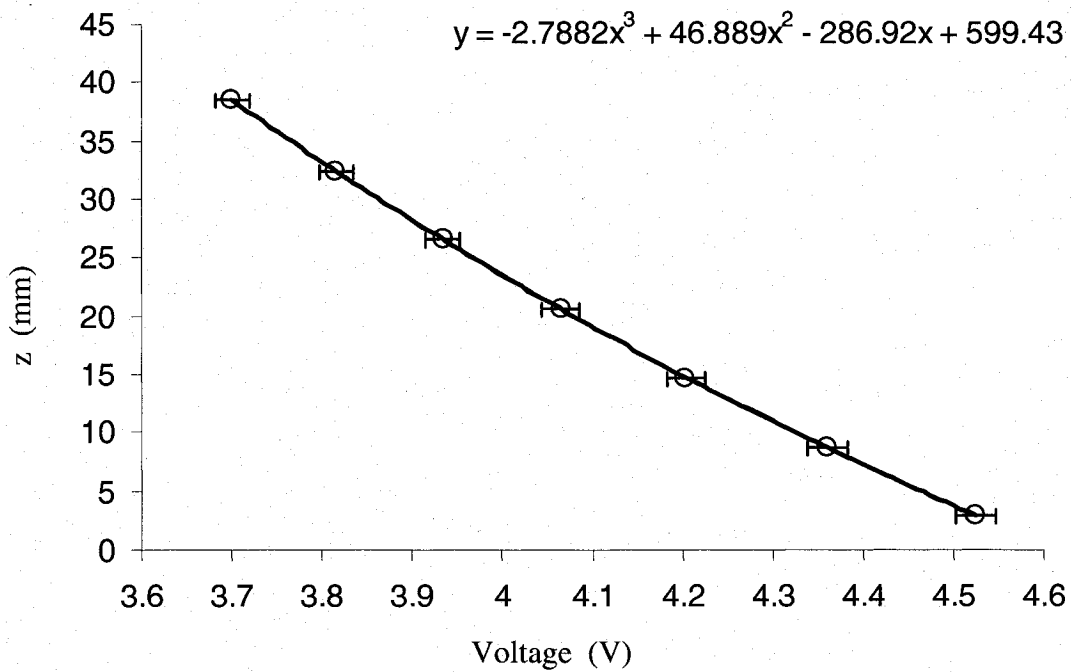


Figure A.6 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 6.

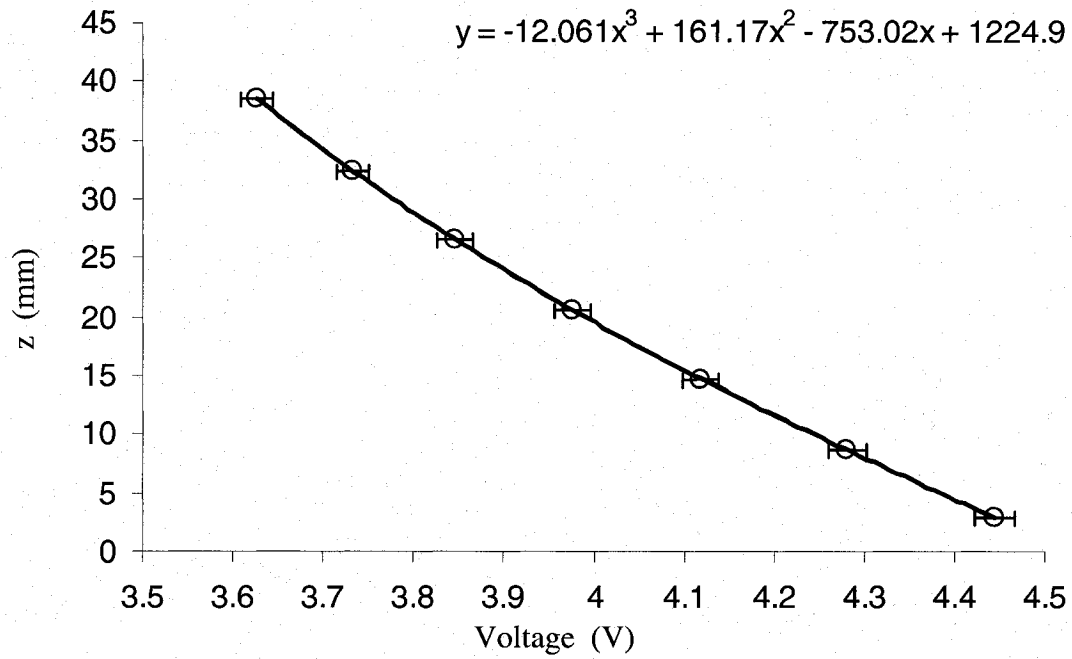


Figure A.7 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 7.

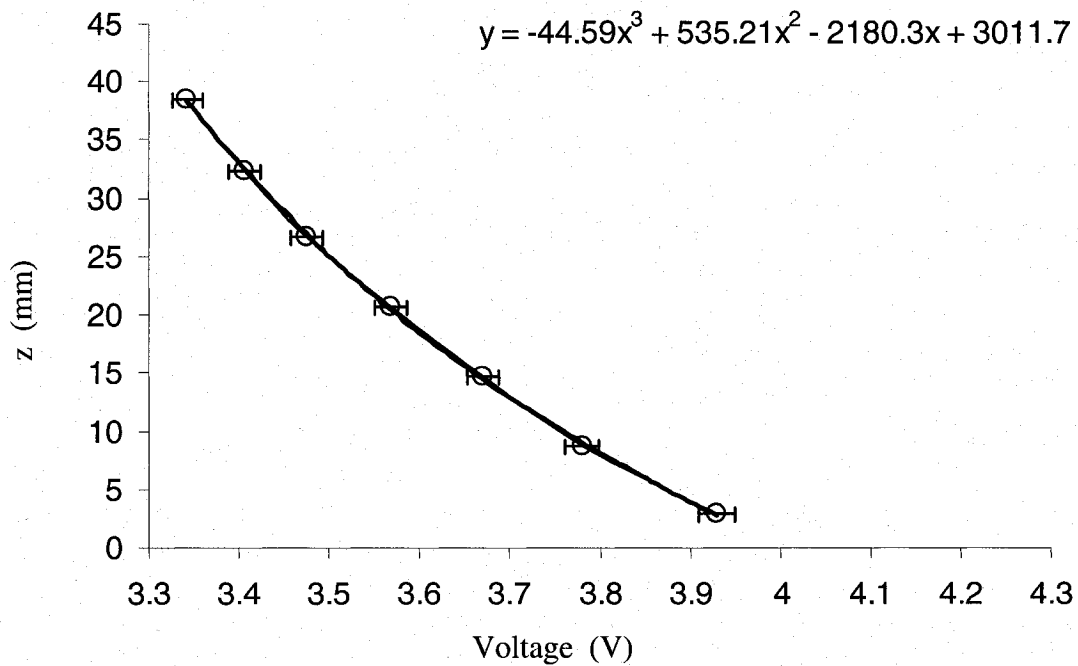


Figure A.8 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 8.

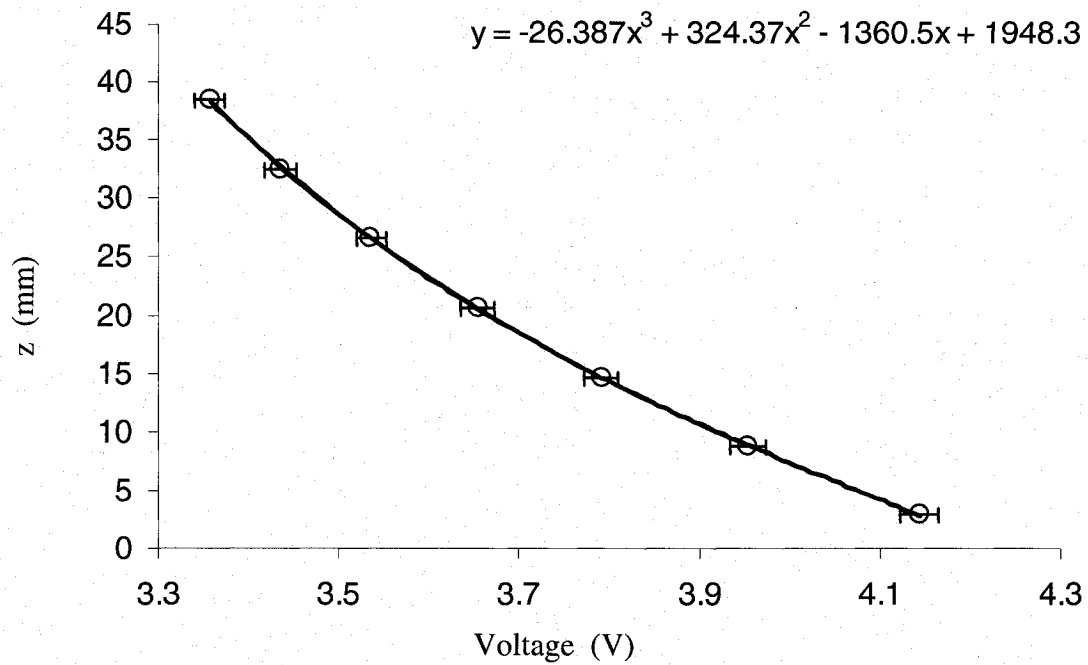


Figure A.9 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 9.

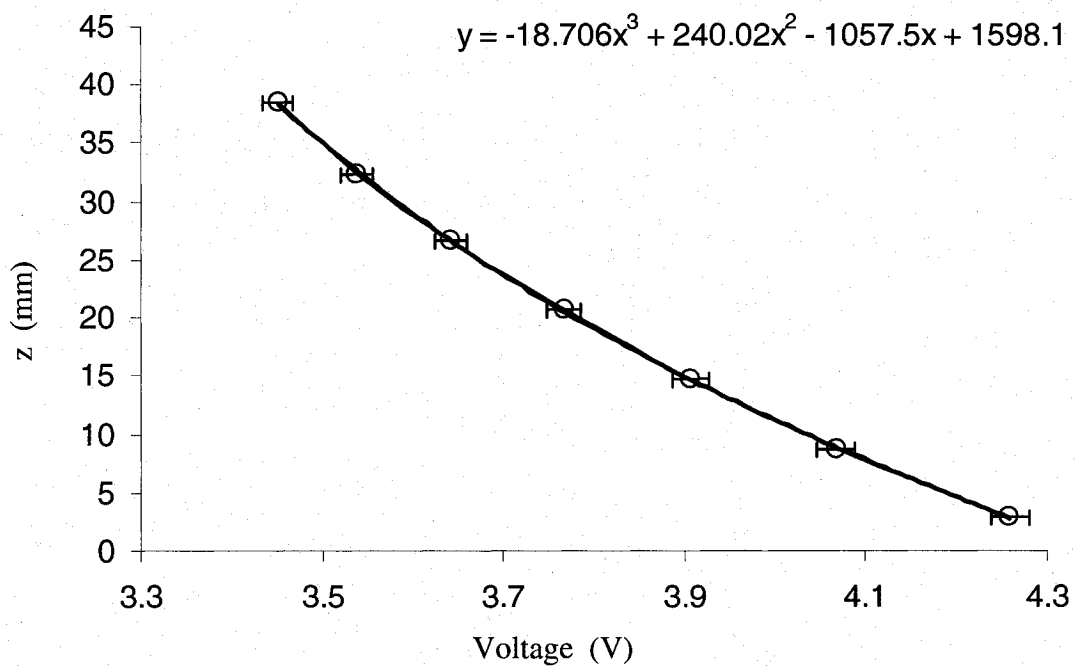


Figure A.10 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 10.

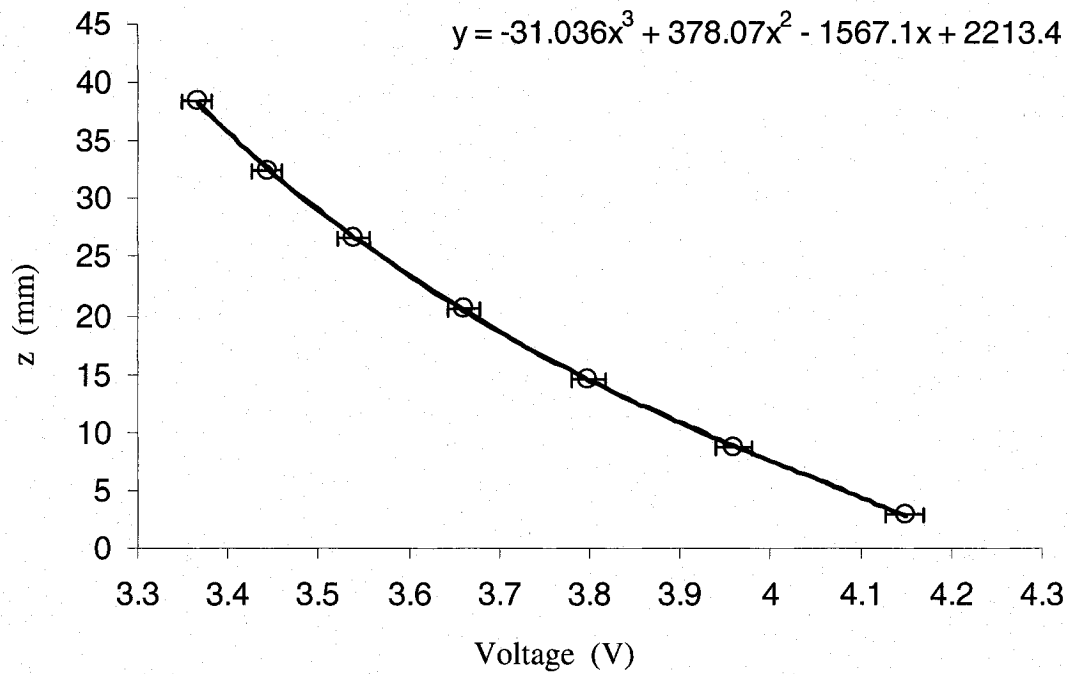


Figure A.11 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 11.

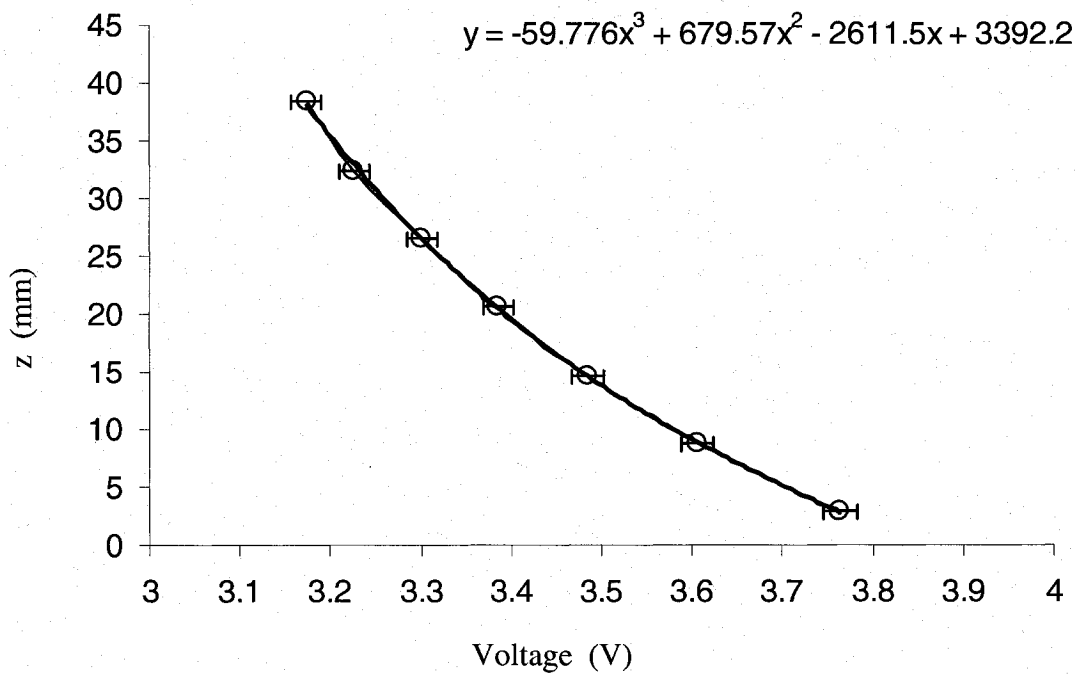


Figure A.12 Co-ordinate z as a function of output voltage, 3rd degree polynomial, sensor 12.

Appendix B

**Experimental data for flow front position as function of time,
random matt reinforcement R1.**

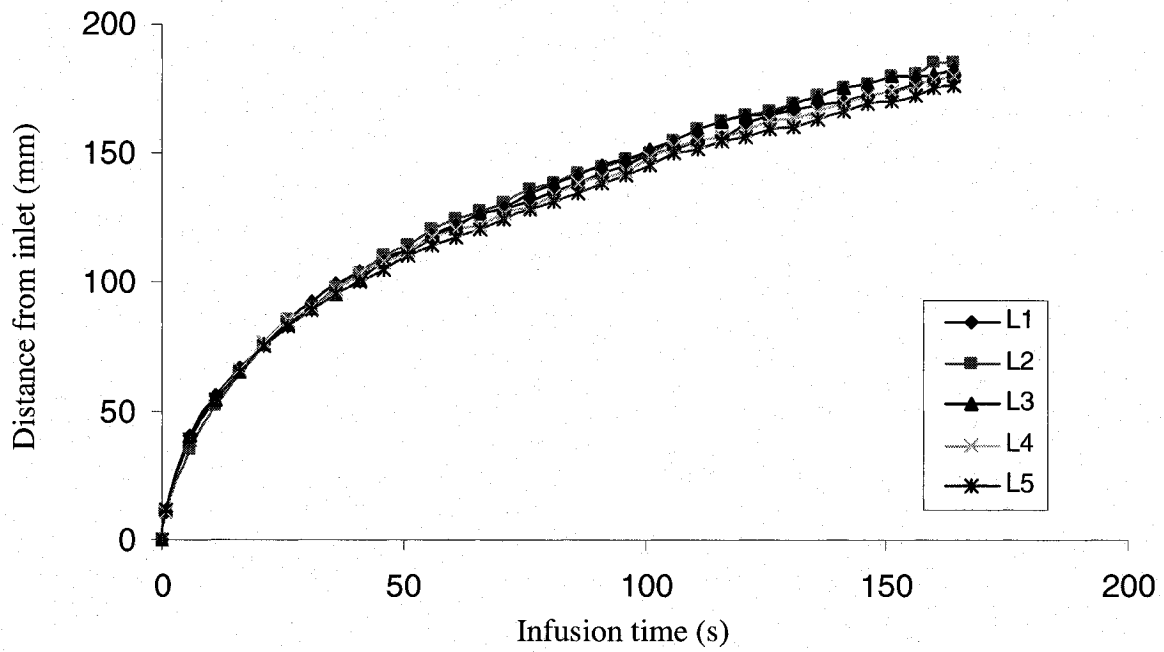


Figure B.1 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C1.

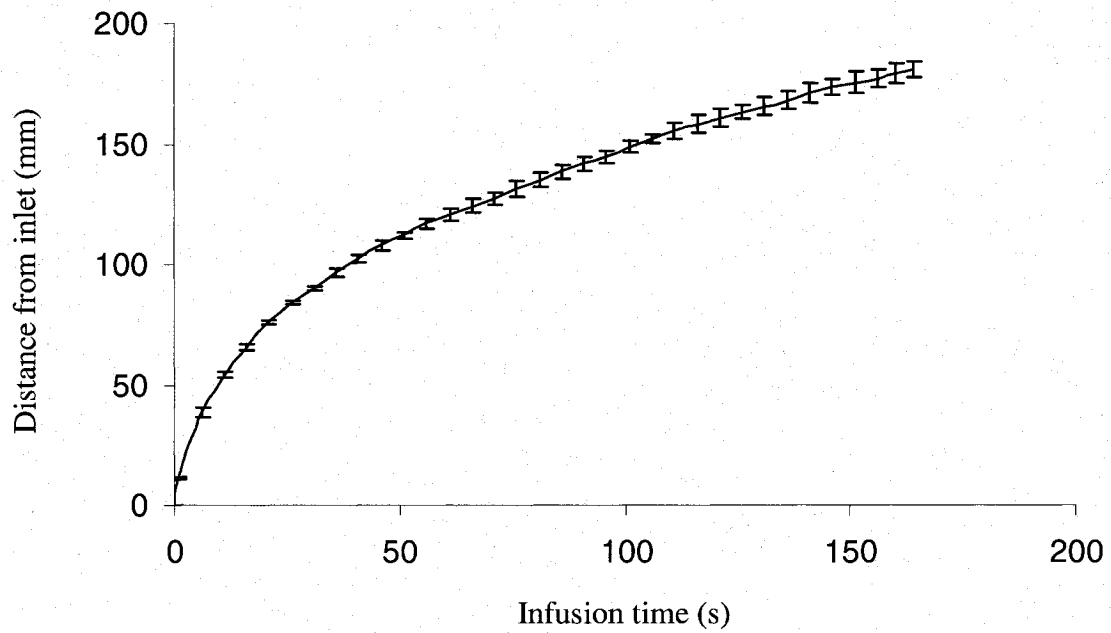


Figure B.2 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C1.

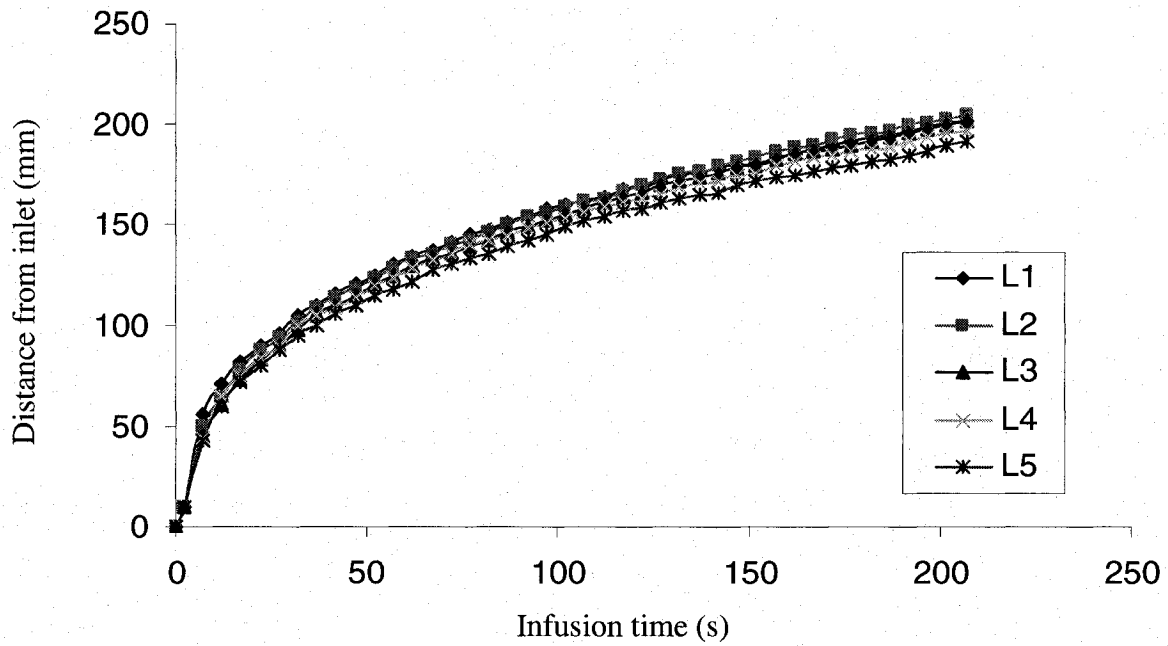


Figure B.3 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C2.

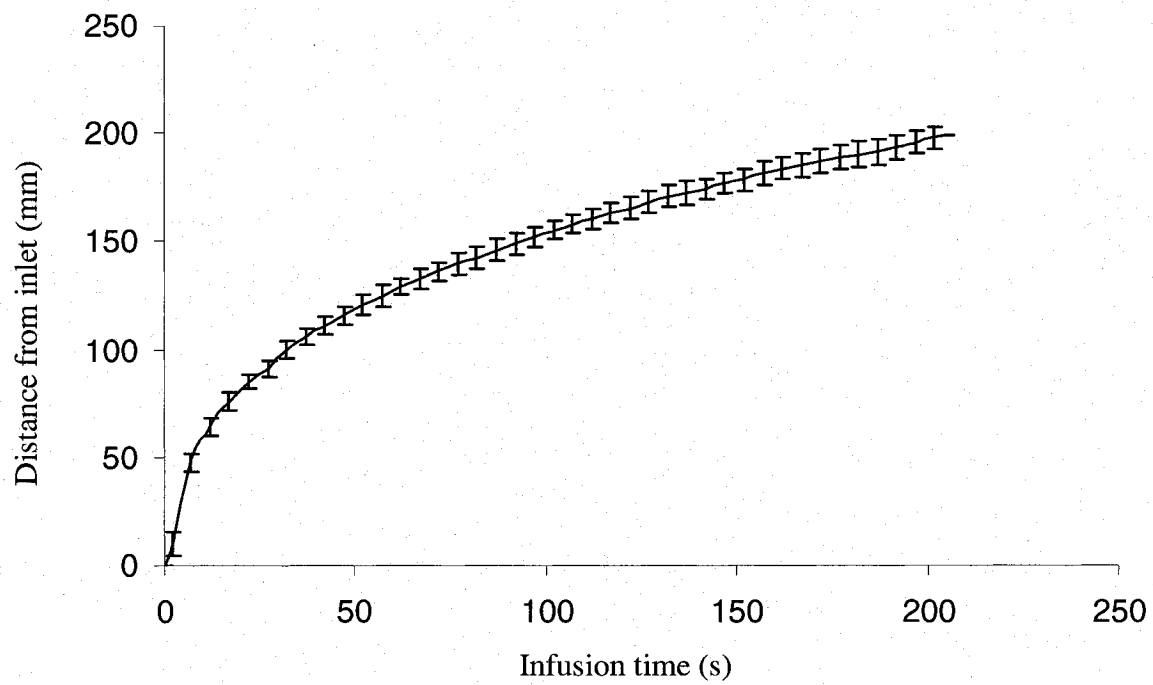


Figure B.4 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C2.

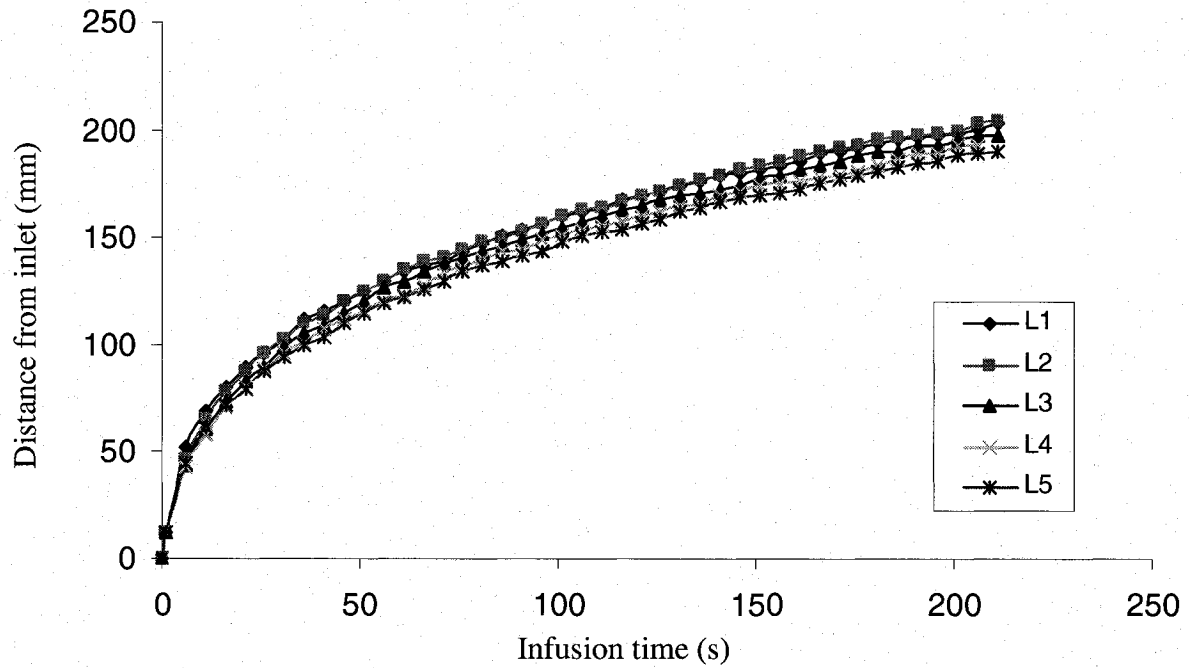


Figure B.5 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C3.

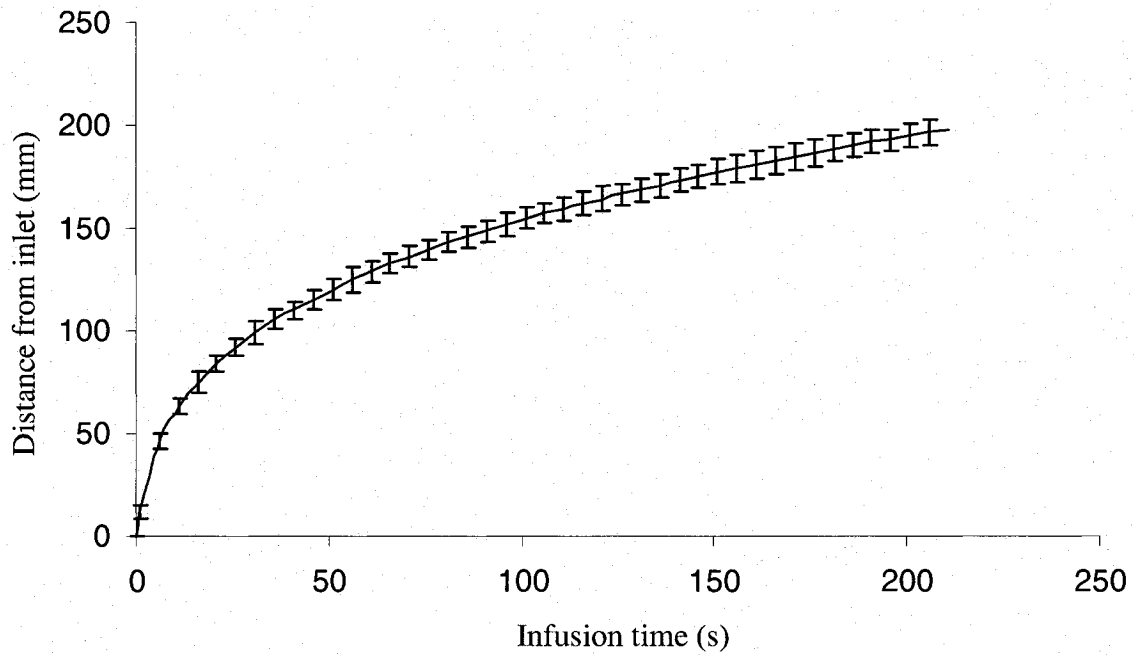


Figure B.6 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C3.

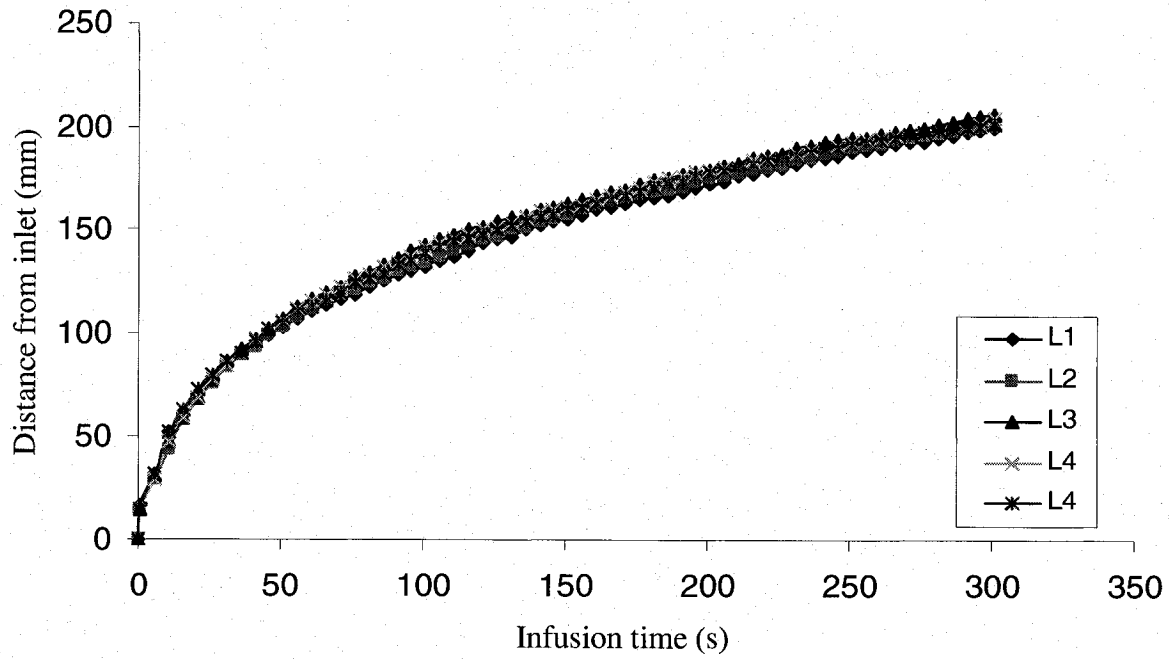


Figure B.7 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C4.

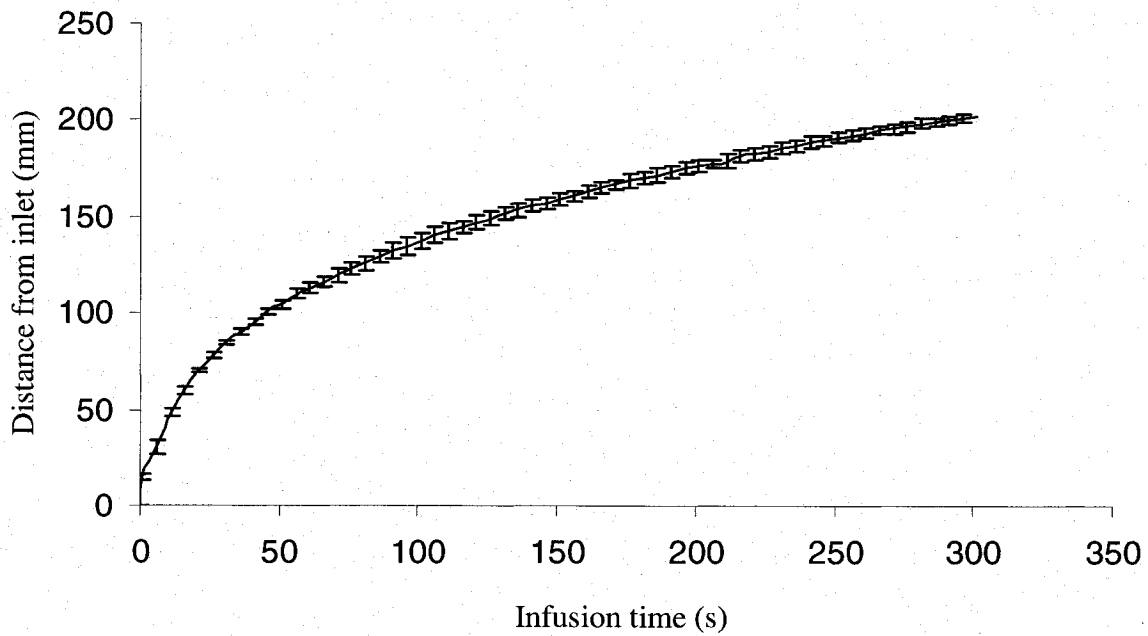


Figure B.8 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C4.

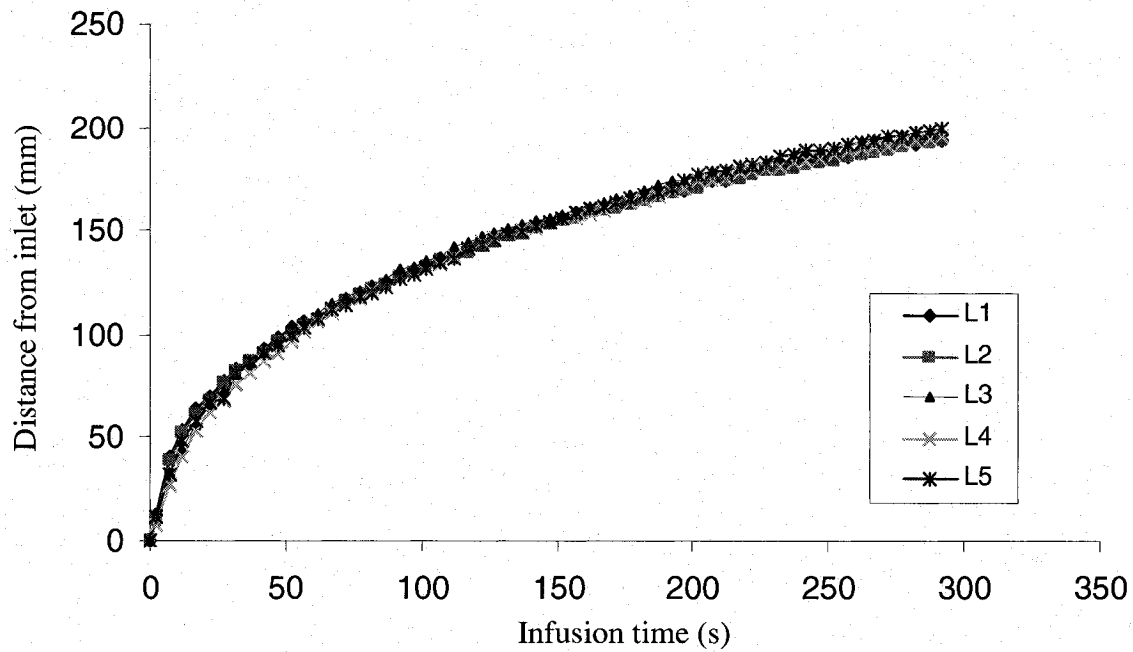


Figure B.9 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C5.

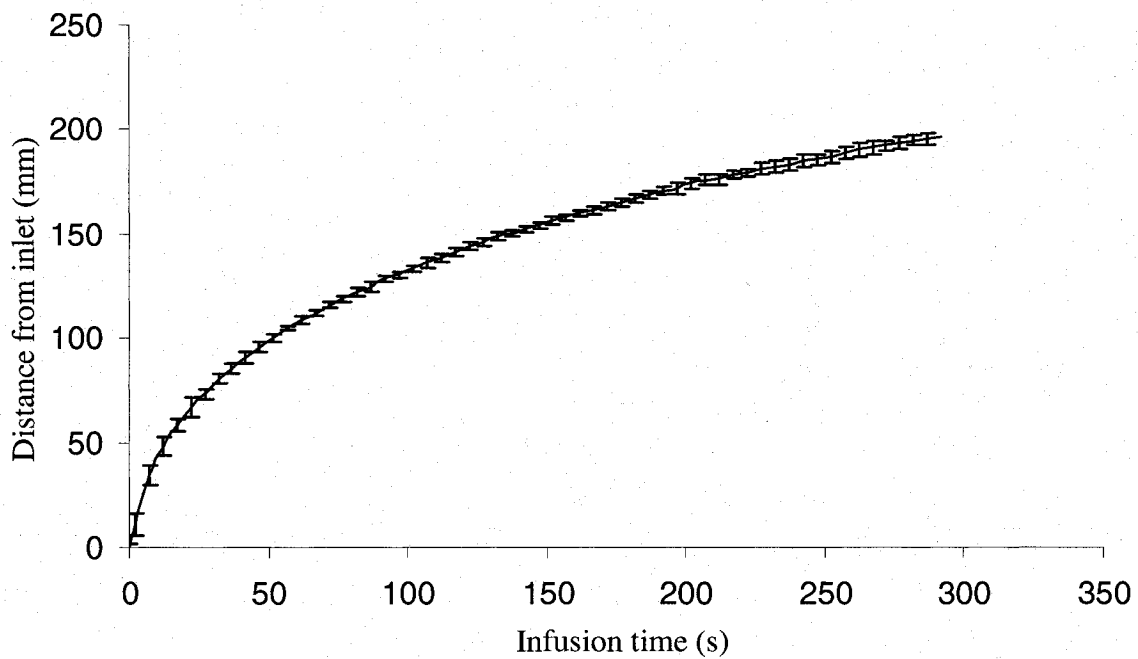


Figure B.10 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C5.

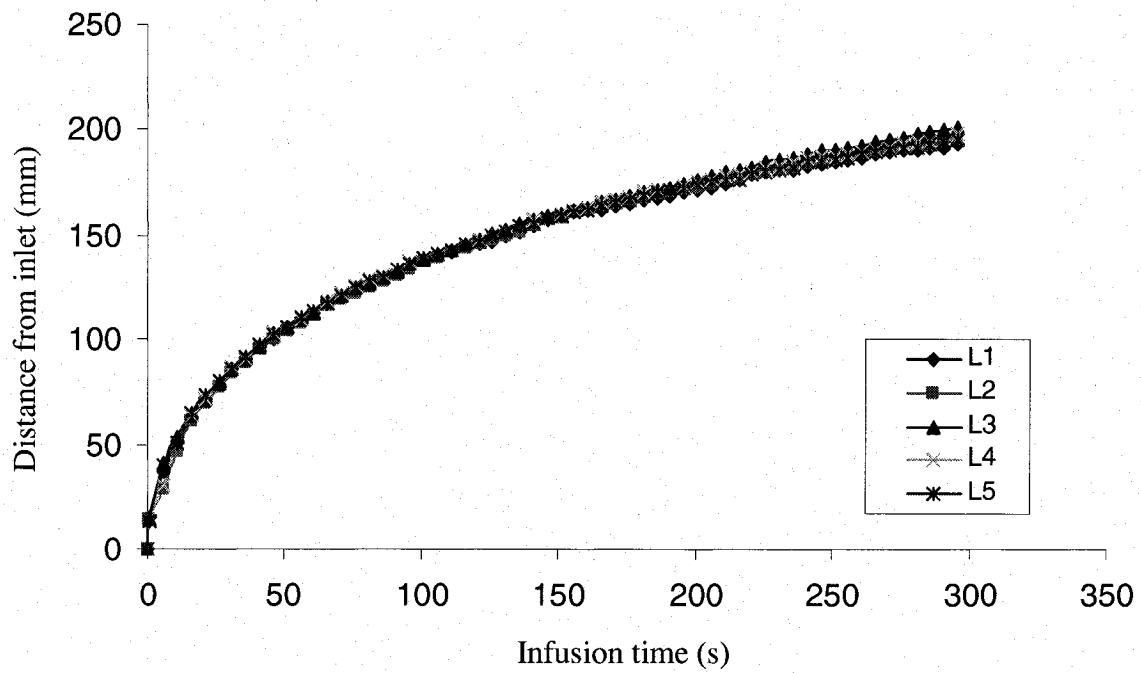


Figure B.11 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C6.

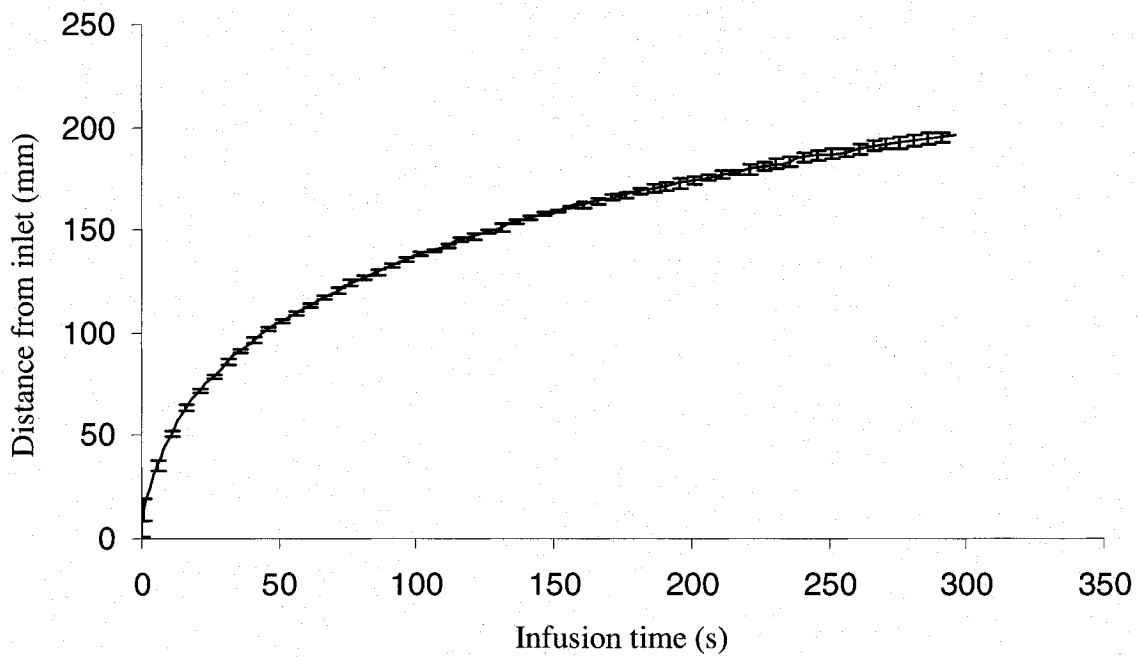


Figure B.12 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C6.

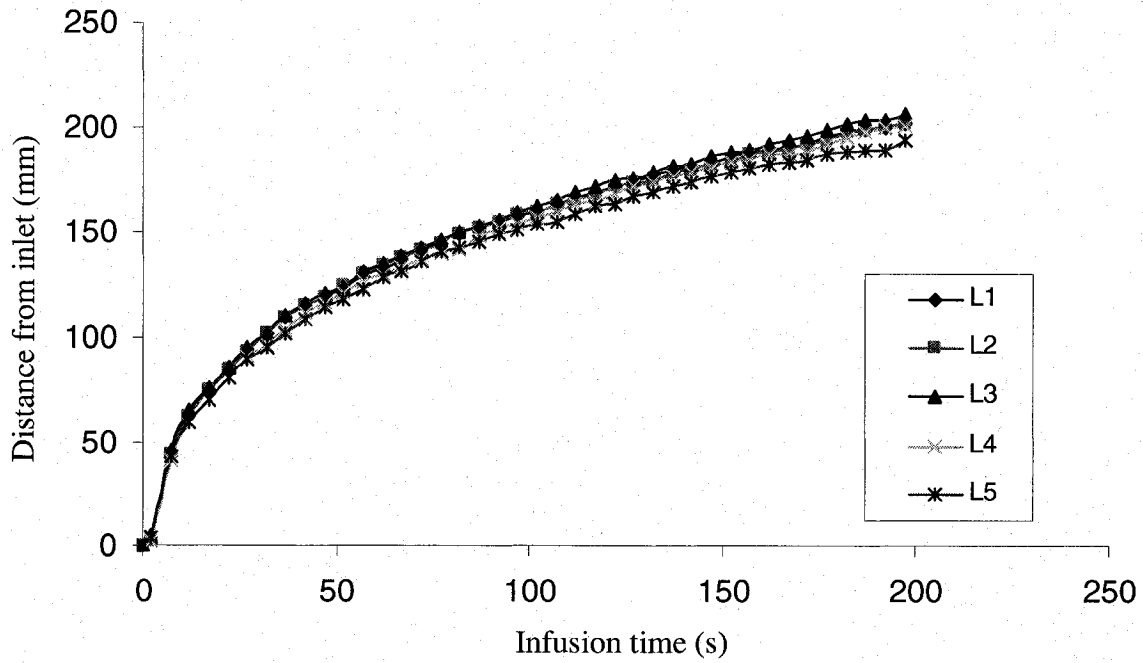


Figure B.13 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C7.

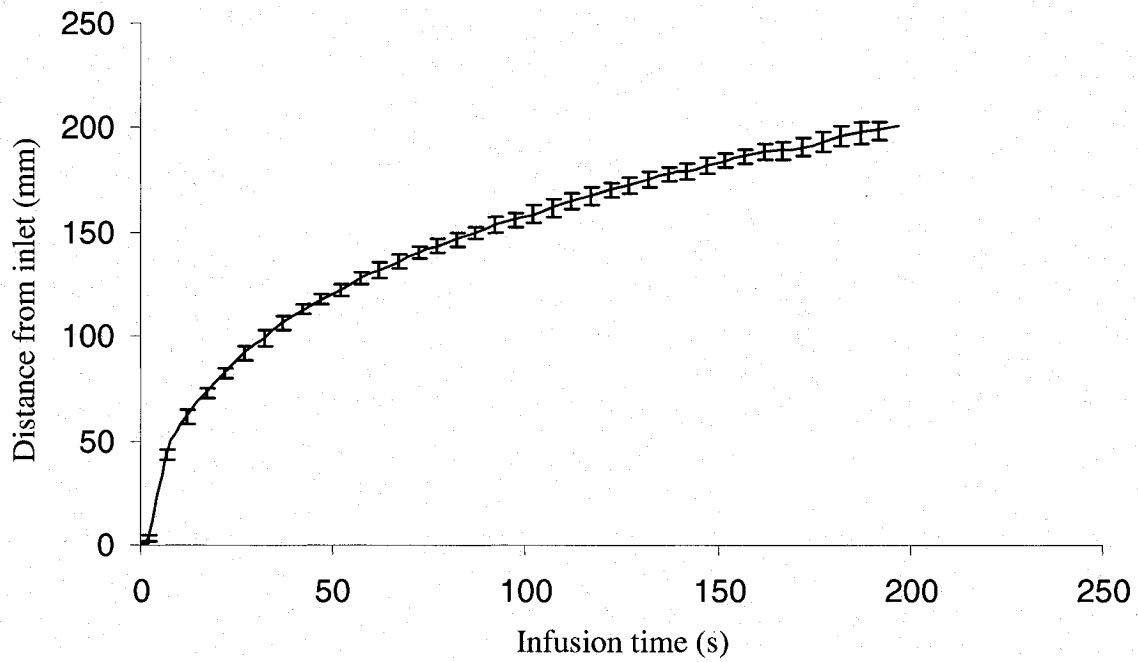


Figure B.14 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C7.

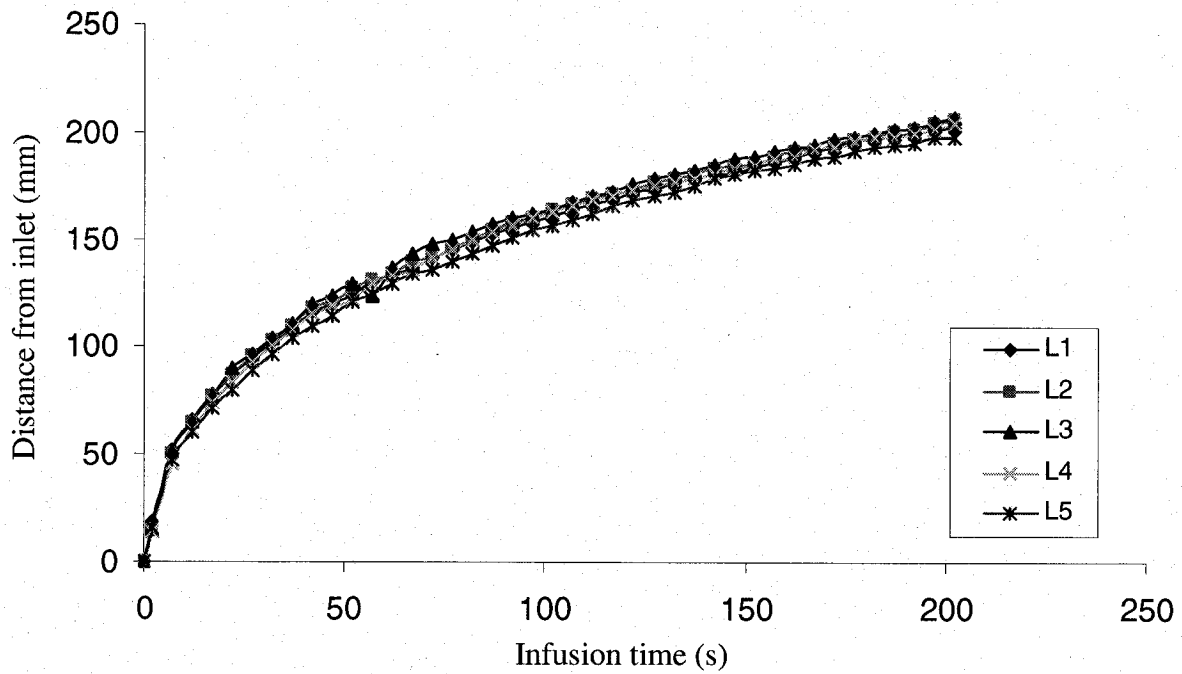


Figure B.15 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C8.

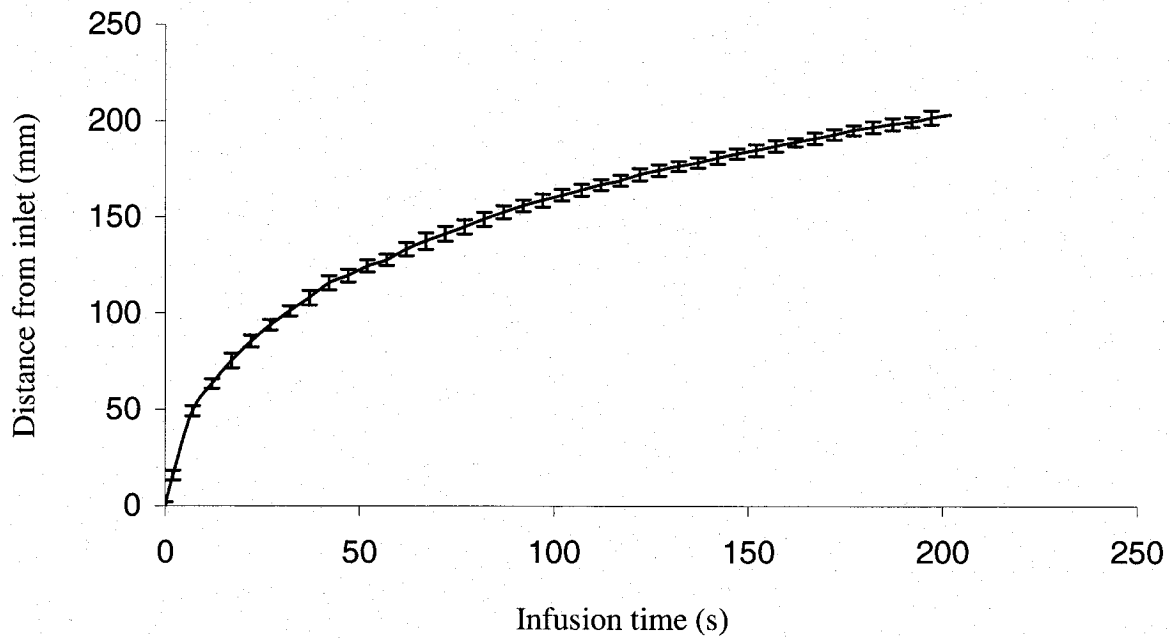


Figure B.16 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C8.

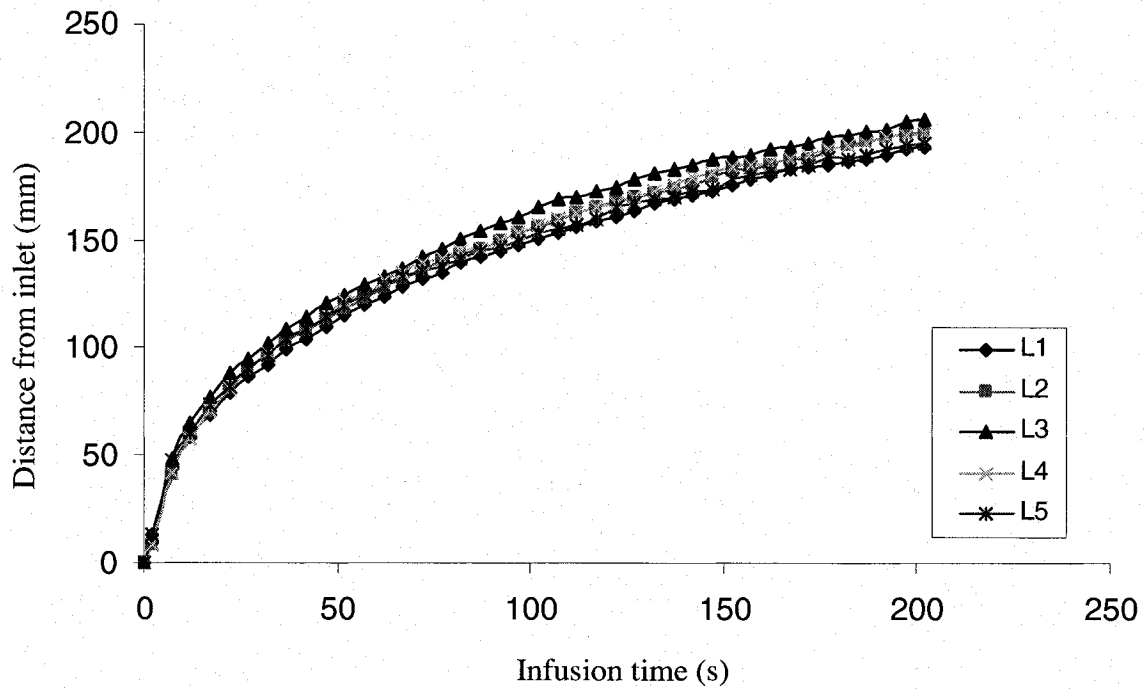


Figure B.17 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C9.

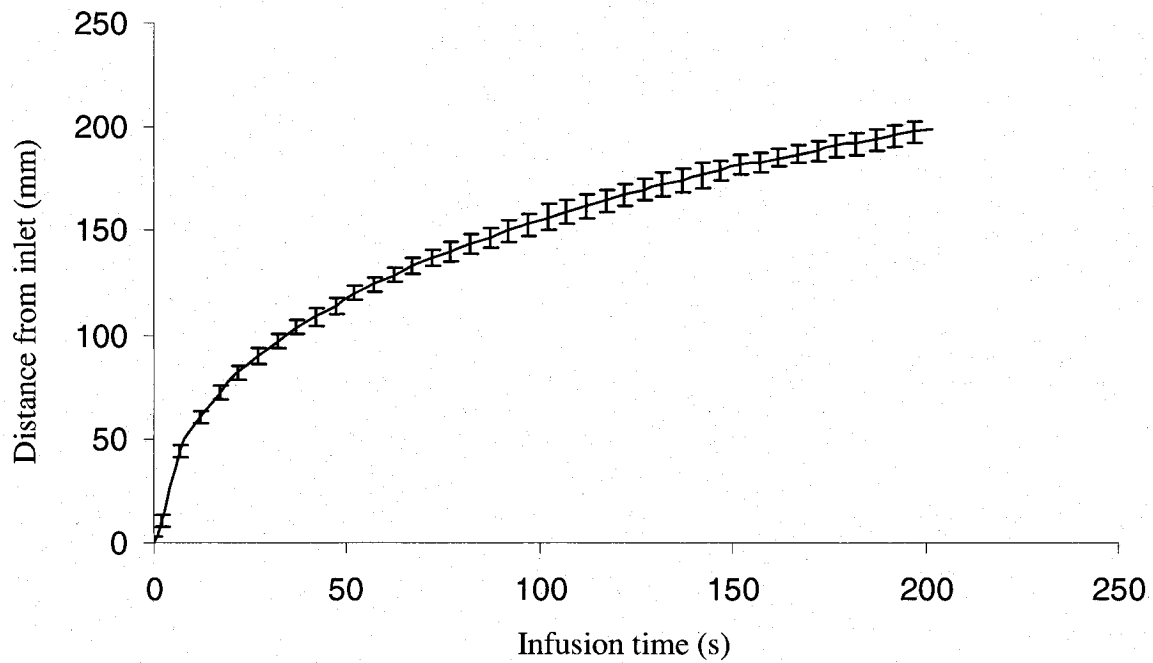


Figure B.18 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C9.

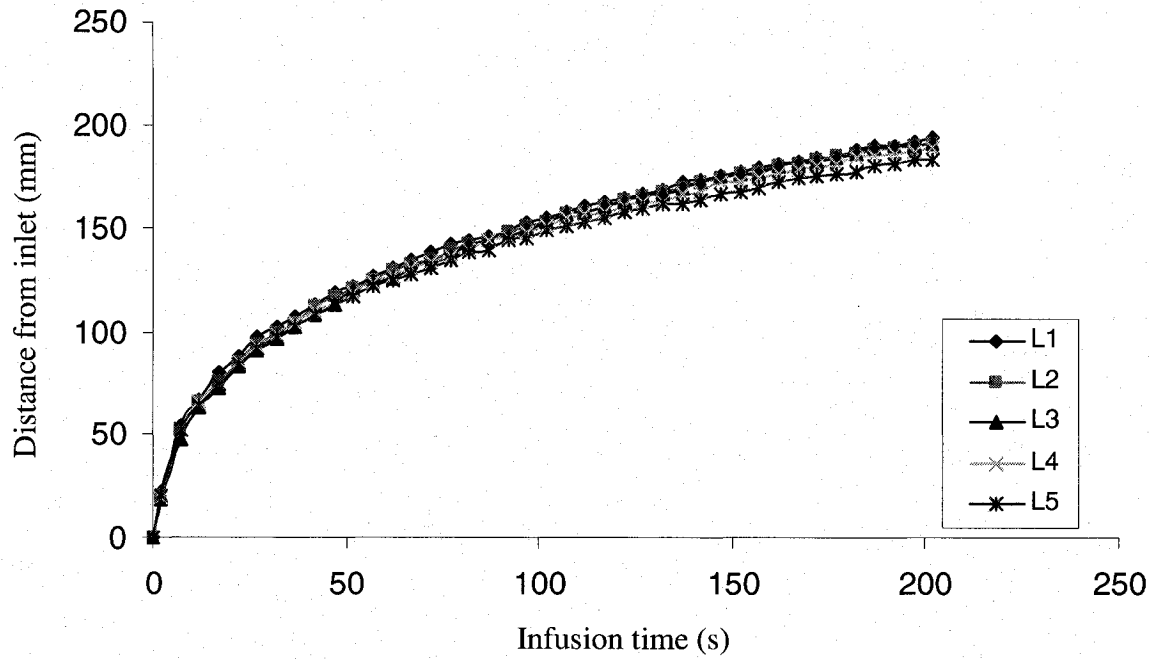


Figure B.19 Flow front position as function of time along path lines L1 to L5, random matt reinforcement R1, configuration C10.

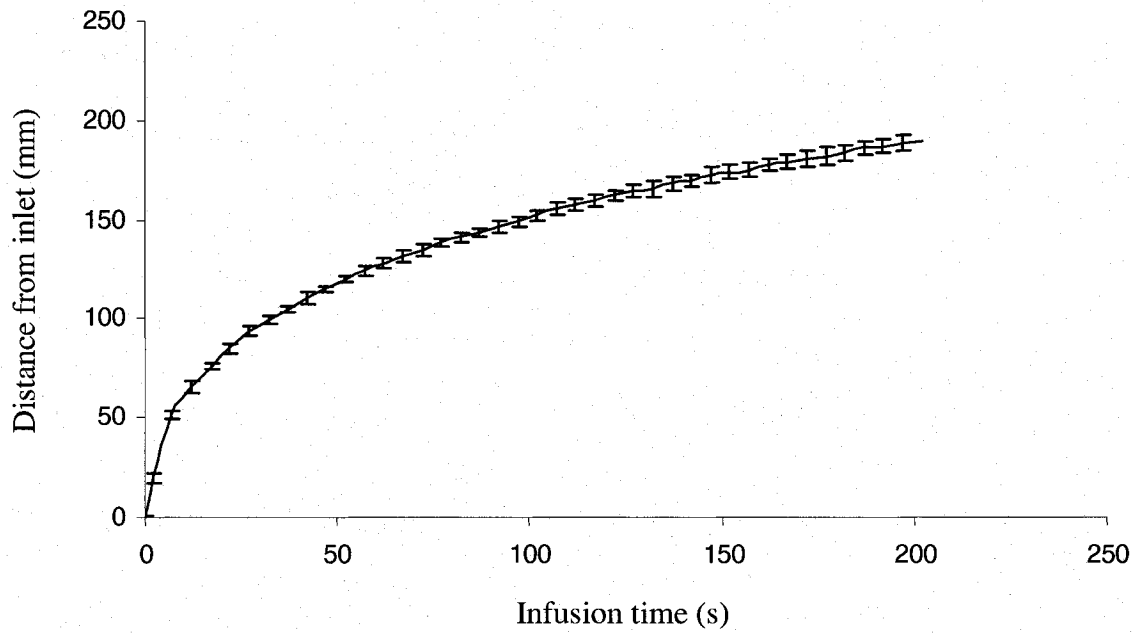


Figure B.20 Average flow front position as function of time and standard deviation on position, random matt reinforcement R1, configuration C10.

Appendix C

**Experimental data for Flow front position as function of time,
woven reinforcement R2.**

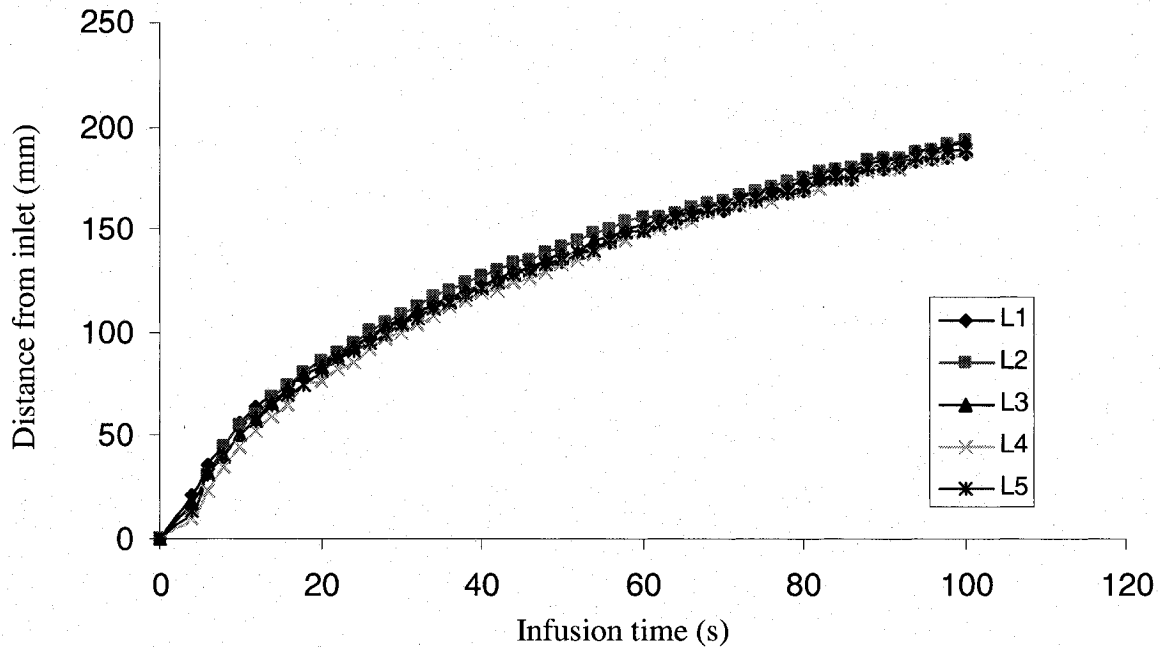


Figure C.1 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C1.

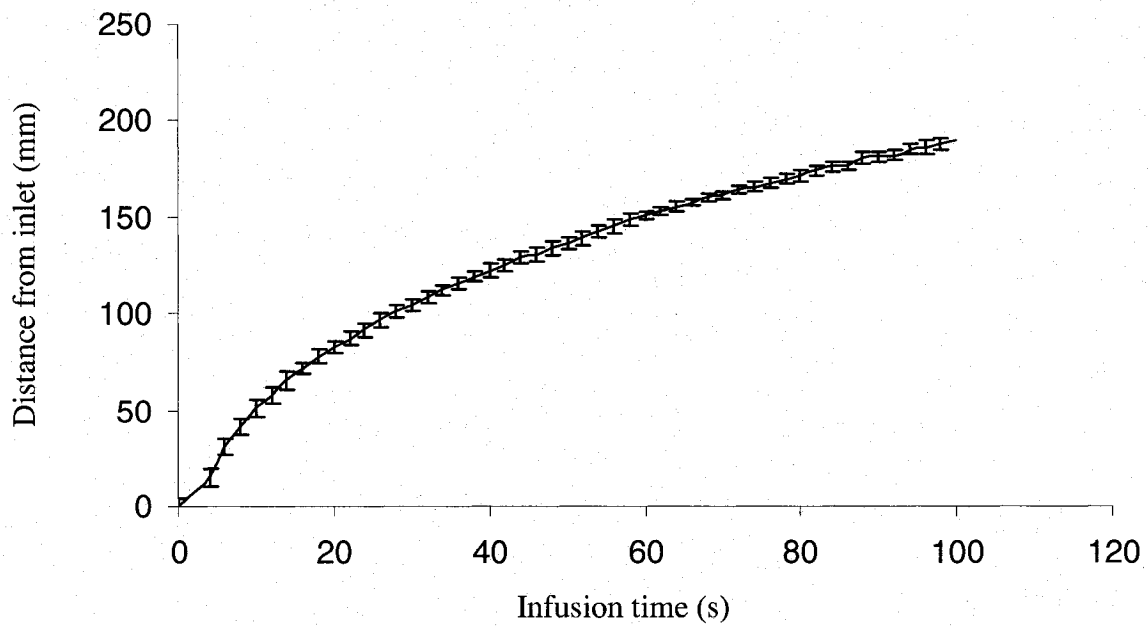


Figure C.2 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C1.

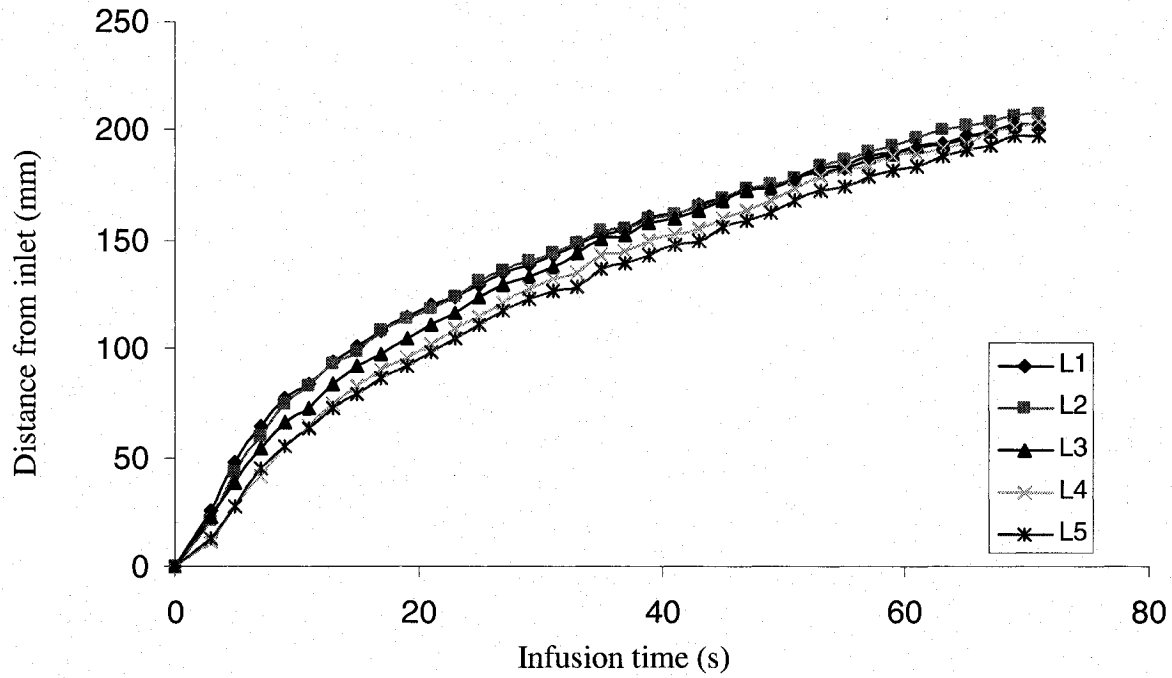


Figure C.3 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C2.

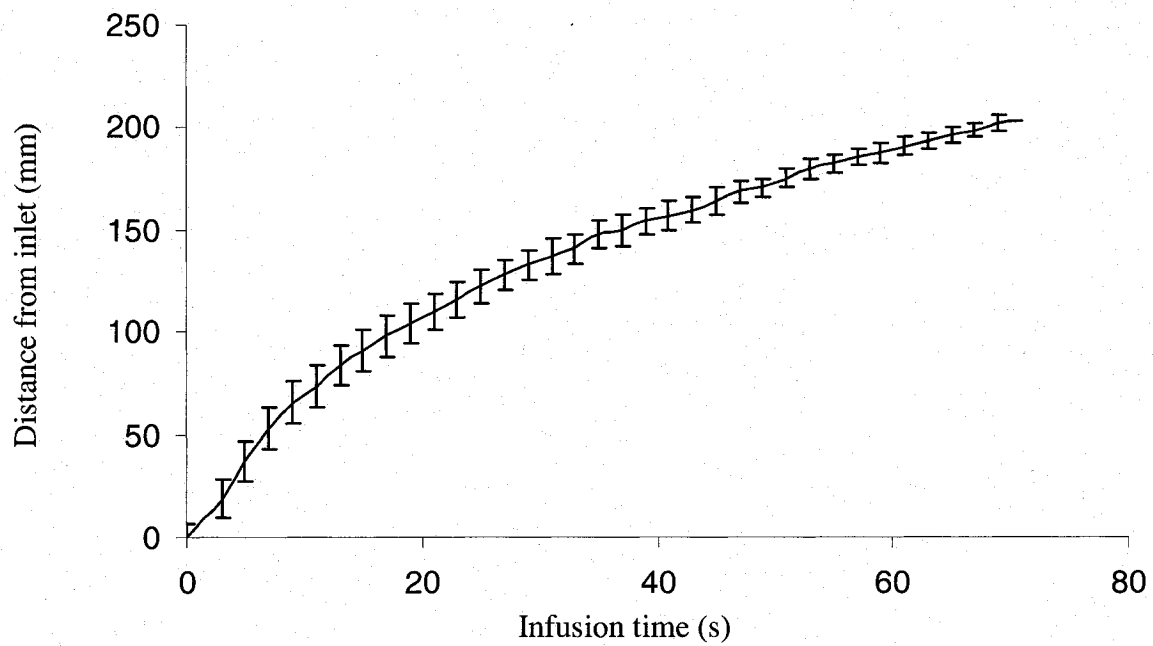


Figure C.4 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C2.

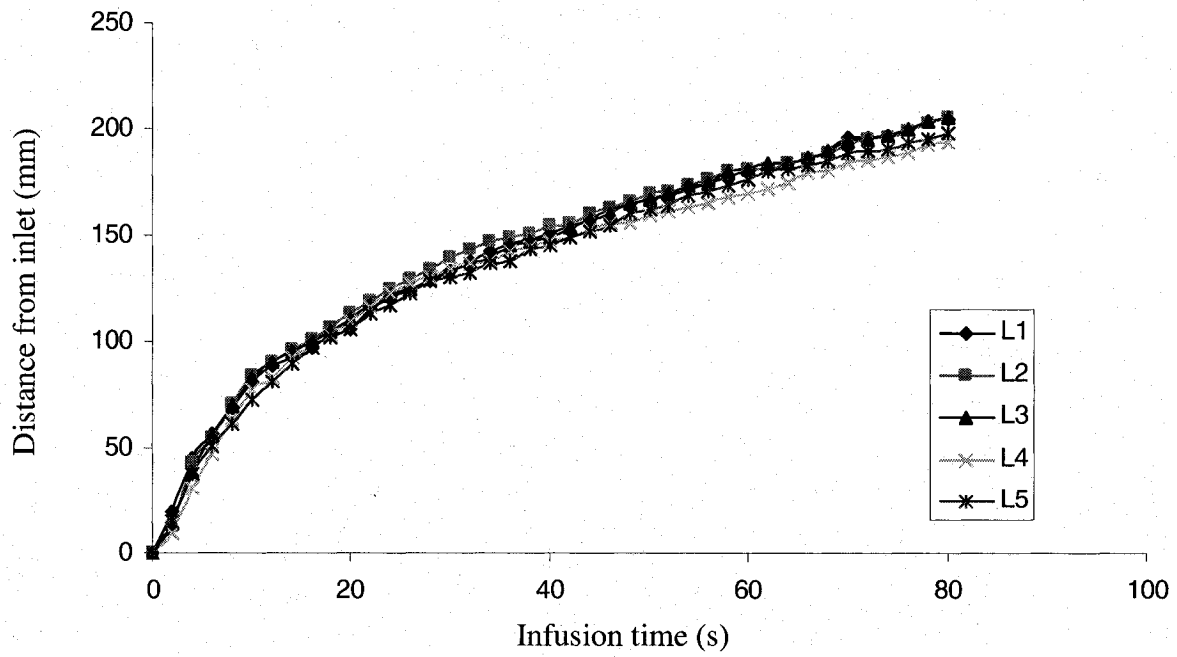


Figure C.5 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C3.

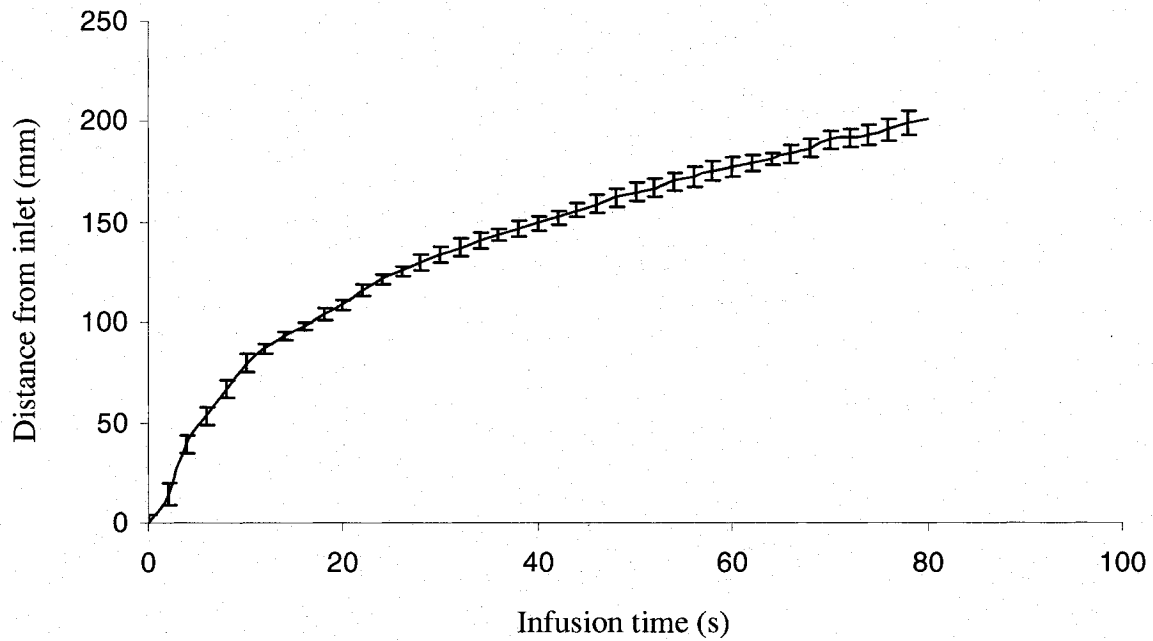


Figure C.6 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C3.

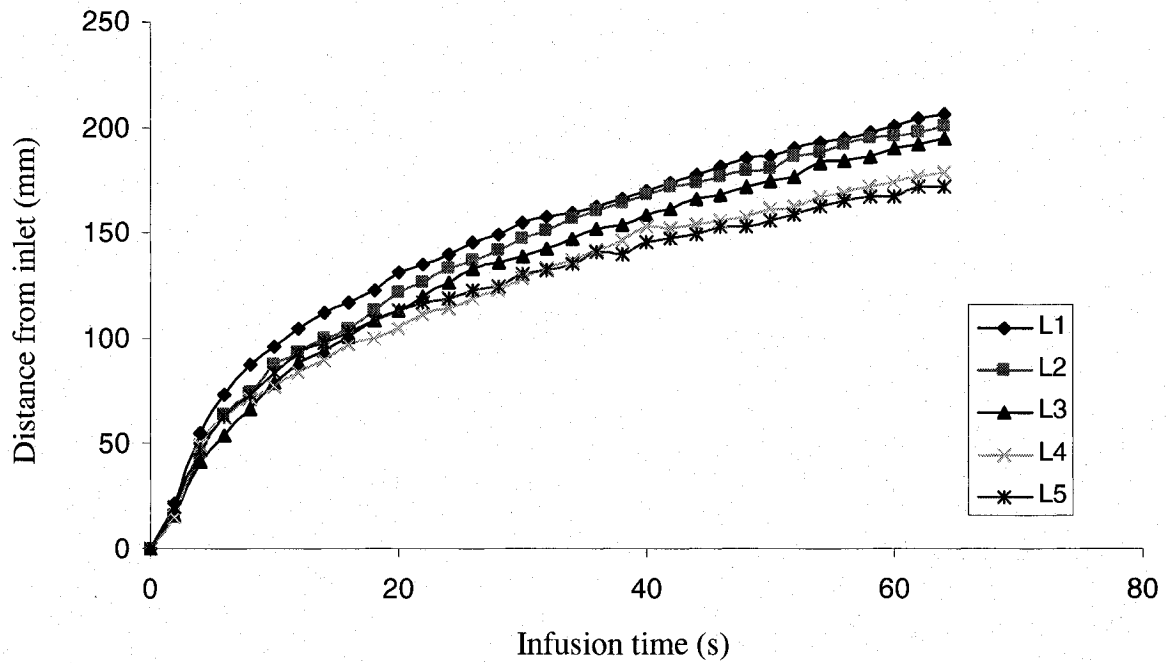


Figure C.7 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C4.

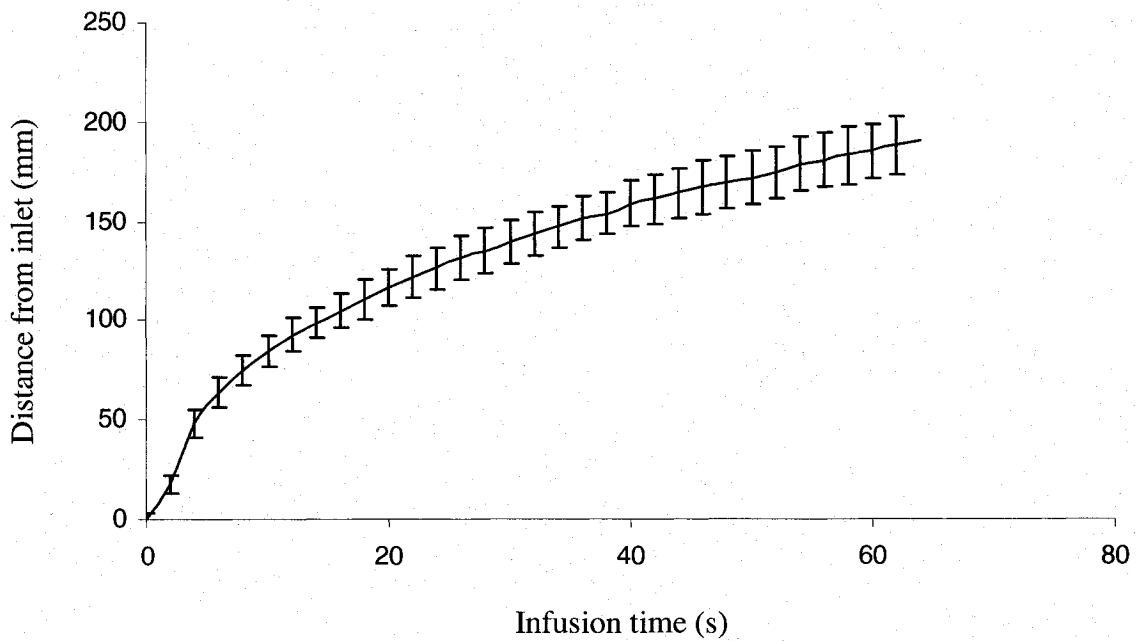


Figure C.8 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C4.

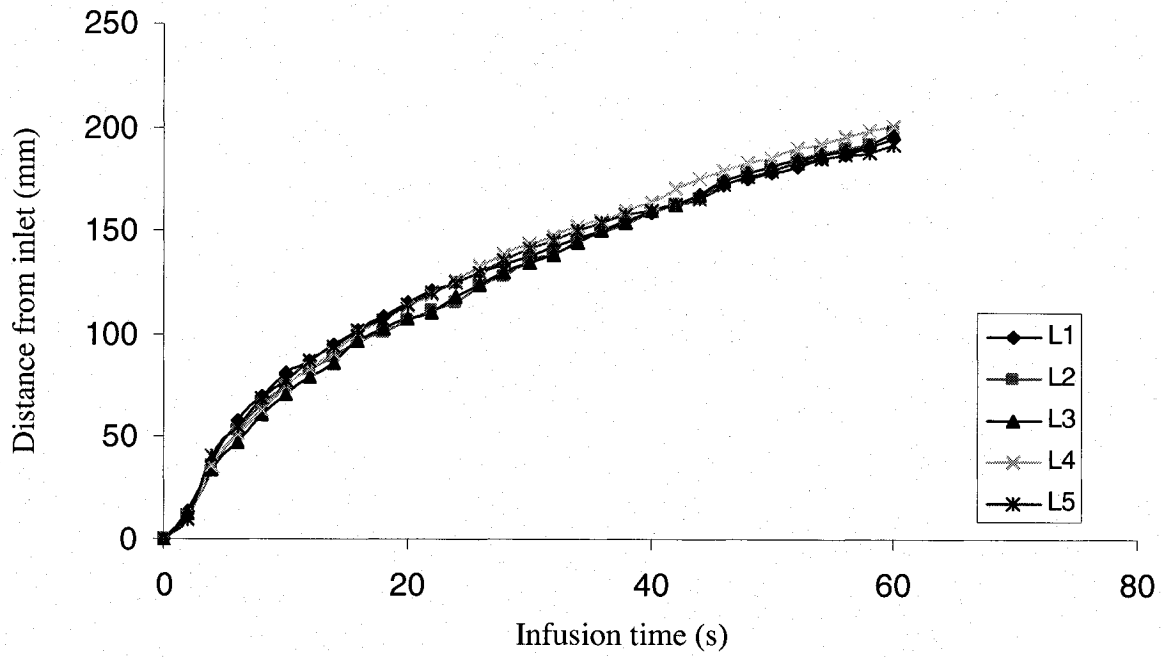


Figure C.9 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C5.

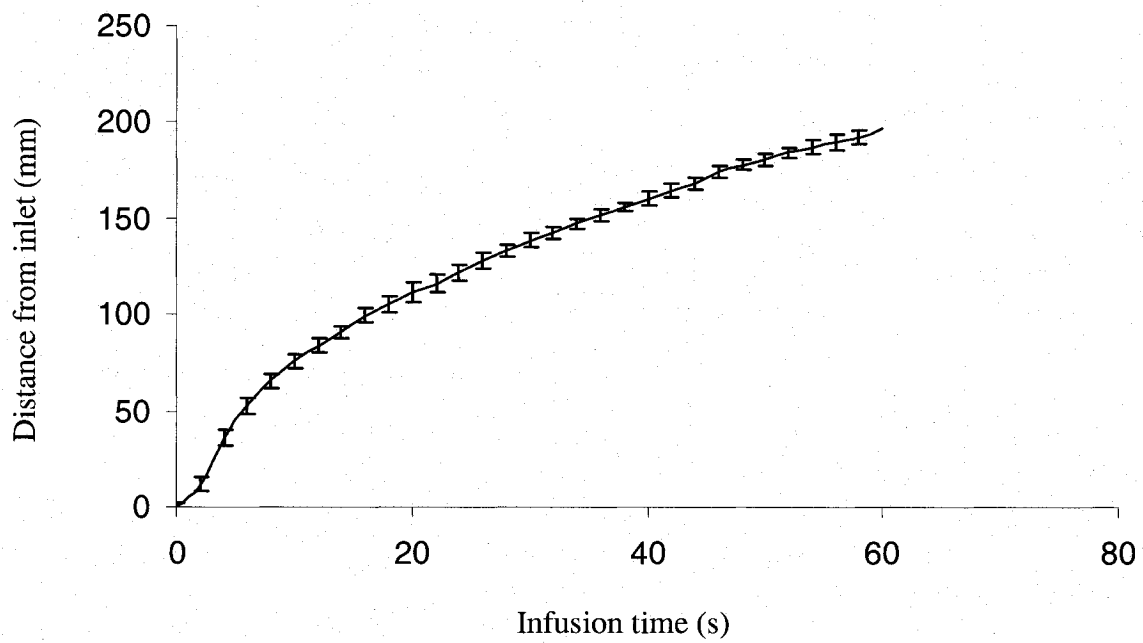


Figure C.10 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C5.

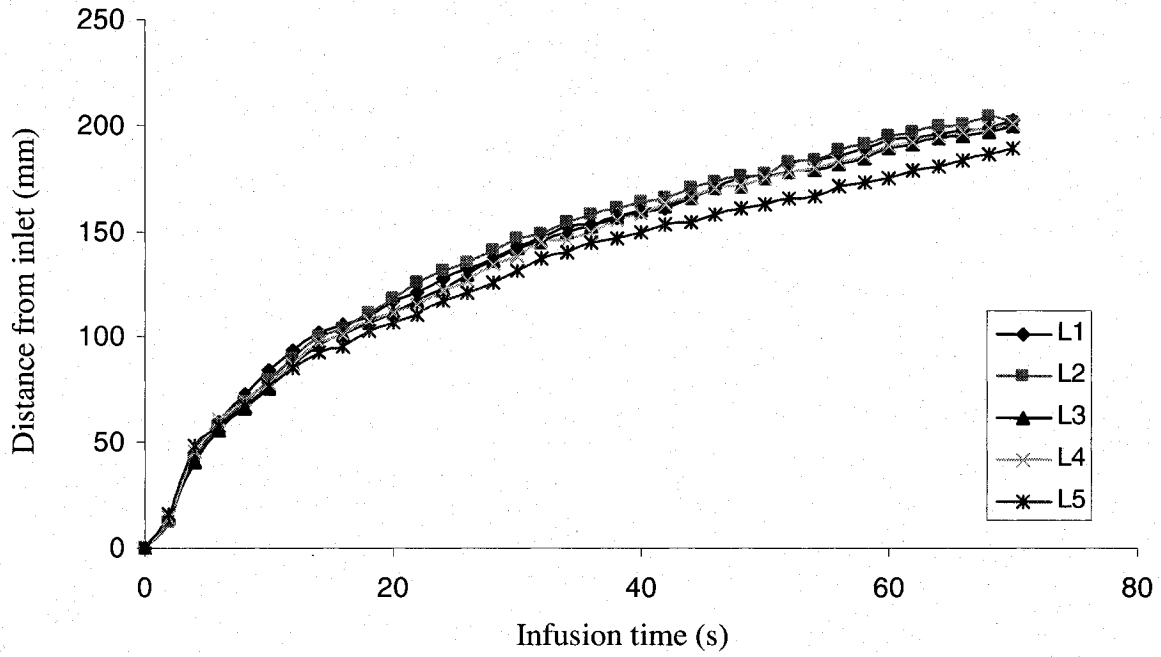


Figure C.11 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C6.

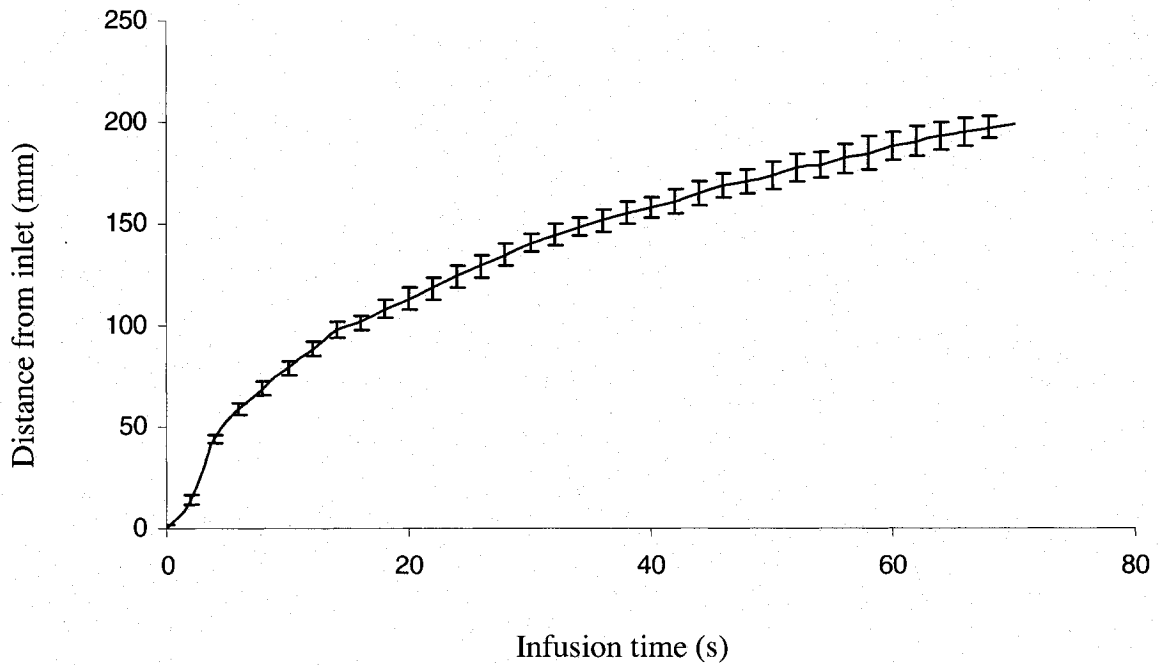


Figure C.12 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C6.

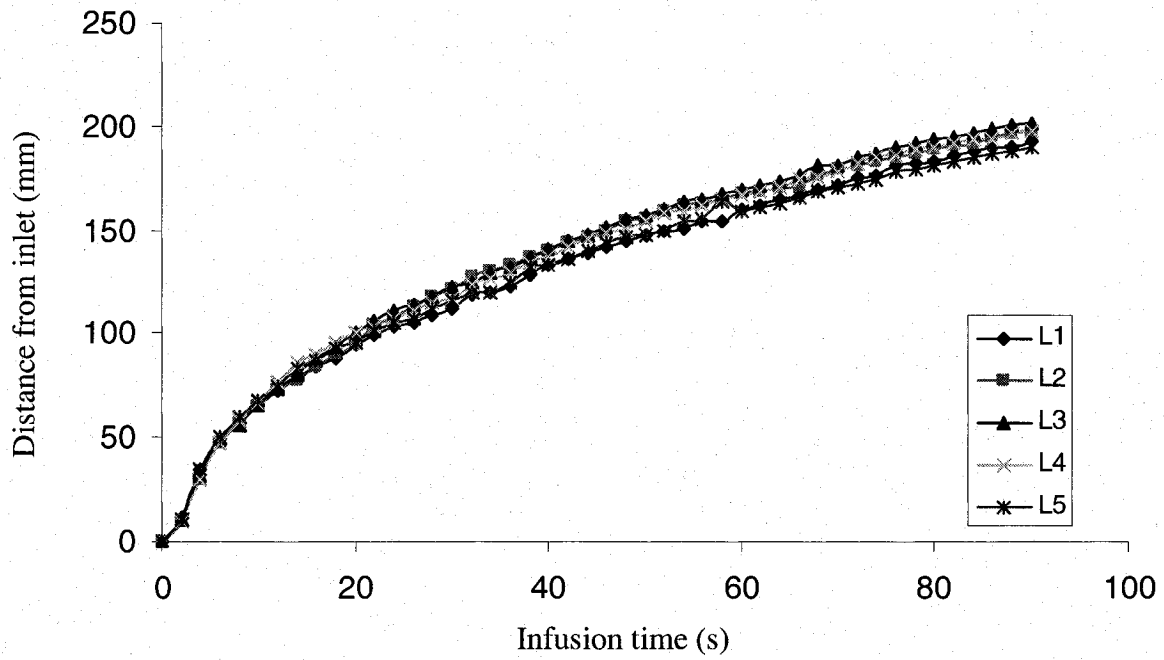


Figure C.13 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C7.

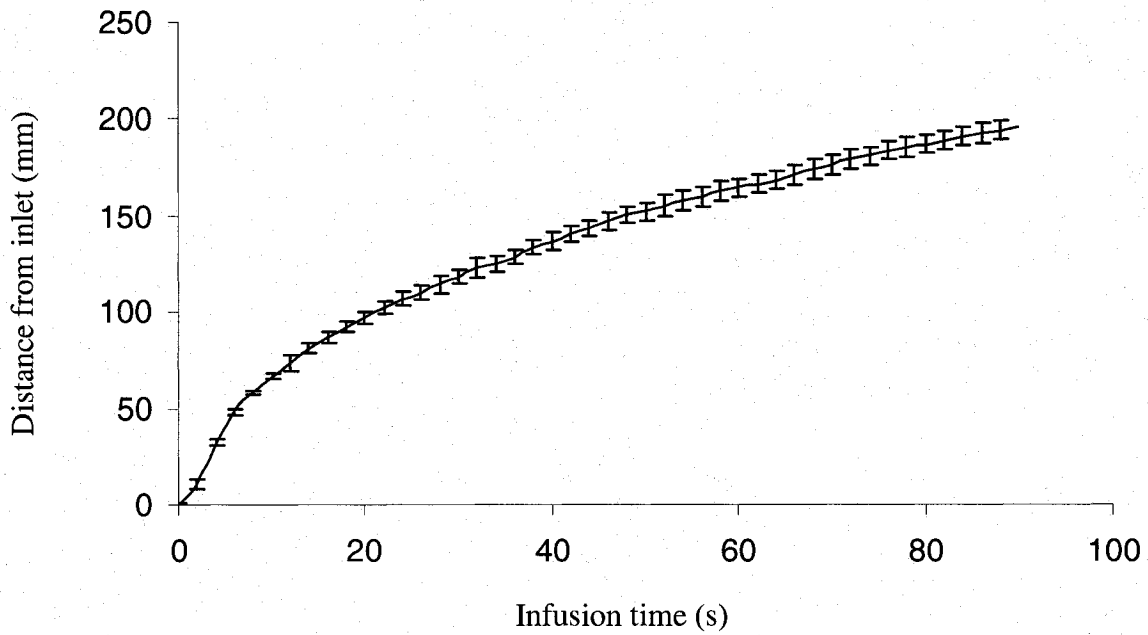


Figure C.14 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C7.

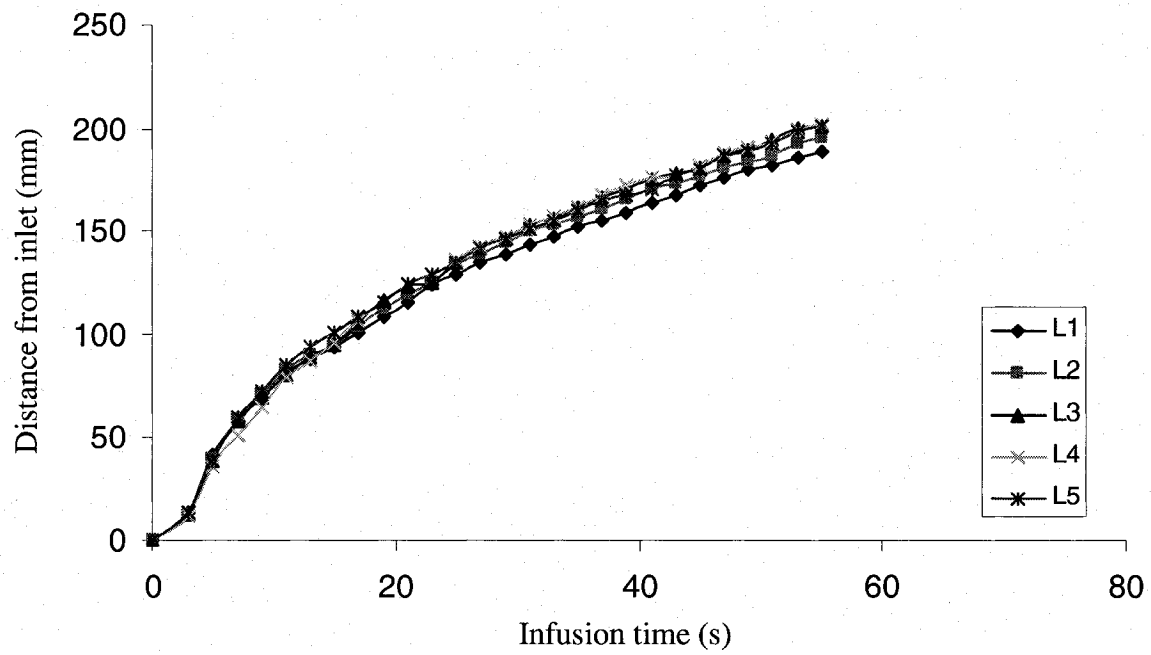


Figure C.15 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C8.

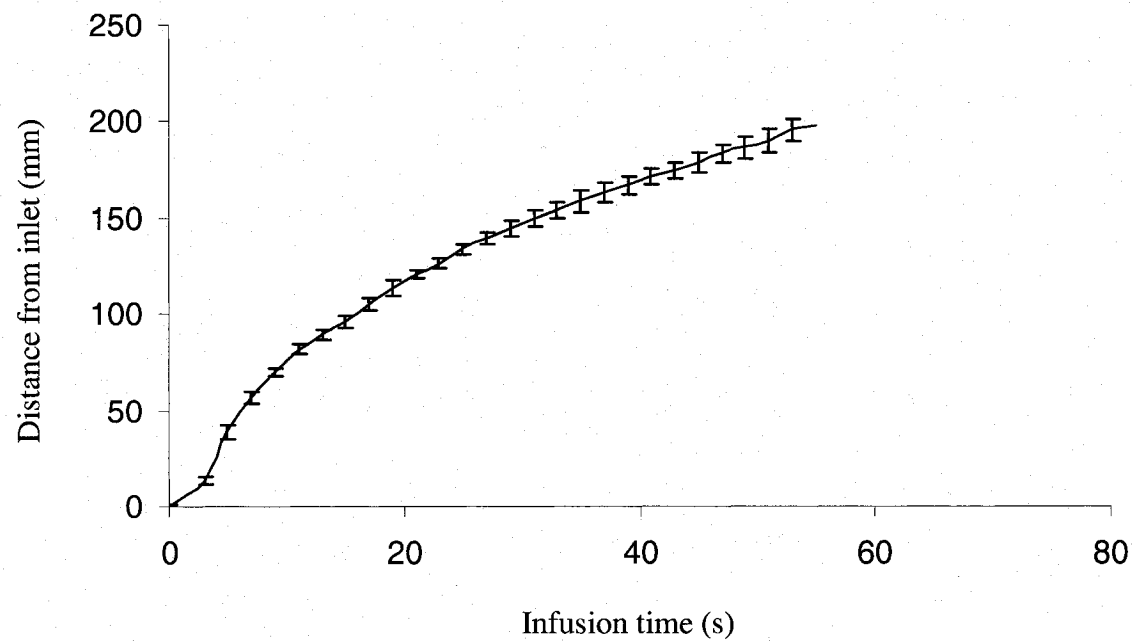


Figure C.16 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C8.

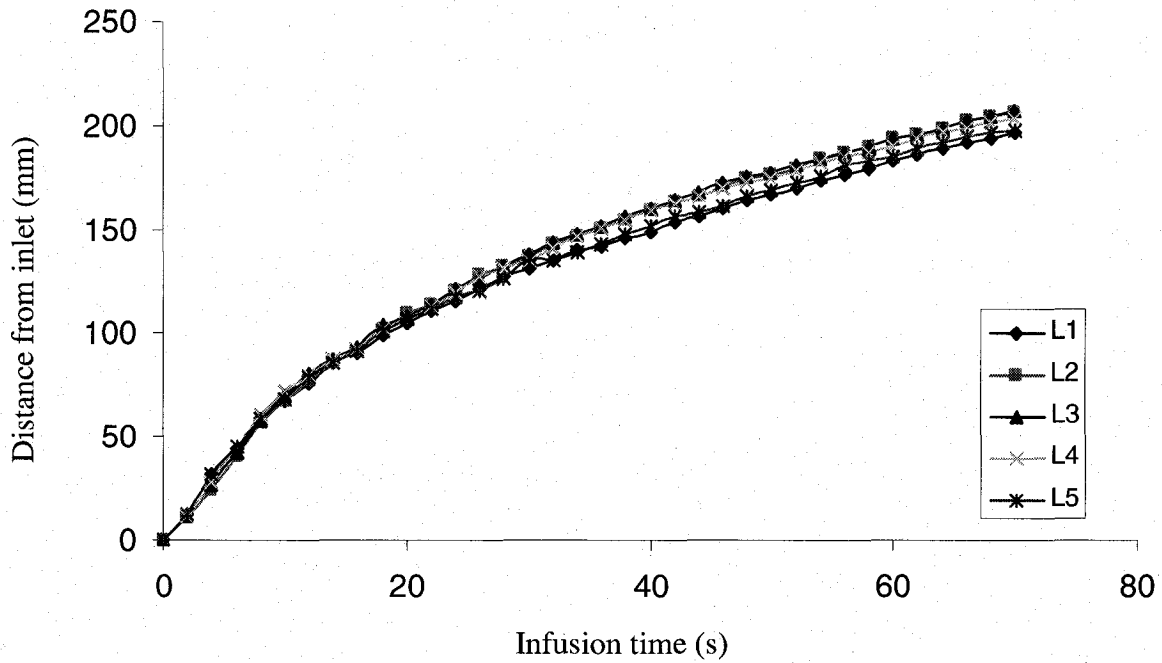


Figure C.17 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C9.

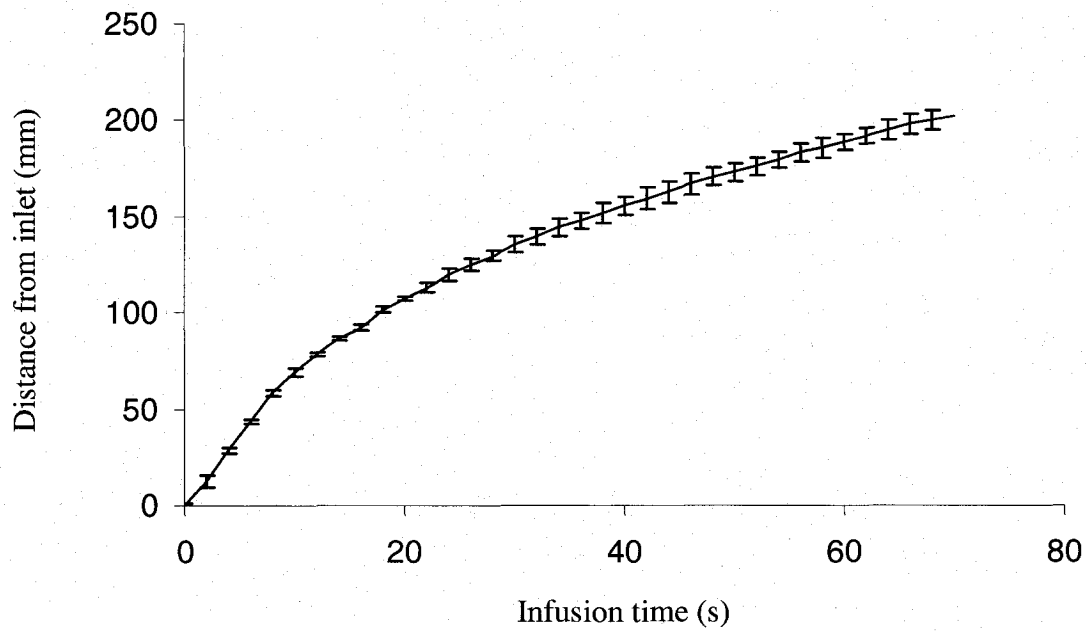


Figure C.18 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C9.

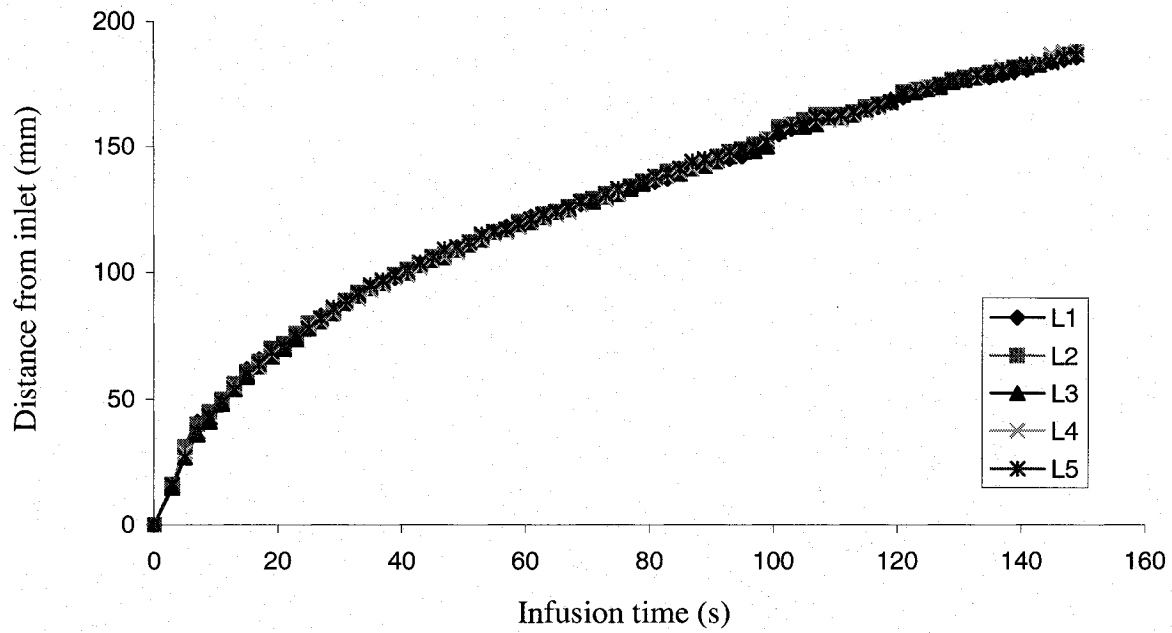


Figure C.19 Flow front position as function of time along path lines L1 to L5, woven reinforcement R2, configuration C10.

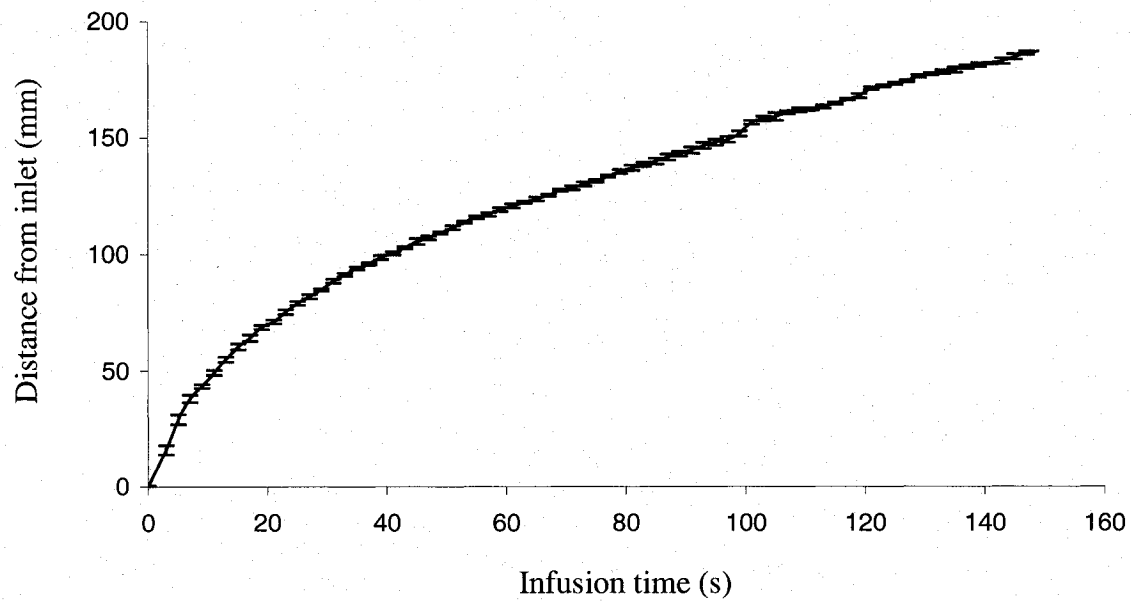
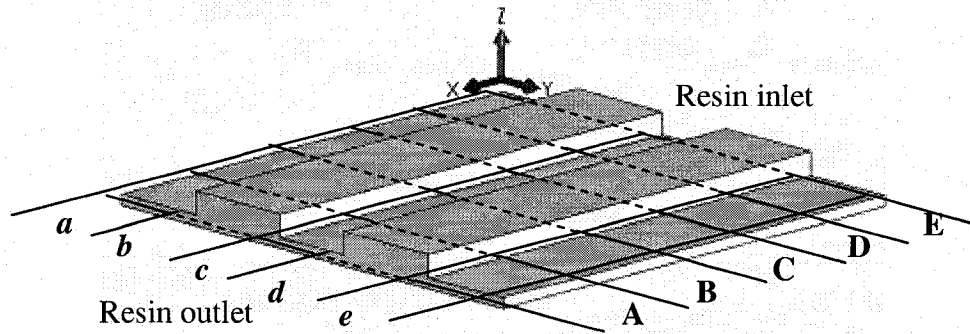
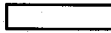


Figure C.20 Average flow front position as function of time and standard deviation on position, woven reinforcement R2, configuration C10.

Appendix D

**Thickness of cured test panels and specimens for
random matt reinforcement R1 and woven reinforcement R2.**



 Joint overlap, 24 layers of reinforcement.
 Preform away from overlaps, 12 layers of reinforcement.
A, B, C Label of specimen.
a, b, c Zone of thickness measurements; 5 measurements per zones, average reported.

Joint overlap, 24 layers of reinforcement.
 Preform away from overlaps, 12 layers of reinforcement.
 Label of specimen.
 Zone of thickness measurements; 5 measurements per zones, average reported.

Table D. 1 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C1.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.11	7.42	5.13	7.49	5.19
B	5.17	7.69	5.13	7.92	5.35
C	5.34	8.01	5.17	8.27	5.53
D	5.47	8.46	5.87	8.51	5.79
E	5.76	8.82	6.01	8.72	5.95

Table D. 2 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C2.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.58	8.03	5.44	7.98	5.46
B	5.60	8.14	5.60	8.27	5.57
C	5.92	8.37	5.95	8.27	5.72
D	6.13	8.68	6.11	8.68	6.04
E	6.50	9.00	6.44	9.00	6.38

Table D. 3 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C3.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.15	7.33	5.27	7.78	5.25
B	5.20	7.79	5.48	8.10	5.48
C	5.58	8.20	5.50	8.35	5.71
D	5.77	8.48	5.38	8.45	6.00
E	6.01	8.81	5.93	8.81	6.27

Table D. 4 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C4.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.18	7.85	5.49	8.08	5.18
B	5.40	8.20	5.52	8.20	5.29
C	5.51	8.49	5.61	8.40	5.56
D	5.74	8.66	5.91	8.79	5.79
E	6.23	9.10	6.27	9.30	6.34

Table D. 5 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C5.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.16	8.00	5.45	8.19	5.21
B	5.37	8.18	5.45	8.01	5.56
C	5.64	8.35	5.45	8.51	5.74
D	6.04	8.72	5.93	8.81	6.01
E	6.30	9.21	6.21	9.26	6.52

Table D. 6 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C6.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.41	7.70	5.30	7.64	5.08
B	5.50	7.93	5.24	7.64	5.20
C	5.53	8.12	5.32	7.90	5.19
D	5.77	8.33	5.64	8.14	5.47
E	6.09	9.01	6.00	8.68	6.24

Table D. 7 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C7.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.26	8.00	5.46	7.80	5.23
B	5.40	8.11	5.71	7.64	5.43
C	5.41	8.11	5.74	8.02	5.46
D	5.74	8.48	5.94	8.42	5.72
E	6.09	8.71	6.38	8.81	5.89

Table D. 8 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C8.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.24	7.75	5.77	7.57	5.29
B	5.47	7.95	5.85	7.92	5.39
C	5.67	8.16	6.28	8.33	5.78
D	5.99	8.72	6.52	8.68	5.94
E	6.31	9.23	6.96	9.33	6.37

Table D. 9 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C9.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	5.56	8.28	6.03	7.89	5.27
B	5.45	8.12	6.02	8.01	5.41
C	5.45	8.30	6.29	8.04	5.56
D	5.83	8.34	6.57	8.34	5.72
E	6.28	8.59	7.06	8.65	6.64

Table D. 10 Thickness of cured test panel (mm), random matt reinforcement R1, configuration C10.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	4.88	4.73	4.89	4.91	4.89
B	5.04	5.04	5.01	5.00	5.01
C	5.20	5.20	5.09	5.09	5.21
D	5.50	5.50	5.66	5.37	5.36
E	6.01	5.80	5.72	5.66	5.77

Table D. 11 Thickness of cured test panel (mm), woven reinforcement R2, configuration C1.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.74	4.44	3.74	5.45	3.67
B	3.74	4.46	3.76	5.57	3.75
C	3.76	5.46	3.77	5.56	3.73
D	3.79	5.57	3.80	5.60	3.77
E	3.80	5.61	3.81	5.60	3.81

Table D. 12 Thickness of cured test panel (mm), woven reinforcement R2, configuration C2.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.64	5.31	3.51	5.28	3.51
B	3.69	5.33	3.60	5.33	3.60
C	3.66	5.41	3.69	5.41	3.64
D	3.73	5.41	3.72	5.33	3.63
E	3.77	5.46	3.70	5.50	3.65

Table D. 13 Thickness of cured test panel (mm), woven reinforcement R2, configuration C3.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.75	5.33	3.70	5.48	3.67
B	3.69	5.39	3.71	5.52	3.79
C	3.70	5.53	3.72	5.61	3.70
D	3.78	5.60	3.80	5.63	3.71
E	3.78	5.73	3.81	5.61	3.67

Table D. 14 Thickness of cured test panel (mm), woven reinforcement R2, configuration C4.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.57	5.44	3.76	4.45	3.19
B	3.60	5.58	3.72	5.45	3.50
C	3.84	5.56	3.75	5.40	3.49
D	3.73	5.49	3.78	5.51	3.70
E	3.88	5.58	3.70	5.49	3.78

Table D. 15 Thickness of cured test panel (mm), woven reinforcement R2, configuration C5.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.68	5.20	3.55	5.27	3.82
B	3.54	5.24	3.56	4.28	3.45
C	3.59	5.39	3.70	5.47	3.55
D	3.71	5.30	3.68	5.25	3.56
E	3.70	5.42	3.60	5.40	3.49

Table D. 16 Thickness of cured test panel (mm), woven reinforcement R2, configuration C6.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.44	5.21	3.56	5.37	3.44
B	3.46	5.31	3.58	5.39	3.55
C	3.53	5.37	3.71	5.48	3.62
D	3.65	5.58	3.77	5.47	3.74
E	3.80	5.53	3.91	5.71	3.85

Table D. 17 Thickness of cured test panel (mm), woven reinforcement R2, configuration C7.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.68	5.40	3.99	5.32	3.74
B	3.69	5.45	4.03	5.37	3.79
C	3.71	5.43	4.04	5.34	3.79
D	3.76	4.49	4.16	5.40	3.74
E	3.73	5.50	4.17	5.54	3.81

Table D. 18 Thickness of cured test panel (mm), woven reinforcement R2, configuration C8.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.61	5.44	3.93	5.49	3.62
B	3.69	5.62	3.99	5.60	3.65
C	3.70	5.50	3.96	5.60	3.72
D	3.71	5.39	3.94	5.46	3.65
E	3.75	5.52	3.87	5.57	3.72

Table D. 19 Thickness of cured test panel (mm), woven reinforcement R2, configuration C9.

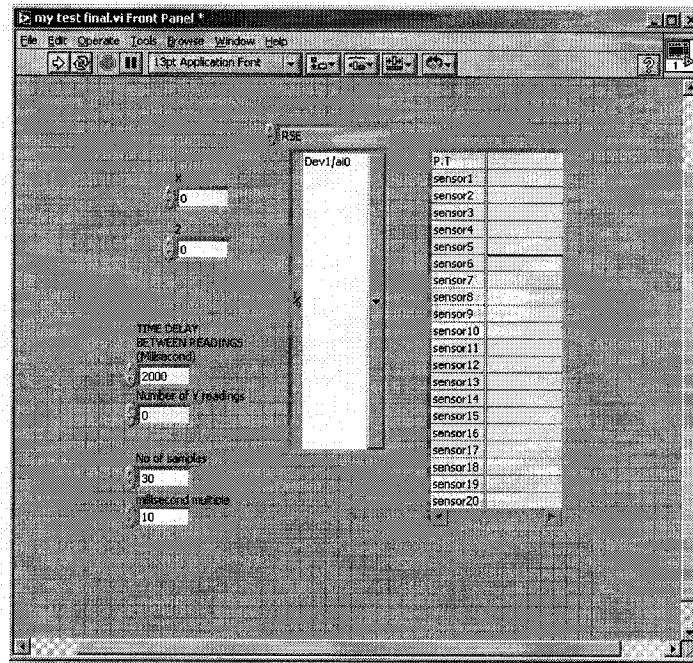
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.54	5.41	3.99	5.39	3.56
B	3.49	5.40	4.05	5.41	3.62
C	3.50	5.34	4.11	5.39	3.67
D	3.70	5.37	4.20	5.52	3.72
E	3.71	5.44	4.20	5.44	3.77

Table D. 20 Thickness of cured test panel (mm), woven reinforcement R2, configuration C10.

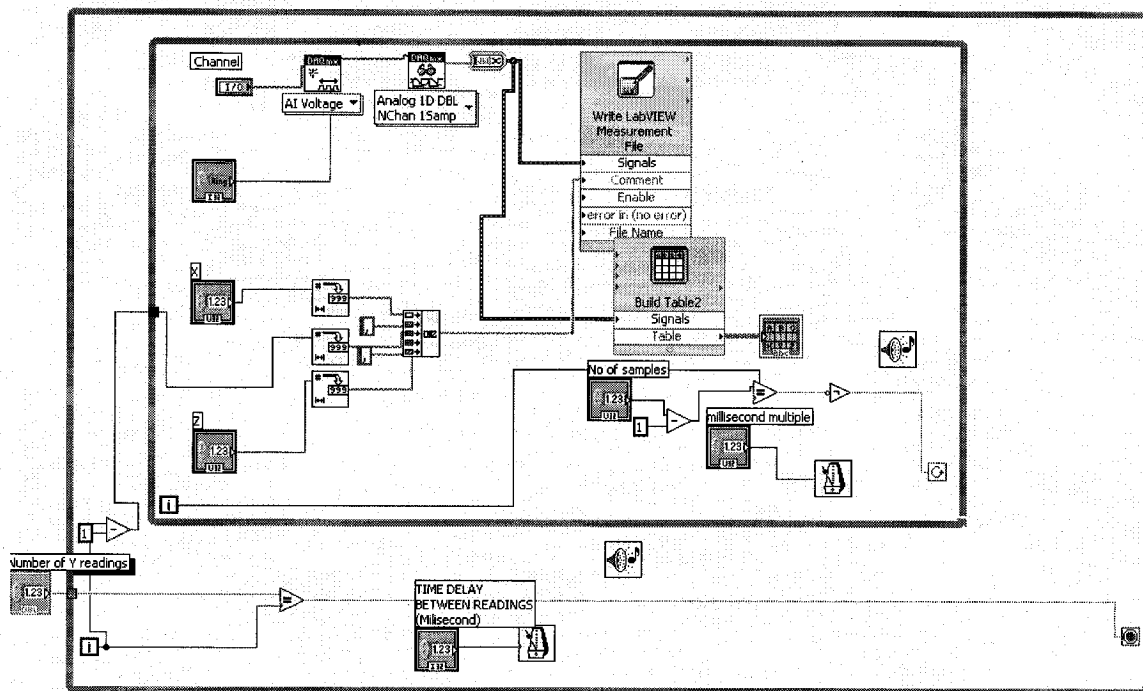
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
A	3.47	3.46	3.43	3.48	3.42
B	3.50	3.46	3.56	3.49	3.50
C	3.49	3.51	3.55	3.46	3.53
D	3.61	3.62	3.59	3.57	3.62
E	3.70	3.71	3.79	3.63	3.82

Appendix E

Labview software package interfaces

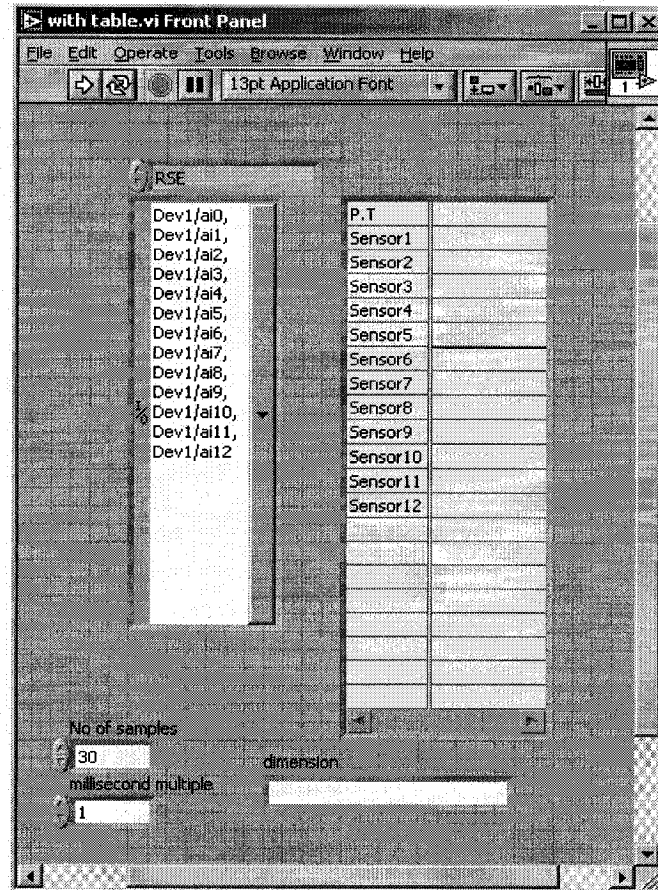


a)

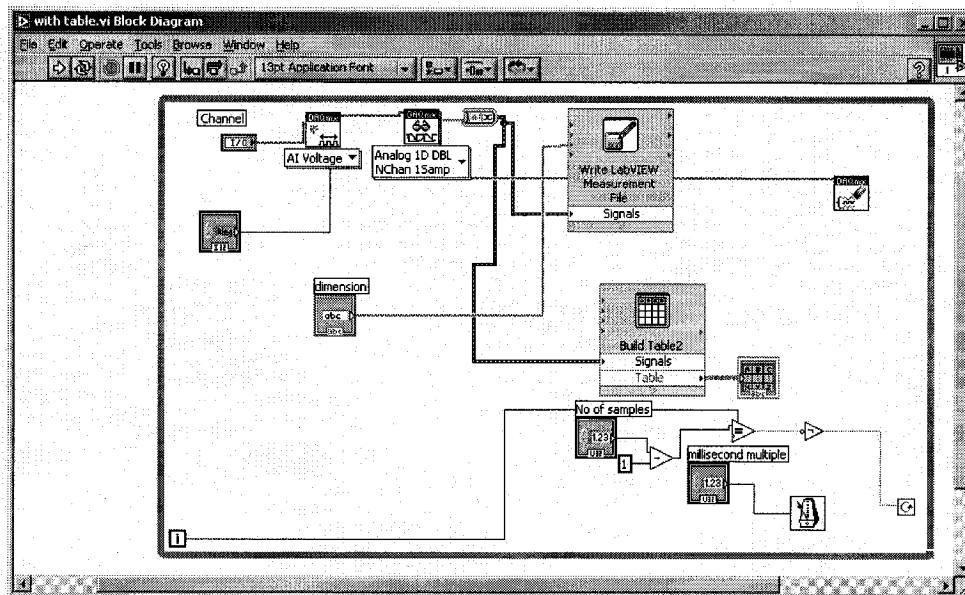


b)

Figure E. 1 Used Labview software package interfaces to measure sensitivity of sensors to height in the magnetic filed.



a)



b)

Figure E. 2 Used Labview software package interfaces a and b, to measure compaction of reinforcements R1 and R2 over the lap joints.

Appendix F

Load as a function of loading point deflection for random matt reinforcement R1 and woven reinforcement R2.

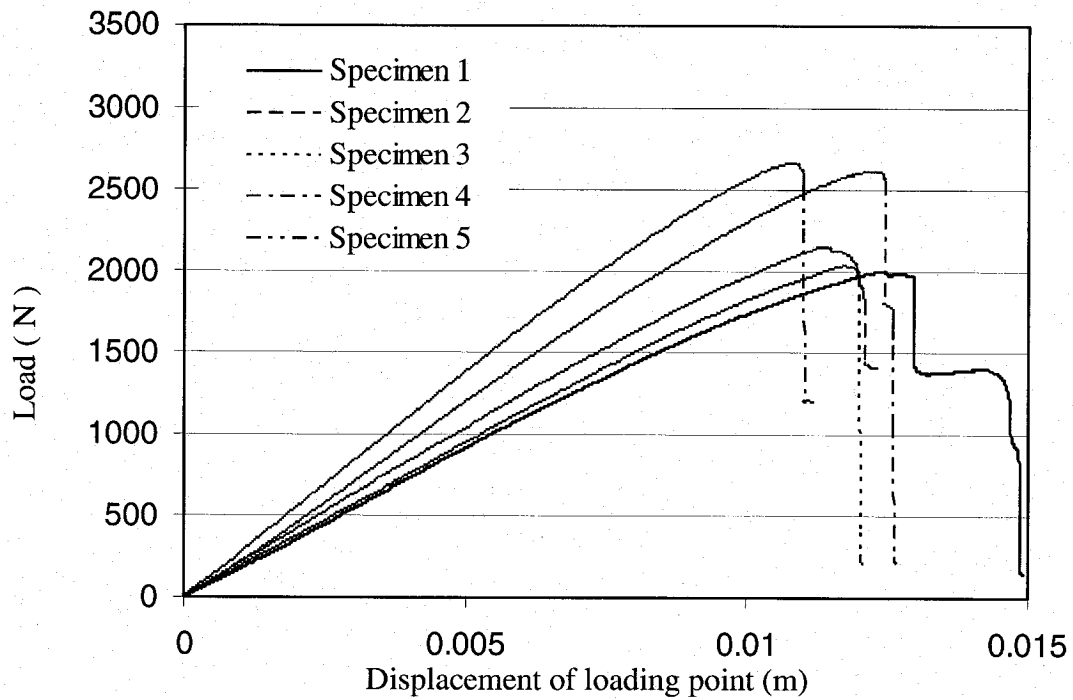


Figure F.1 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C1.

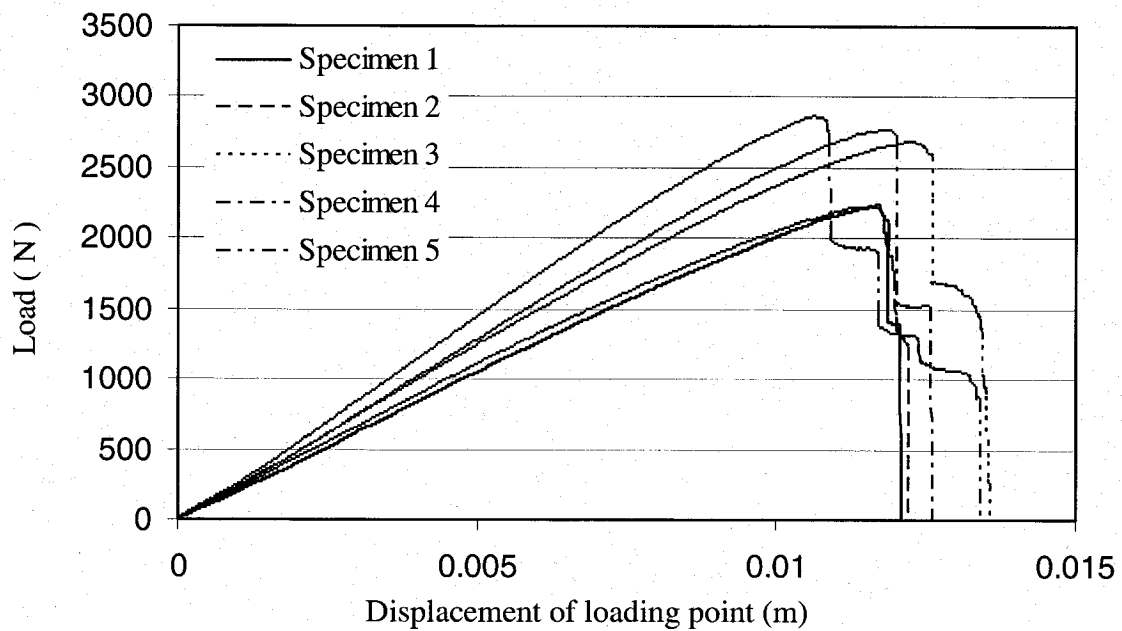


Figure F.2 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C2.

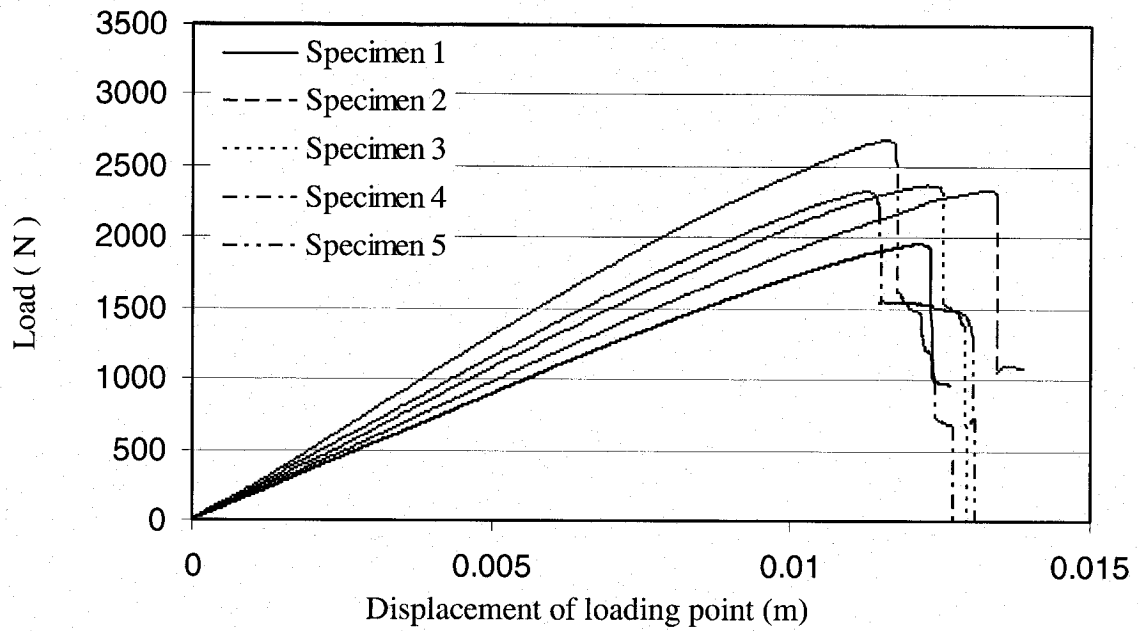


Figure F.3 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C3.

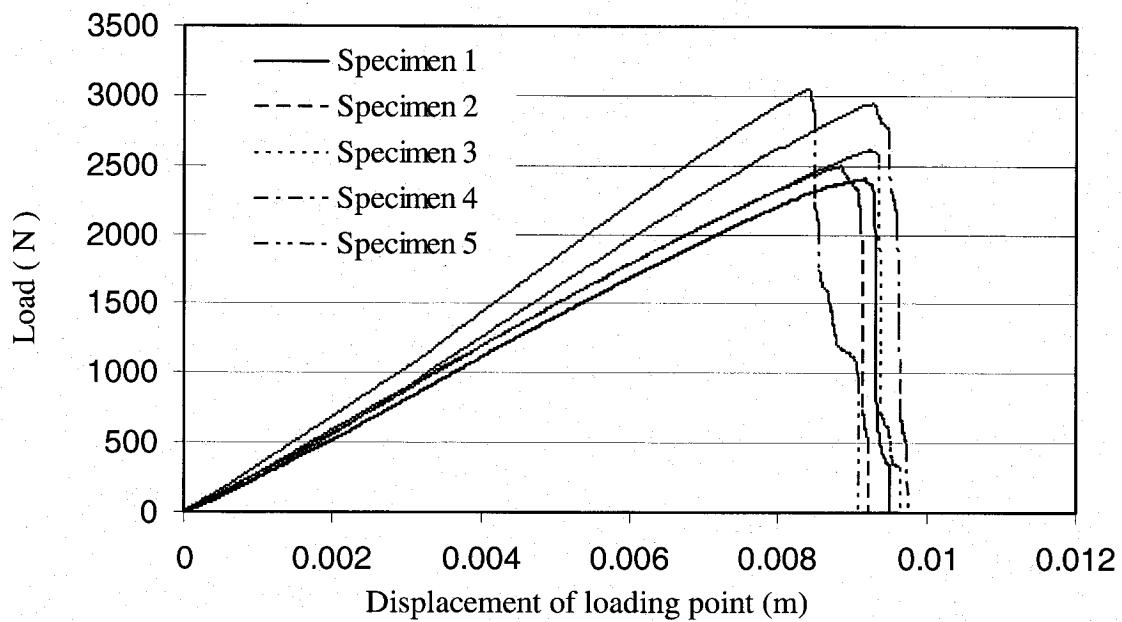


Figure F.4 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C4.

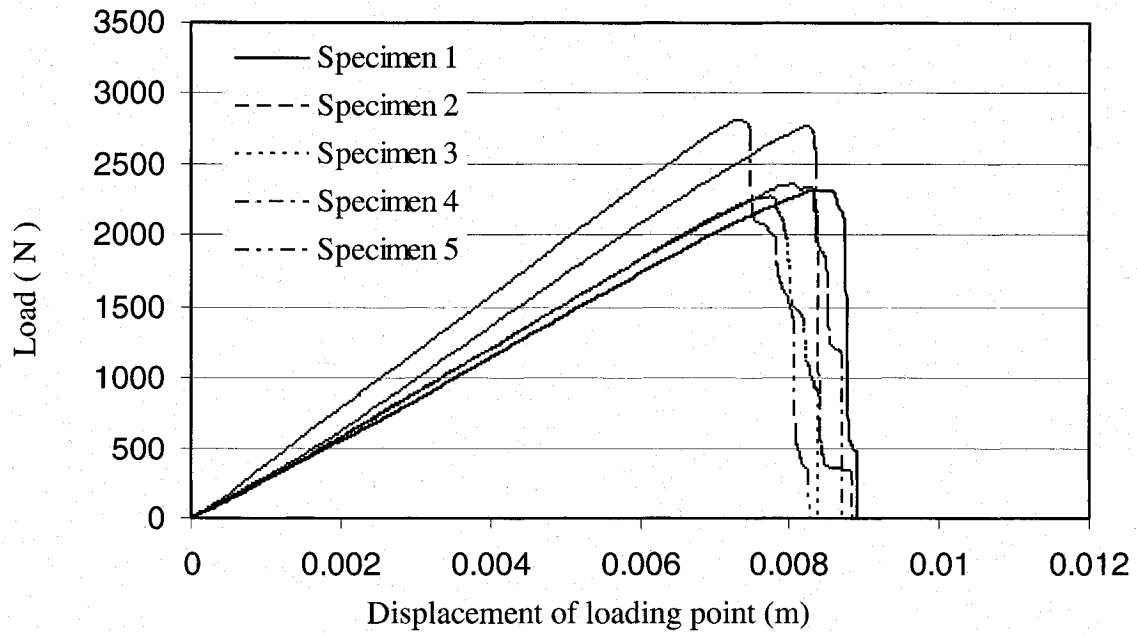


Figure F.5 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C5.

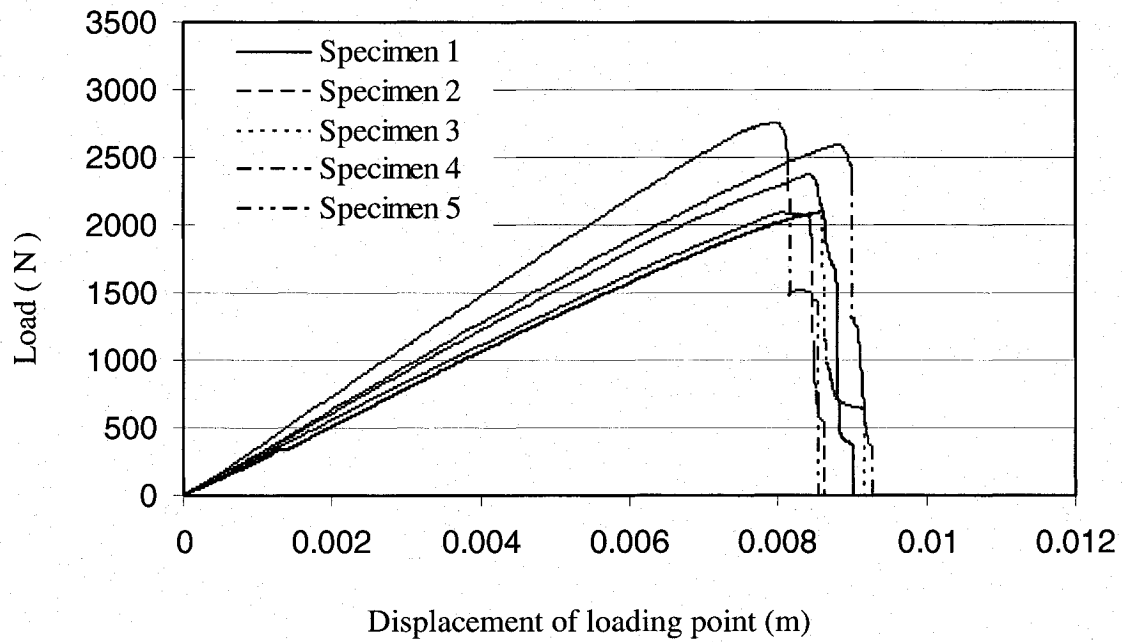


Figure F.6 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C6.

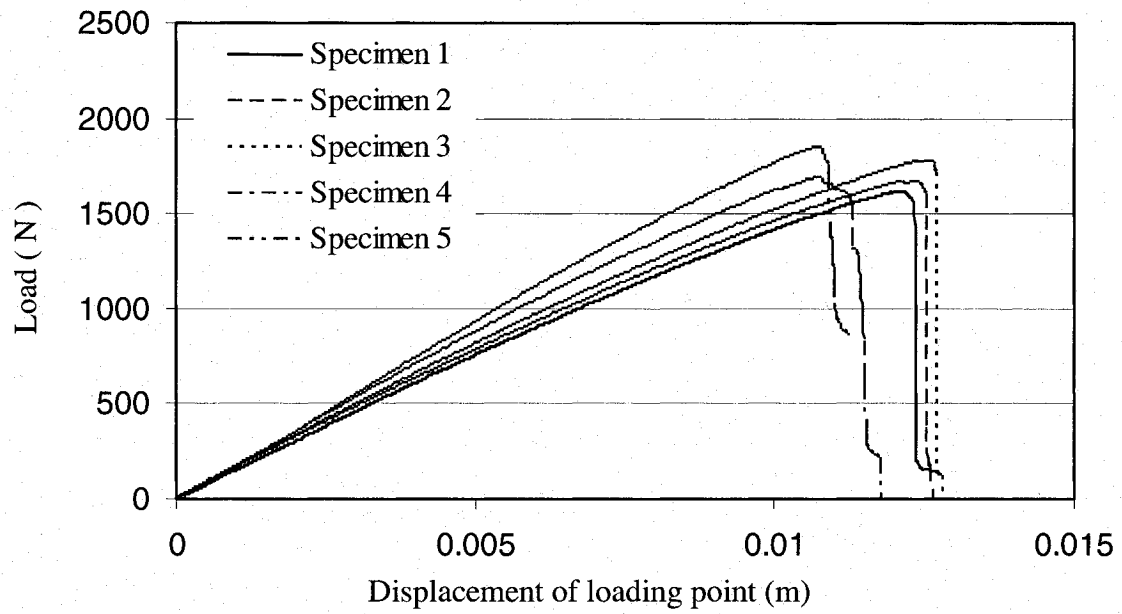


Figure F.7 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C7.

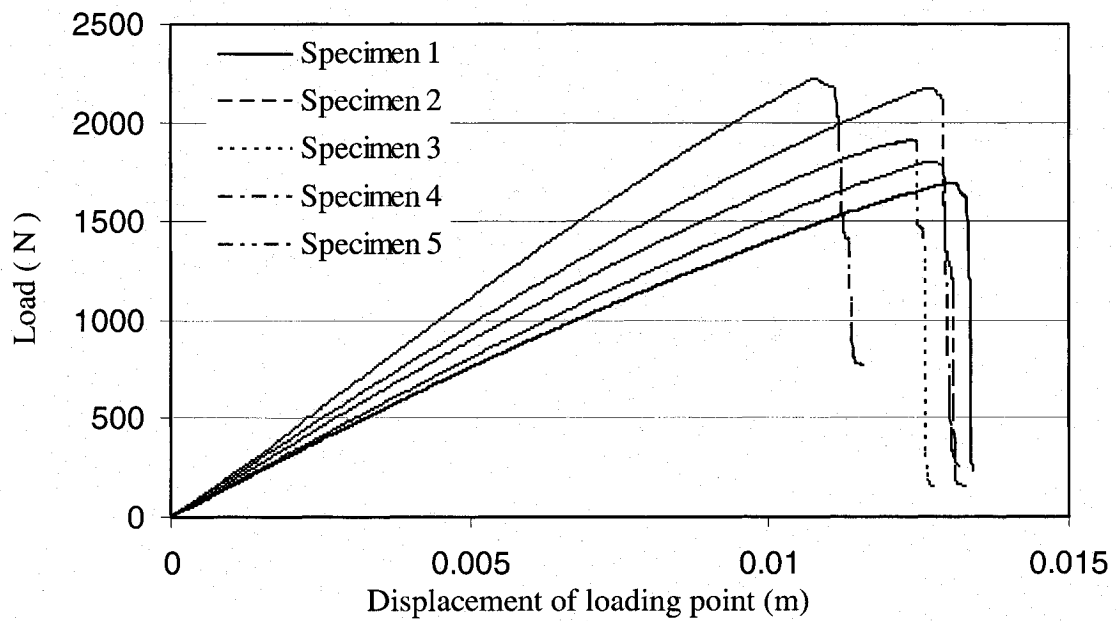


Figure F.8 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C8.

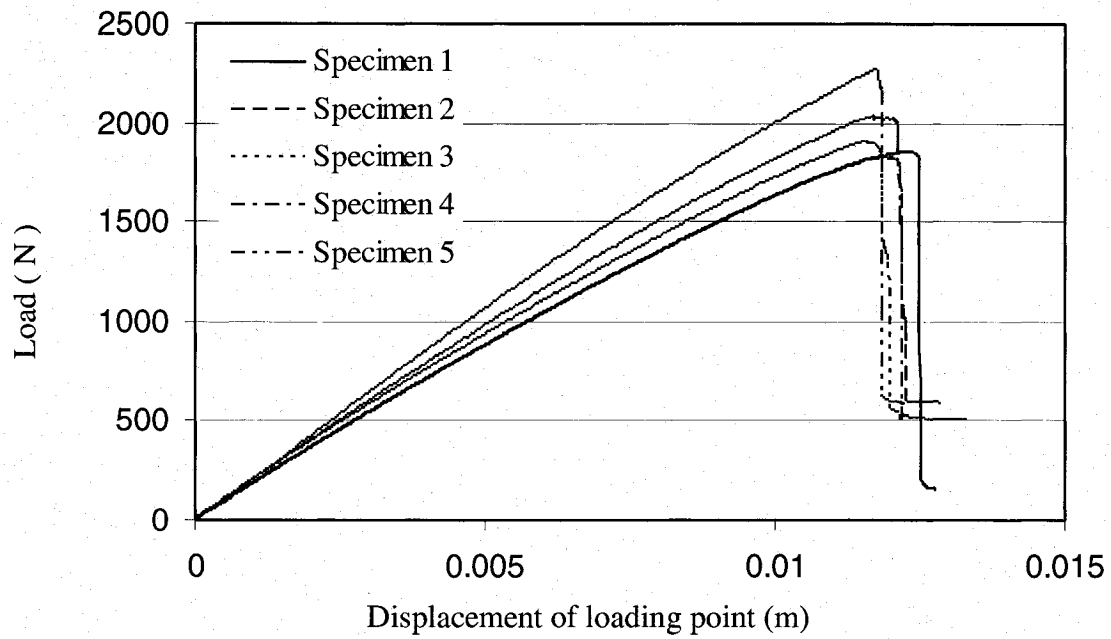


Figure F.9 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C9.

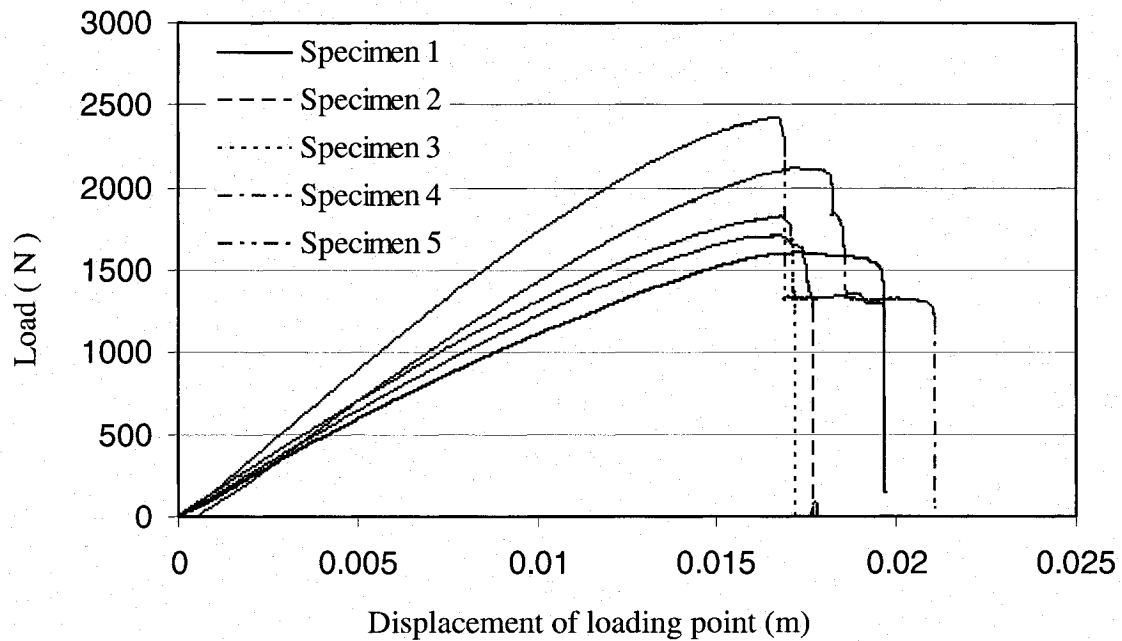


Figure F.10 Displacement as function of load, specimens S1-S5, random matt reinforcement R1, configuration C10.

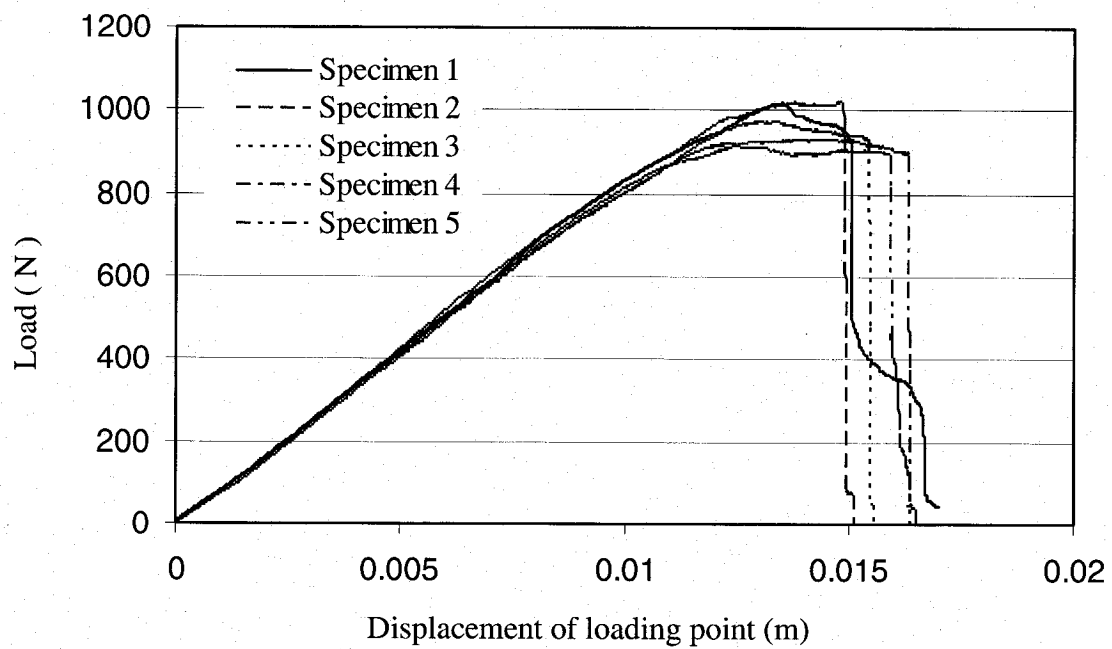


Figure F.11 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C1.

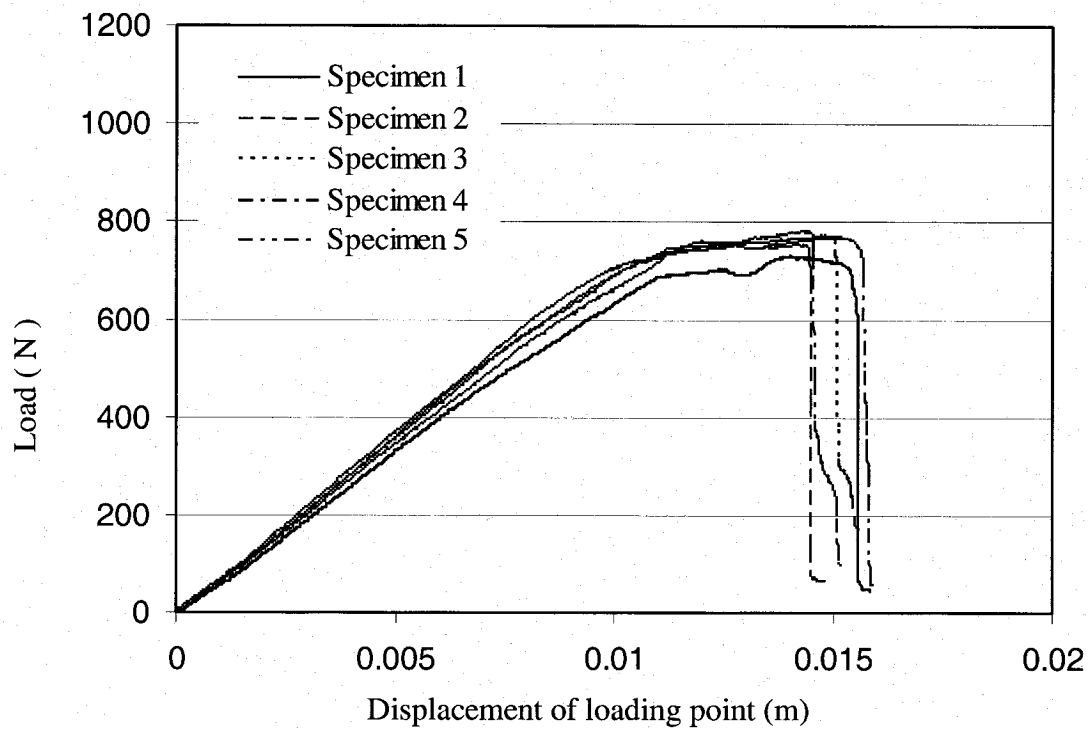


Figure F.12 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C2.

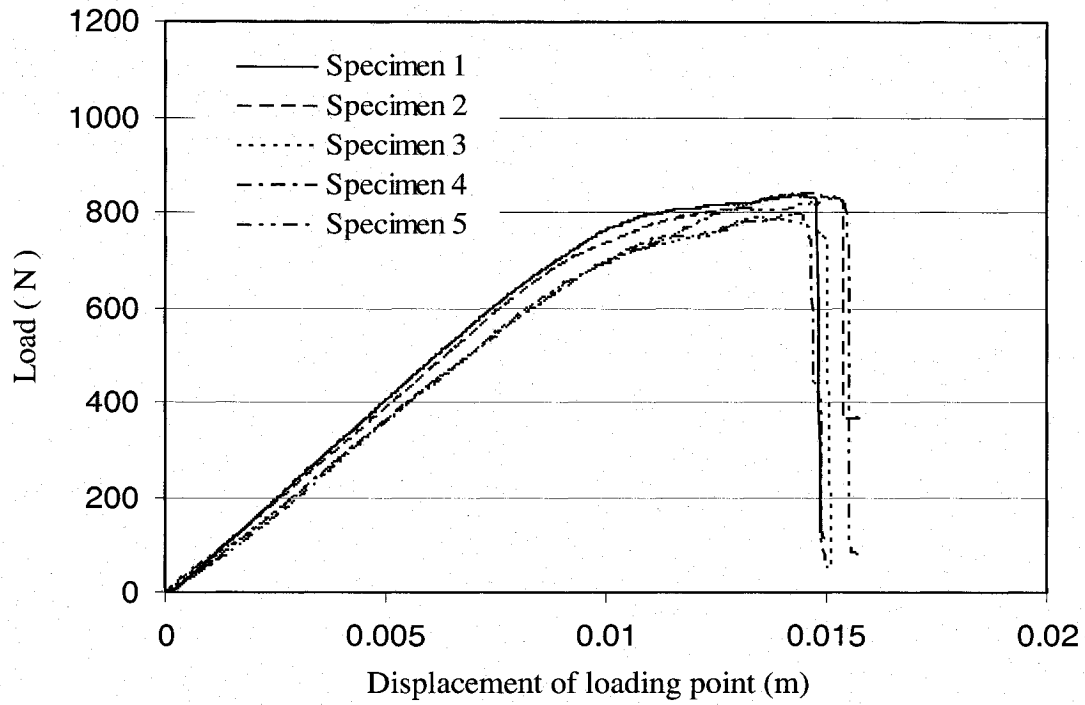


Figure F.13 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C3.

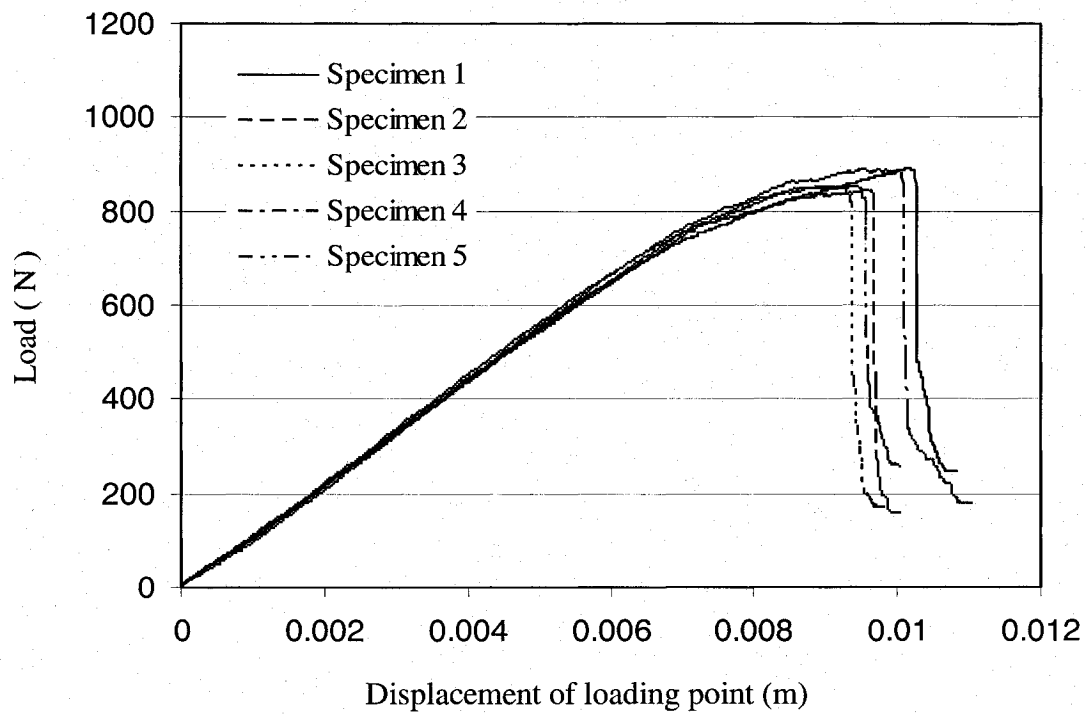


Figure F.14 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C4.

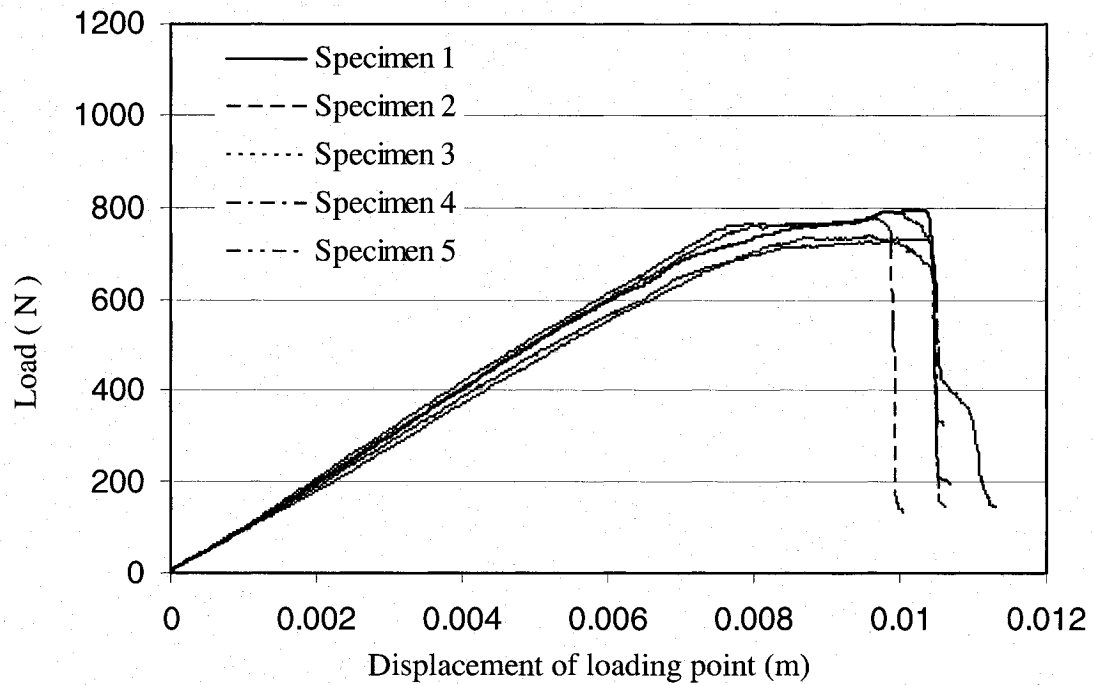


Figure F.15 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C5.

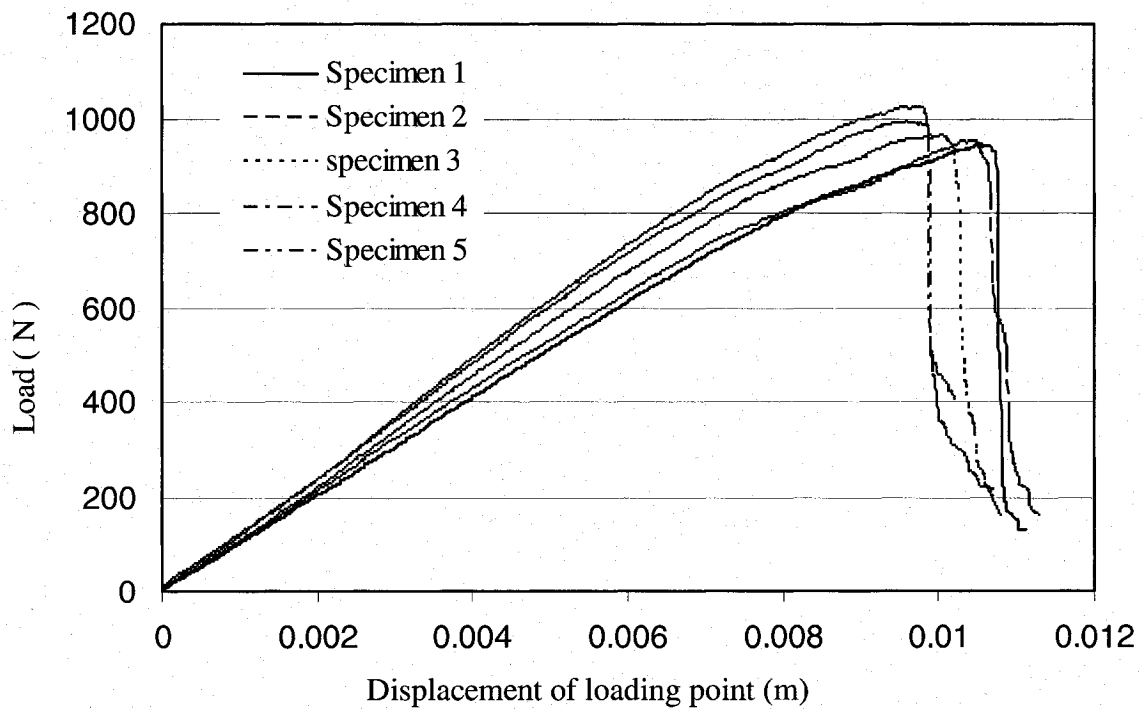


Figure F.16 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C6.

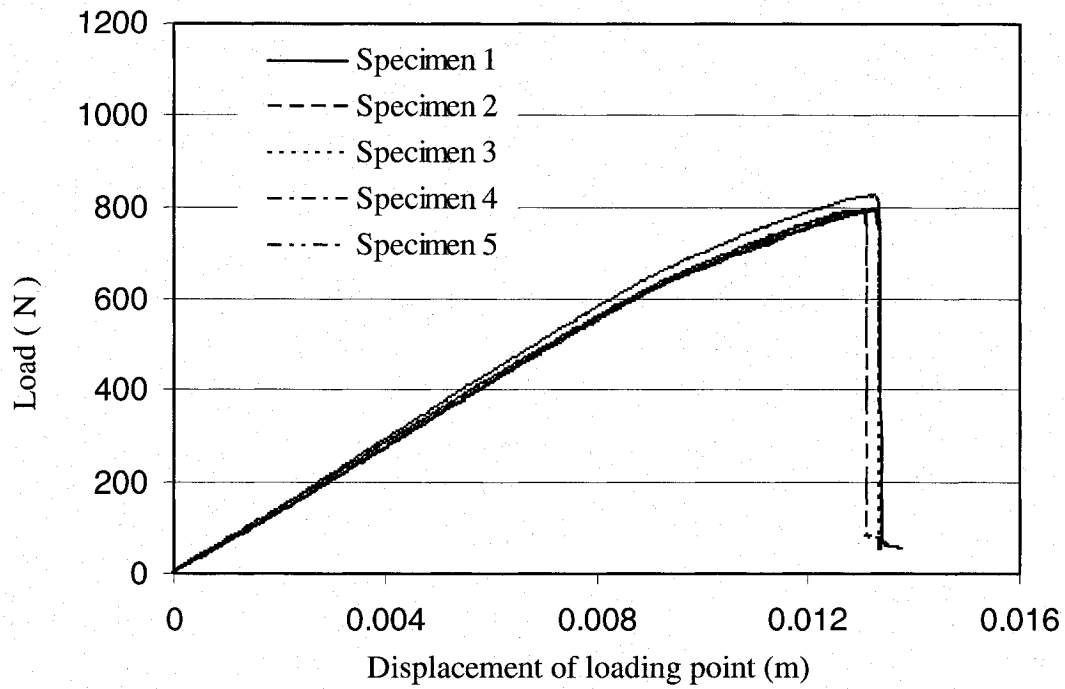


Figure F.17 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C7.

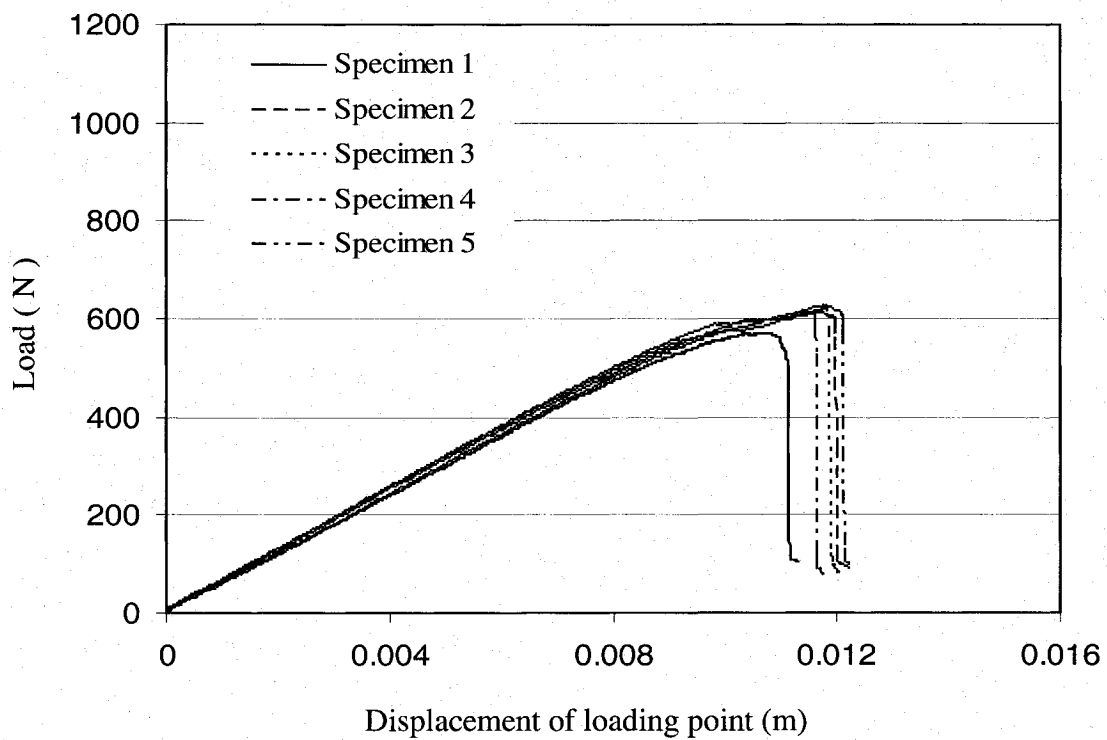


Figure F.18 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C8.

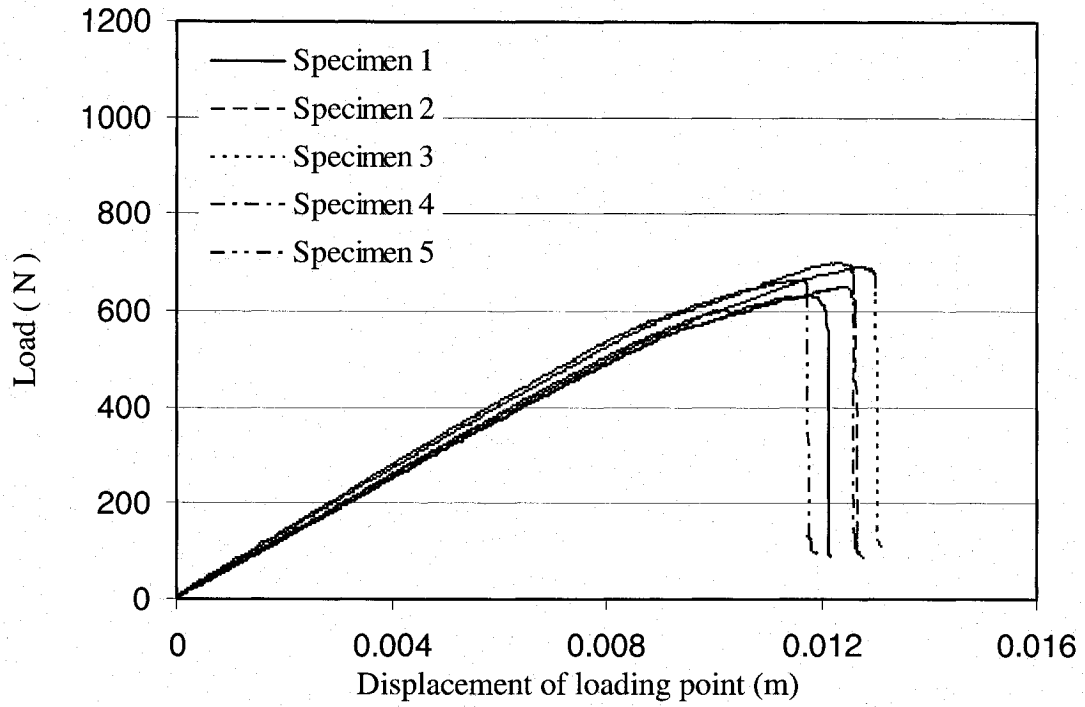


Figure F.19 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C9.

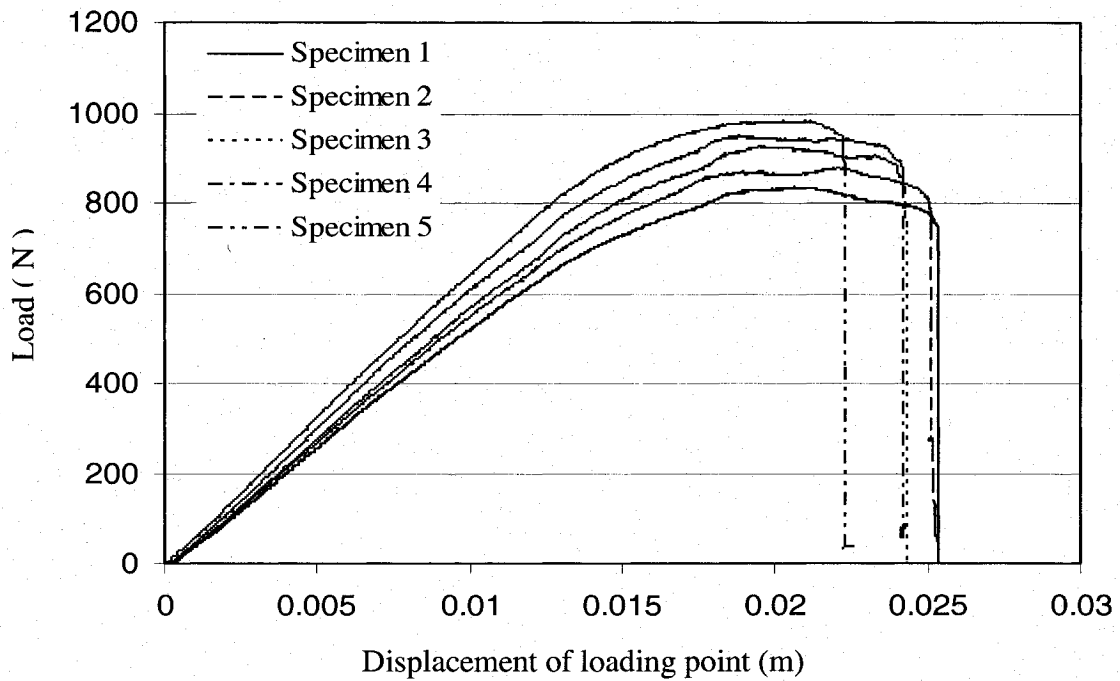


Figure F.20 Displacement as function of load, specimens S1-S5, woven reinforcement R2, configuration C10.