An Investigation into Fibre Spreading

By

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Abstract: An investigation into the effect of fibre spreading on the physical properties of filament wound tubes has been conducted. Two custom-built spreading rigs were experimentally tested for their ability to spread a single or multiple E-glass fibre bundles. Two sets of filament wound composite tubes were manufactured. One set was wound using a conventional resin bath system. The second set incorporated an optimised spreading station prior to the resin bath. The results of the analysis of physical properties suggest that fibre volume fraction is slightly lower in tubes wound using a spreading station and these tubes also have a higher void content. The average density values are relatively similar although the tubes wound with the spreading station have less variance in the individual values. Further analysis is needed to determine the effect of spreading during manufacture on the mechanical properties of filament wound composite tubes.

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1.0 Introduction.

There are many processes used to produce composite parts for specified types of applications. These manufacturing processes include pultrusion, filament winding, hand lay-up resin transfer moulding, vacuum bagging and autoclaving. Filament winding is a popular common method that is used for manufacturing tubular composite parts.

Conventional filament winding has certain common and distinct features when compared to other manufacturing techniques; firstly there are the fibre tows. Commonly used fibres include glass or carbon however, other fibres such as Kevlar™ and polyethylene can be used. The number of tows is generally dictated by the product specification and dimensions. The tows are passed through a tensioning system and guided to an impregnation zone. Impregnation is achieved by passing the tows through a bath containing the mixed resin and hardener system or over an impregnation drum that is placed in the resin bath. Typical examples of commonly used resin systems include polyester, vinylester and epoxy/amine. It is important to ensure that the matrix is compatible with the fibres. The impregnated tows are then guided to a traversing carriage and are wound onto a rotating mandrel. The number of layers wound, speed of winding and the length of the tube are dictated by the product specification. Figure 1 shows the set-up of a conventional wet-filament winding machine.

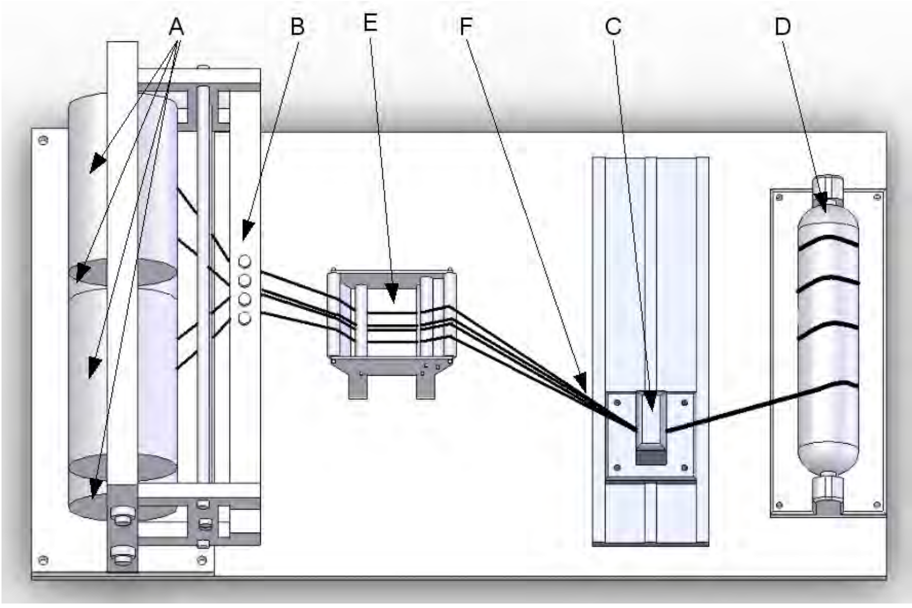


Figure 1: Schematic diagram of a conventional wet-filament winding machine. Pandita, S.D et al, 2007; Labelled components are A) Fibre creels B) Tensioning rig C) Traverse mechanism D) Mandrel E) Resin Bath F) Fibre bundles.

Although wet-filament winding is used commonly, there are a number of problems associated with this manufacturing technique. The main issue is the waste that is generated by premixing the resin system. Any material that is left in the impregnation bath post-winding is unable to be used in the process again as it will start to cure (cross-link). The mixed resin on the tows can also drip onto the floor and this is also an issue at the mandrel when it is not rotating and/or during transport of the mandrel with the impregnated tows to the oven. Since a resin bath is used to impregnate tows, a specified volume of resin is retained at the end of production. In general, the tows are over impregnated and this then dictated the need for the excess resin to be removed manually during or just after the filament winding.. This waste is sometimes reintroduced into the resin bath or disposed. By minimising the excess and mixing the resin system at the last feasible moment, it is possible to create a much cleaner and economic process. Such a process has been developed recently (Shotton-Gale et al, where the fibres are spread prior to impregnation. The impregnation is achieved via a custom-designed impregnation device instead of the resin bath. In this new process, the resin and hardener are stored separately and are pumped on demand via precision gear pumps to a static mixer prior to delivery to the resin impregnator. This technique overcomes some of the limitations associated with wet-filament winding.

Filament wound composites are used extensively in applications such as pressure vessels, printer-rollers and pipes. Therefore if the process is to be changed it is important to understand fully all the factors that affect the properties of the final product. As stated by Kugler & Moon (2002), ‘the online automated processing often used with the process is by no means impervious to a range of process induced defects’. Therefore by changing the process existing issues may be made worse and or new problems may arise. For example, the tension in the tow affects the spreading of the fibres during the process which in turn has an influence on the degree of impregnation. Tow tension and impregnation also influence the overall properties of the composite product. Hence it is essential to understand fully the influence of the key process variables and their effects on the composite properties in order to optimise the process. The next sections present a review on the effect of winding parameters on the physical and mechanical properties of filament wound tubes.

2.0 Literature Review

2.1 Tension

It has been suggested that tension has an influence on the overall mechanical and physical properties of filament wound composites. It exerts this influence through its effects on spreading and impregnation during the process; and through the force generated within the tow during winding onto the mandrel as more layers are added.

Mertiny and Ellyin (2002) studied the influence that tow tension during processing has on both the physical and mechanical properties of a filament wound composite product. In that study, 8-tows of Owens-Corning E-glass fibres were used with an EPON826/EPI

CURE9551; a two-part resin system. Samples were wound using a tension of either 26.7 N or 44.5 N. Excess resin was removed at the end of the winding process using a foam brush and then the tubes were cured through a two stage process. The specimens were cured for 1 hour at 80 °C then post-cured for 2.5 hours at 120 °C.

The main physical property studied in this experiment was fibre volume fraction; this was done by conducting a resin burnout test of 25.4 mm rings taken from different locations on the tube. Standard test methods were to measure the average fibre volume fraction of each tube.

For mechanical testing each specimen was subjected to multi-axial loading; different loading conditions were achieved by alternating the ratio of hoop to axial stress. The ratios used were:

- 1H:0A Pure hoop Loading
- 3H:1A Stress Coincides with Applied Fibre Direction
- 2H:1A Unconstrained Loading
- 0H:5A Pure Axial Loading

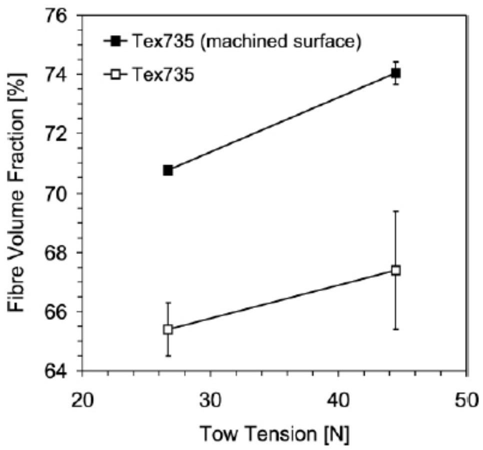


Figure 2. Fibre Volume Fraction as a function of Tow Tension. Mertiny & Ellyin (2002)

Each specimen had an electrical resistance strain gauge mounted in the axial and hoop directions at the mid-point of the tube.

A strong correlation was found between the tow tension used and the fibre volume fraction (FVF) of the final product. Figure 2 shows the relationship between tow tension and FVF. The lower tow tension of 26.7 N resulted in a FVF of 70.8 % and the higher tow tension, 44.5 N, resulted in an increase in FVF up to 74 %. This increase in FVF was attributed to the fact that the higher tension will result in more resin being squeezed out from the fibres on the mandrel. Variability in this can occur however with manual removal of the excess resin from the tube surface and also from the resin dripping from the tube. Manual removal of excess resin may also result in a change in fibre architecture and lead to unintentional damage to the fibres. These factors can influence the physical and mechanical properties of the final product.

Mertiny and Ellyin (2002) also found that the stress that arises during both structural failure and functional failure was different depending on the winding tension used to manufacture the specimen. The functional failure tests involved the use of a bladder system inside the tube to apply internal pressure to the tube using water as the pressurising medium. These tests determine the point at which the composite can no longer perform to its requirements. Once matrix cracks began to form due to the applied internal pressure, water was observed to seep out from the wall of the tube. The results from the mechanical tests showed that there was not an exact relationship between the tension and performance of the tube. With an increase in winding tension there was an increase in the performance during fibre dominated loading conditions; fibre dominated loading refers to loads in the hoop direction and stresses parallel to the fibres. However during matrix dominated loading conditions; matrix dominated conditions refers to loads that are axial or transverse to the fibre direction. The greater fibre compaction due to high winding tension resulted in a decrease in failure strength. These two points are important to consider. It is important to ensure that the final composite properties are appropriate for the application and hence that the manufacturing process is designed to provide these optimum properties.

In the study reported by Mertiny and Ellyin (2002), the winding tensions that were used were low and there was not much of a difference between the upper and lower values. Further research would need to focus on a greater range of values below and above the lower and upper values respectively with a few in between. In addition it would also be difficult to say whether the difference in fibre volume fraction were significant. Using the error bars as a reference point for the fibres without a machined surface, it would suggest that there is not a significant difference between the two data points. For the tows that did have a machined surface however there is a more significant change in the fibre volume fraction. Further testing and analysis is needed to confirm the significance of the difference found.

Chen and Chiao (1996) studied consolidation during the filament winding process and found that tension can have various effects on the filament wound part. It was found that altering the tension resulted in different fibre arrangements being obtained. An increase in the tension resulted in a reduction in the distance between each layer of fibres wound. Greater squeezing of resin through the fibre layers was also observed with this reduction in distance and increase in tow tension. The increase in squeezing and decrease in distance between fibre layers would most likely result in a greater fibre volume fraction; as has been stated before this is a desirable effect especially for a fibre dominated service life. This study provides further evidence that the winding tension can have an influence on the FVF of filament wound parts. Another observation was the reduction in total consolidation time (the time taken for the resin to be squeezed through the fibres and for the fibres to align) with an increase in the winding tension. It was also found that a reduction in winding tension below a critical value could result in inefficient consolidation of the final layer wound and therefore an increase in processing time.

Another study that looked at the effect of tension was conducted by Kugler & Moon (2002). As well as studying tension, the mandrel material was changed and any effects recorded. It has been previously found that fibre waviness and a large number of voids can occur during the processing of composites. However it is suggested that these can be moderated or controlled using certain aspects of the process.

In that study, the mandrel used was made of either aluminium which has a high coefficient of thermal expansion or steel which has a relatively lower coefficient of thermal expansion. The mandrels were identical in terms of dimension. As with Mertiny and Ellyin (2002), high (44.5 N) and low (13.3 N) tensions were used. This is a larger difference in tension values than those used by Mertiny and Ellyin (2002) however the value chosen as high tension is the same. The tubes were cooled from the processing temperature of 343 °C using natural or forced convection cooling. Two sets of specimens were made; the first set had a thickness of 1.3 cm and the second a thickness of 0.6 cm.

With the thin cylinders, it was found that tow tension had no effect on the waviness resulting from the process however for tubes wound on a steel mandrel there were fewer observed areas of waviness than with those wound on aluminium. This observation was also true for the thick cylinders wound under a high tension (44.5 N). Thick tubes wound on an aluminium mandrel showed no effect of tension on waviness; i.e. the thick tubes wound on an aluminium mandrel exhibited the same waviness as was observed with the thin tubes. On the other hand, for the thick tubes wound on a steel mandrel no waviness was observed. There was no visible difference noticed for tubes cooled using either natural or forced convection. Although there was a reduction in the waviness with an increased tow tension the effect was put down mainly to the mandrel material. Therefore it cannot be assumed that tow tension always reduces process induced fibre waviness. The biggest influence that was found for an increase in tow tension was that it can act to reduce the void content of the composite product. This is linked to previous claims stating its effect on FVF.

Whilst it has been stated that fibre waviness is an undesirable process induced defect, it is possible that it may have a beneficial role in the mechanical properties of fibre reinforced composites. A review by Parlevliet et al (2006) states that that 'fibre waviness lowers the difference in the coefficient of thermal expansion in the transverse and longitudinal direction, consequently lowering the residual stress in the composite.'

From the literature, it would appear that tension mainly affects the consolidation of the composite and therefore the fibre volume fraction and void content.

Cohen (1997) investigated the influence of a variety of filament winding process parameters and their effect on the strength and final quality of the composite. A total of five key variables were selected from a list of twelve. Variables were chosen on both importance and controllability. Variables that cannot be controlled by the filament winder include the degree of fibre damage during winding and the variability of fibre strength. The five parameters considered to be most important were:

- Winding tension
- Laminate stacking sequence
- Winding tension gradient
- Winding time between layers
- Cut-versus-uncut helicals (refers to manufacturing process where helical layers are occasionally cut before the matrix has had time to gel)

A total of 9 tubes were manufactured with one being a duplicate to measure variability between tubes. Any parameter that was not a variable was maintained at a constant value. For example, winding speed and resin content were kept constant throughout. Composite tubes were tested for their physical and mechanical properties.

The results from pressure burst and short-beam shear testing was analysed statistically. It was found that the variables having the greatest effect on composite vessel strength were related to the tension gradient and the winding tension itself. Tension as well as other variables also had an influence on the strain at failure. The hoop modulus of the composite was mostly influenced by the winding tension and the strength of the composite was mainly influenced by the fibre volume fraction. It has been suggested that fibre volume fraction is influenced by winding tension; therefore the winding tension could be linked to the observed effects of fibre volume on strength.

It was also found that the winding tension has an effect on the final wall thickness of the cylinders. An increase in the winding tension resulted in a decrease in the thickness of the tubes. This could be due to an increase in the consolidation and compaction of the fibres during winding. As a result of the increased tension there is an increase in the amount of resin squeezed out of the layers of fibres into subsequent layers. This was also reported by Mertiny and Ellyin (2002) who suggested that the observed increase in the fibre volume fraction with a greater winding tension was due to more resin being squeezed out of the fibre bed. As well as an increase in fibre volume fraction there was a corresponding change in the void content of the tubes. With an increase in winding tension a decrease in the overall void content was observed. Winding tension was the only variable found to have any effect on the void content. This was also observed by Kugler and Moon (2002).

2.2 Impregnation

2.2.1 Theory

Many theories of impregnation have their roots in Darcy's Law of liquid flow through a porous medium. This law was first developed on observation of fluid flow in 'macroscopically isotropic beds of spherical of sphere-like particles' (Astrom et al, 1992). Darcy's Law is for Newtonian fluids and has been used as a resin flow model before (Astrom et al, 1992):

$$q = K\frac{\Delta P}{L}$$

Equation 1; Darcy's Law for Newtonian Fluids (Astrom et al 1992).

'where q is the fluid flow rate per unit area, K is coefficient depending on the permeability of the fibre bed and ΔP is the fluid pressure drop over the bed thickness, L'. The problem with many of the earlier studies that employed Darcy's Law as a resin flow model is the assumptions that were made. It was often assumed that the permeability and porosity of the fibres to be impregnated was constant. Another issue with studies that use Darcy's law as a basis for impregnation models is that it is not possible to relate the findings to random fibre arrays; this is because many of the studies looked solely at single fibre arrays.

Another widely used relationship is the Kozeny-Carman equation. According to Astrom et al (1992) this relationship 'assumes that the porous medium is macroscopically isotropic and that the particles are of near equal size'. Again it is difficult to transfer this directly to the aligned fibre beds that occur within composites processing methods. A number of factors such as the friction between neighbouring fibres and defects such as fibre waviness (which can occur during the filament winding process; Kugler & Moon, 2002) mean that aligned fibre beds are rarely isotropic.

Astrom et al (1992) studied the application of the Kozeny-Carman relationship to composites processing. The concern was that whilst Darcy’s Law and the Kozeny-Carman relationship have been applied to resin flow through aligned fibres there has been a lack of consideration concerning the accuracy of transferring these models when taking into account many of the assumptions that have been imposed. A simple issue with the early models is that they describe flow of Newtonian fluids through a medium. In composite processes such as pultrusion and filament winding that involve online consolidation, the flow is affected by high shear rates in the matrix. Another issue with these processes is that the matrix can flow perpendicular to the fibres as well as parallel. ‘If flow occurs perpendicular to the fibre then viscoelastic effects need to be accounted for in any modelling or assumptions; this is because there is an increase in flow resistance associated with any viscoelastic activity’ (Astrom et al, 1992).

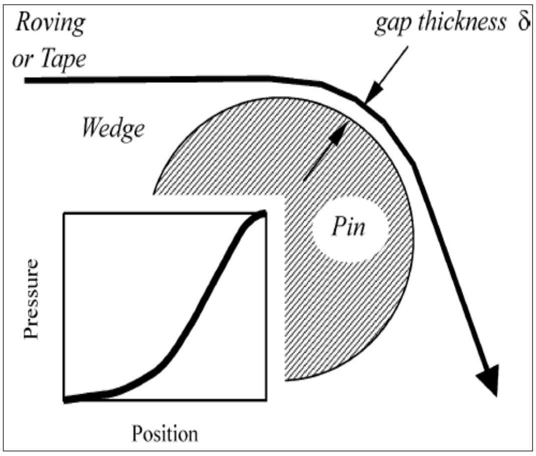
Astrom et al (1992) found that even though both Darcy’s Law and the Kozeny-Carman relationship have proved accurate in the prediction of flow of Newtonian fluids through spherical particle beds, there is doubt concerning the validity of the application of such models to flow of generalised Newtonian fluids for impregnation of aligned fibre beds. It was found that there is an insufficient correlation between the flow rate pressure drop relationship and current experimental data.

With regard to the Kozeny-Carman relationship, in particular it was discovered that there is a dependency, among other factors, on the fibre volume fraction value. This imposes a further issue as it is noted that there is also a poor relationship between predicted values of FVF and those values obtained experimentally. Astrom et al (1992) suggest that the most likely cause of this variance is the non-uniform packing nature of actual fibre beds; this can occur during the manufacturing and consolidation process.

Chen and Chiao (1996) used a model to determine the fibre consolidation of unidirectional fibres during filament winding. They stated that mechanical performance of filament wound parts is dependent on specific process variables. For example, fibre volume fraction has a significant influence on strength and therefore, their view was that it has to be optimised. Chen and Chiao state that it is difficult to model the average behaviour of a random fibre array by transferring models such as Darcy's Law that are based on single fibre arrays. With consideration of the fibre consolidation process it is important to note that earlier research has assumed porosity to be uniform across the fibre bed. However during fibre consolidation this is constantly changing with the structure changes associated with the process.

Their study used an intermittently undulating channel representation of a unidirectional fibre bed to study fibre consolidation during the filament winding process.

Bates et al (2000) measured the pressure build-up in the gap between a glass fibre tow and cylindrical metal pin. It is known that a wedge of resin will occur in the gap between the fibre tow and the pin. If pressure builds up it is likely that the resin will be forced up or down (depending on the position of the pin) into the tow. Figure 3a shows schematically the position of the wedge in relation to a tow and pin, a pressure profile of the wedge region is also shown on the diagram; Figure 3b shows the experimental set-up used.



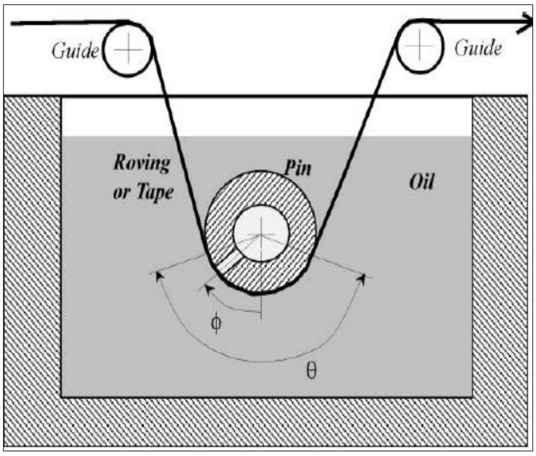


Figure 3a: Schematic diagram showing the cross-section of a fibre tow being pulled across a metal pin. The postion of the wedge is marked and a pressure profile for the wedge region is shown. Figure 3b: Schematic digram of the experimental set-up . Bates et al (2000)

The friction that occurs between the fibre tow and the pin is dependent on a value known as the lubrication number. Friction occurs when the gap between pin and tow is reduced. The size of this gap is influenced by certain process parameters; the width of the fibre tow and the tension applied, the viscosity of the impregnating liquid (in this study oil was used) as well as the radius of the pin being used. The interaction of these parameters is used to calculate the lubrication number using Equation 2 below:

$$\frac{\delta}{R} = 1.4(\frac{U\eta W}{T})^{2/3}$$

Equation 2; Equation used to determine the lubrication number used in Bates et al (2000)

‘where R is the pin radius, δ is the gap thickness, U is the relative speed of the tow, η is the viscosity of the impregnating liquid, W is the width of the tow and T is the tension in the tow.’

Bates et al (2000) obtained experimental values of the pressure in the wedge region and recorded them as ratios of measured pressure to a theoretically obtained value for a maximum pressure. This maximum pressure was calculated using the measured tension in the tow, the width of the tow and the radius of the pin being used in the impregnation bath. It was found that for any experiment in which the lubrication number was >0.0001 there was an increase in the pressure in the wedge region with an increase in the lubrication number up to this critical value. After the critical value the pressure ratio becomes more linear.

For the glass fibre tow used in that study, it was found that the pressure in the gap region only reached 60-70% of the theoretically obtained maximum pressure for the set-up used. This value also gradually reduces to 0 throughout the wedge region. Bates et al (2000) suggest that this means part of the tow will always be in direct contact with the pin. Furthermore, the contact of the glass with the pin results in greater frictional forces. If the friction forces are so great as to be introducing damage to the fibre tow or even the pin itself through abrasion damage, the process must be adjusted to increase the lubrication number greater than 0.0001.

Bijsterbosch and Gaymans (1993) also recognised the importance of using pins not only for the impregnation of reinforcing fibre bundles but also for the spreading. There are two important factors during impregnation of a fibre bundle. The first factor is the direction of flow of the impregnating liquid. Radial flow, flow that is perpendicular to the fibres, must occur before axial flow, parallel to the fibres, can occur. The second and potentially more important factor is the geometry of the reinforcing fibre tow itself. The combined effect of the pin is to reduce the thickness of the fibre tow and create a pressure gradient enhancing impregnation. Earlier studies looking at impregnation using pins have shown that the pin diameter may have an effect on the pressure build up in the wedge region. Therefore a second set of experiments were conducted using pins of varying diameter (1, 2, 3 and 6 mm). It was found that the pin diameter had little effect on the pressure build up in the wedge.

As has been suggested before, it is possible that spreading the fibre tow during composite processing enhances impregnation (Wilson, 1997). This is because the as received fibre tow will become thinner when passed over spreading bars. Wilson (1997) proposed a simple equation to predict the width of a fibre tow after it has been passed over a bar.

$$\omega = (12AH)^{1/3}$$

Equation 3; Wilson's simple equation to determine the spreading of a fibre tow over a cylindrical bar. (Wilson,1997)

where ω is the width; A is the cross section area of the tow and H is the lateral displacement of the bar; and also gives a prediction of thickness. The method of fibre spreading is important. Using pins has been suggested to be effective in spreading a fibre tow however this results in an increase in the tension of the tow. This can lead to fibre damage through friction. The use of rollers and profiled rollers may be more effective methods and lead to a reduction in fibre damage due to high tension.

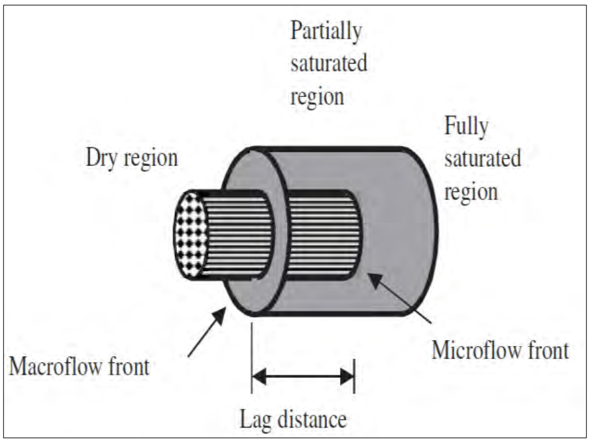


Figure 4: Macro and Micro flow in an as received fibre bundle. Foley & Gillespie (2004)

With a reduction in the fibre thickness there is a decrease in the distance the impregnating liquid has to travel. Figure 4 shows an as received fibre tow during impregnation and the infiltration changes in different areas. Impregnation of a fibre tow occurs in two stages. The first is macroflow which is the flow of resin around the outside of the fibre tow; gradually the resin infiltrates the tow and the inner fibres become wetted, this is known as microflow and occurs between the individual fibres at the core.

From Figure 4, it is clear to see that there is a difference in the flow fronts. The microflow occurs later than the macroflow. This is because it takes the resin time to infiltrate the core of the tow during which time the macroflow front is constantly advancing. By using a pin it has been shown that impregnation can be enhanced but also that the tow will become thinner.

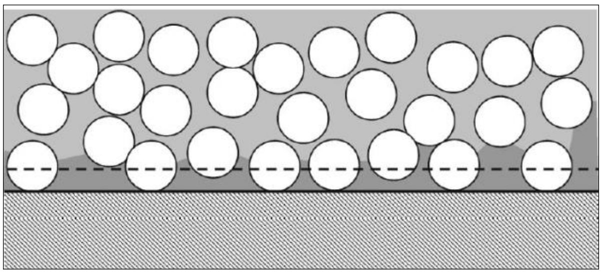


Figure 5: Schematic of tow being pulled over a pin. The dotted line indicates the wedge region where pressure is increased. Bates et al (2000)

Figure 5 shows the effect of passing the fibre tows over a pin. Bijsterbosch and Gaymans (1993) also studied the effect of pin geometry on the spreading of reinforcing fibre bundles. The line speed and the pin diameter were kept the same so as to keep the contact time constant. Three shapes of pin were used; U-shaped, cylindrical and convex. They found that as the spread of the fibre increased the impregnation improved. They ranked the pins from least spreading to highest spreading; finding that U-shaped<cylindrical<convex.

Marissen, *et al.* (2000) also suggested that using convex bars would improve the spreading of fibre tows. This paper states that there is less drag with convex pins than normal pins. The spreader bars in this study were also allowed to rotate which can help decrease the tension in the tow compared to when static bars are used. In addition, due to their convex shape there would have been a degree of tension release in the fibre tow which could improve spreading. One problem that can arise with convex pins is the fibres slipping of the edge. This would cause fibre damage as the slipped fibre entangles around the rotating axel. Marissen *et al.* (2000) also suggested that small pins could be added to the bars to further separate the tow. However this can result in fibre breakage which could build up resulting in a severely damaged composite.

2.2.2 Monitoring the impregnation process

Impregnation is a critical parameter in the processing of filament wound composite parts. It is vital that all the fibres are properly wetted by the resin system so as to produce the highest quality products. If parts of the composite are not impregnated properly then there will be dry regions which have a detrimental effect on the physical and mechanical properties of the product. It is therefore important to understand how impregnation works and how to measure it.

Ahn *et al.* (1994) measured the impregnation of 3-dimensional preforms using three separate techniques and compared the results. The first method they used was the pressure drop technique. Rectangular or circular samples were cut from fibre preforms. Rectangular samples were then placed in a mould with two parallel plates and circular samples were placed in a cylindrical mould. A liquid of known viscosity is then added to the mould and then the inlet pressure and flow rate of this liquid are measured as it infiltrates the sample. This method while useful would need to be adapted to be suitable for measurement of impregnation in the current experiments.

The second method investigated in this study is the flow visualisation technique in which a thin sample taken from the preform is placed between two transparent plates. As with pressure drop technique a liquid of known viscosity is then introduced to the set up. However with this method it is introduced at the centre of the sample. As the resin impregnates the sample the movement of the liquid front is visually measured as a function of time.

The final method used in this study involved the use of fibre optics. Small sections of the fibre optic sensors were declad. Once the fibre was prepared, it was embedded within the preform. On each fibre there are a number of declad areas. Light is transmitted down the fibre at the end of which light intensity is measured. As the liquid penetrates the preform it passes over the declad areas at which point there is a dramatic decrease in the recorded light intensity. Using this technique a 3-dimensional grid of fibres can be embedded into the preform enabling the measurement of impregnation in all 3 directions. The main issue with this technique is that the fibre optic sensors are much larger than the fibres used in the manufacture of the preforms. This means that they are likely to influence impregnation and change the behaviour that would be found in a preform with no sensors.

Amico and Lekakou (2002) looked at rates of axial impregnation in a single fibre bundle. Any manufacturing process involving the infiltration of a fibre tow with a liquid will have an element of axial impregnation. Axial impregnation can vary in importance depending on the structure of the fibre bundle and also the processing conditions under which it occurs. The capillary pressure is known to play a role in the formation of voids during composites processing.

A prepared fibre bundle was suspended at one end from an electrobalance. The free end had a small weight attached and was then placed into a beaker containing the infiltrating fluid. As the experiments were conducted on a balance it was possible to measure the infiltration in two ways. Firstly the rise of the fluid height in the bundle was measured using a microscope; there was also a graticule displayed behind the bundle. Secondly any weight increase in the fibre bundle was recorded by the balance as this indicated the uptake of the fluid.

They found that to obtain values of capillary pressure close and comparable to predicted values experiments lasting around 23 hours were needed. Shorter experiments lasting a couple of hours resulted in drastic underestimation of pressure.

One issue with this study is that neither of the two impregnating liquids involved the use of the complete resin system i.e. resin and hardener. Adding the hardener changes the viscosity of the resin and this could change the impregnation characteristics. However an important point to be considered if hardener was to be added is chromato-separation. This is where the lowest weight component will infiltrate the fibres quicker leading to separation of the resin system. During shorter experiments this is unlikely to be an issue but during longer experiments such as those used in this study it could drastically alter the results.

It is particularly important in the clean filament winding process to be able to monitor the impregnation process not only in terms of the degree of impregnation but also the chemistry of the matrix. As the two parts of the resin system are mixed at the last minute in precise amounts there is a need to be able to monitor the stoichiometry of the mixture. Any small changes can result in changes in the performance of the final product.

Liu and Fernando (2000) studied the development of a fibre optic monitoring technique and reported the results. Previous work using near infra-red spectroscopy has shown that fibre optic sensors can be used to determine cure kinetics in a resin system. However the sensors used in these studies would not be fast enough to provide real-time information to monitor the stoichiometry and mixing on-line. Liu and Fernando (2000) state that to gain the required resolution of 1 mm the response time needed is >1 ms.

In that study a new low cost sensor was developed. The sensor used two light sources; one emitted near infra-red light (NIR) and the other emitted red light. The NIR was used to measure the amine as it is absorbed by the amine. The red light was used 'for correction of the scattering effects'. The results of this study showed that the proposed fibre optic sensor was adequate to monitor real-time the amine concentration. There was some scatter in the obtained spectra and this was attributed to a number of factors. As a resin dispenser is used instead of a resin bath any deviation in the dispense rate will result in a change in the amine concentration. Some scatter can also be caused by air bubbles in the resin system. In addition to the amine concentration monitoring the application of this sensor to mixing monitoring was also studied. Again it proved to be a feasible technique in the determination of the level of mixing within the resin system.

2.3 Filament Spreading

In the literature, there appears to be a lack of experimental work on the method, effects and influences of fibre spreading during composite manufacturing. The paper referred to above by Wilson (1997) is mainly a model proposal with very little experimental evidence to support the theory. Many papers mention spreading in passing as an aside but few focus on the many factors surrounding methods of spreading and its influences on processing.

Much of the proposed methods of spreading are to be found in patents. A range of patents exist referring to varying methods of fibre spreading. At a glance the methods proposed include; mechanical spreading (Lifke, 2000) , electrostatic spreading (Peritt, 1993), pneumatic spreading (Daniels, 1974), vibration induced spreading (Akase, 2000) and finally acoustic induced spreading (Iyer, 1991).

In order to review these methods it is important to look at potential issues with each. A major issue that can arise with any method of fibre spreading is fibre damage. In composite materials in general it is the fibres that provide the mechanical strength. Therefore if fibre damage occurs then the composite performance will be affected.

The two methods that appear most likely to result in fibre damage are mechanical spreading and pneumatic spreading. Mechanical spreading often involves rotating rods or rollers. These are advantageous in the sense that they reduce tension and friction in the line. Both are desirable if fibre damage is to be kept to a minimum. However if a fibre breaks it can become loose from the tow and wrap around the roller. This problem is also more likely when using convex rollers such as those proposed by Knight (1975). Gradually more and more fibres wrap around the roller resulting in large scale damage of the tow. This build-up of fibres may also break the spreading system. Pneumatic spreading involves the use of a venturi. This may result in damage to the fibres due to the force of the air required to pass the tow through the venturi.

Another concern with these methods is the ability to reproduce consistent tow widths over a long period of time. Mechanical spreading provides an easily controllable set of parameters and it is possible to assume that each section of the tow will experience the same forces. However for processes involving vibration, electrostatics or acoustic induced spreading it is possible that different parts of the tow may spread to a variety of widths and not in a uniform manner. Pneumatic spreading is also a method in which there is very little control over the forces experienced by the tow. It is very difficult to produce a uniform yarn via this method. Sometimes this is not even considered (Daniels, 1974).

The process proposed by Yamamoto (1988) is a combination of mechanical and the vibration techniques. The fibre tow is passed through a series of rollers which vibrate as well as the normal action of rotating. It is suggested that this method will produce a more uniform yarn than by using electrostatic methods.

With regards to cost most of the proposed methods are undesirable. For example most of the methods would require an external power source. This is not advantageous when trying to make a process more efficient and reduce the cost. Another problem associated with these methods when trying to improve a process is the space that these methods require. It would not be a straight forward task to retrofit these methods to existing composite manufacture processes.

From the literature review the aims and objectives of the current study were determined. The main purpose of this study is to determine the most effective method of fibre bundle spreading. As can be seen from the literature review there hasn't been a comprehensive study into spreading of a fibre bundle. The patent literature is the main resource for methods of spreading however in the scientific literature there isn't a review of any of the methods. In addition, the degree of fibre spreading achievable is to be quantified. Once this has been conducted the effect of spreading on fibre bundle impregnation is to be examined. In the current literature there is no link between fibre spreading and impregnation, especially the effect of spreading on impregnation in the Z-axis or through-thickness direction. Finally, the effect of fibre bundle spreading on the physical properties of filament wound tubes is to be quantified.

3.0 Experimental Method

3.1 Filament Winding

The filament winding machine used is an Iceni 2AX provided by Pultrex UK Ltd. The winding speed, pitch and number of dwell turns are all kept constant using the control box using Siemens Sinumerik software. The winding speed used for the manufacture of filament wound tubes in this study was 7 m/min. Four layers were wound onto the mandrel (outer diameter of 100 mm) by the hoop winding method. A total of six fibre creels were used. The fibre tows go over a rotating drum, the surface of which is covered in the matrix system. In one set of trials only the resin drum was used. In the second set they were passed through a spreading station prior to going into the resin bath. The tows are then passed through a D-eye ring to bring them back together and form a band which is then wound onto the mandrel.

3.2 Materials

The fibres used in this study were 1200 or 2400 Tex E-glass fibre provided by PPG Industries UK Limited. The resin system consisted of Huntsman LY3505 epoxy and Huntsman XB3403 hardener, provided by Huntsman Advanced Chemicals UK. The resin and hardener was mixed manually in a ratio of 100 parts resin to 35 parts hardener.

3.3 Fibre Spreading

Two sets of fibre spreading experiments were conducted. One involved the use of a motorised tension-release set-up, which can be seen in Figure 6, and the second involved the

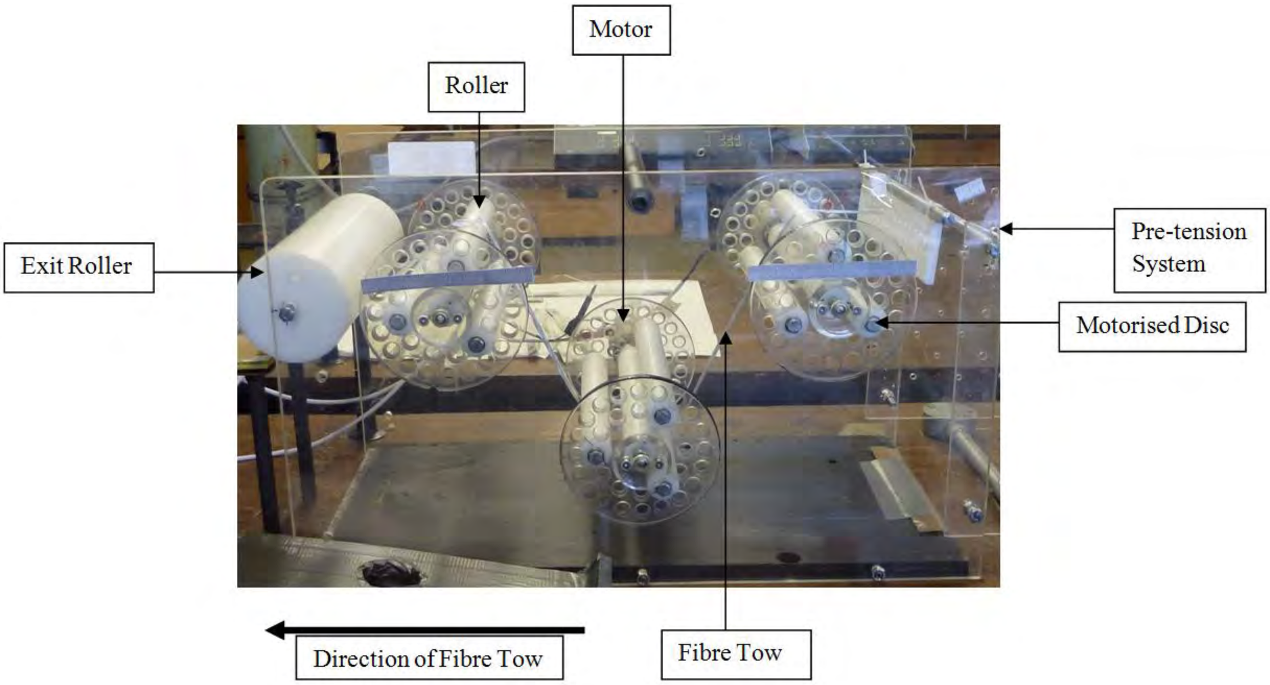


Figure 6: Image shows experimental set-up of the tension-release mechanical spreading unit.

use of the spreading station as shown in Figure 8.

For the first set of experiments a tension release system was used; shown in Figure 6. This involves the use of motorised discs that have between 1 and 6 rollers attached. Due to the high number of variables Taguchi method (Guijun, 2006) was used to determine an experimental matrix. The Taguchi method is a design of experiments (DOE) method. Dobrzanski et al (2007) define the Taguchi method as ‘a form of DOE with special application principles’. The Taguchi method is often used in experiments in which the output is dependent on a number of parameters or variables, it allows for a concise but thorough investigation without the need to explore all possible combinations of variables. For the current experiments an experimental matrix with four levels (variables) were chosen; roller configurations, pre-tension, pull speed and the speed of disc rotation. Using these four levels an L18 orthogonal array was created. Each of the experiments in the array were conducted and repeated 10 times. The fibre used for these experiments was 2400 Tex E-glass fibre provided by PPG Industries UK. The as-received width of the fibre tow was 5 mm. Fibre spreading was measured at four points along the system as shown in Figure 7.

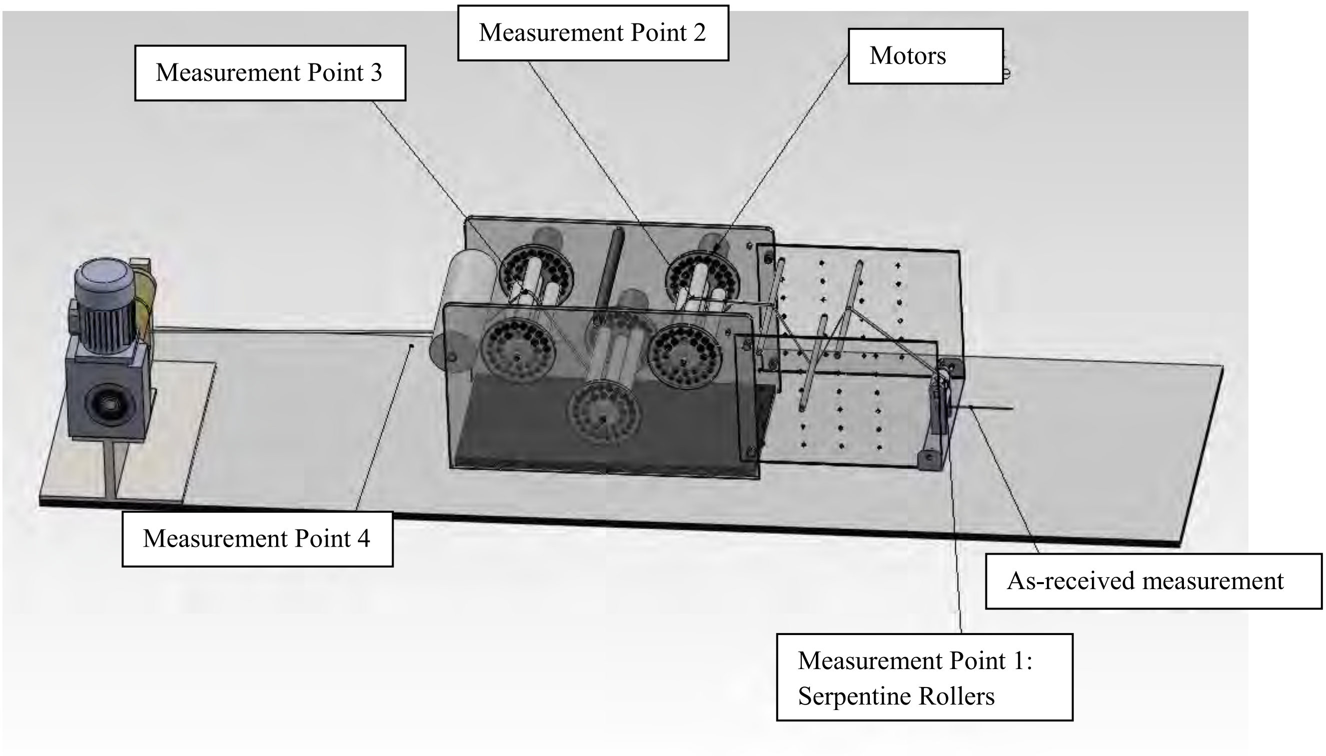


Figure 7: Schematic diagram of tension-release mechanical spreading system with measurement points and key features identified.

The fibre tow was passed through a guiding device then passed through nip rollers in an S-shape. From there the tow went through a pre-tensioning rig before continuing on to the rotating discs. There are 3 of these discs in series each of which is powered by a roller. The fibre is passed over the first disc, under the second, then over the third before being passed under an exit roller and being wound onto a fibre haul off system provided by Pultrex UK. The first point of measurement was the serpentine rollers (Point A), the second point was the first rotating disc (Point B), the third point was the third rotating disc (Point C) and the final point was where the fibre exited the system (Point D). A ruler was used to measure the spread at each point and each measurement was recorded. Once one test had been done the fibre was marked at the start of the system. The next repeat test was then started and winding stopped once the mark had passed through the entire system. This meant that no length of fibre was ever measured more than once.

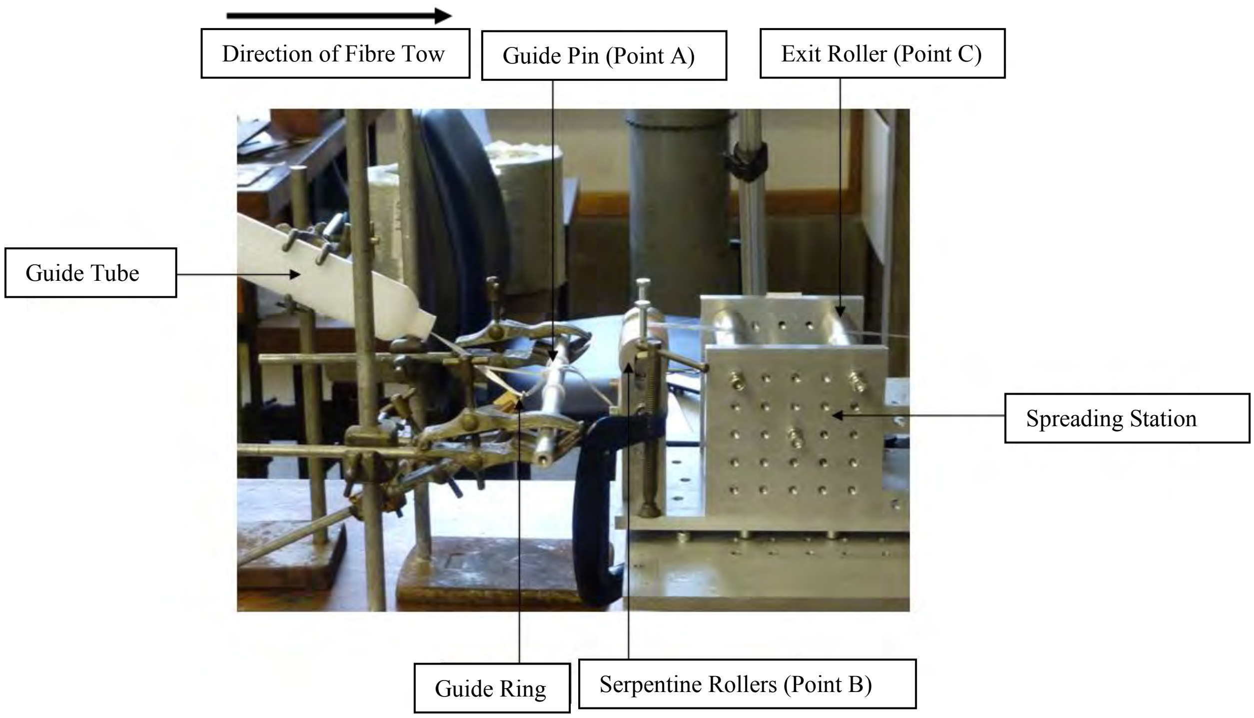


Figure 8a: Image showing prototype-V set-up with key features and measurement points labelled.

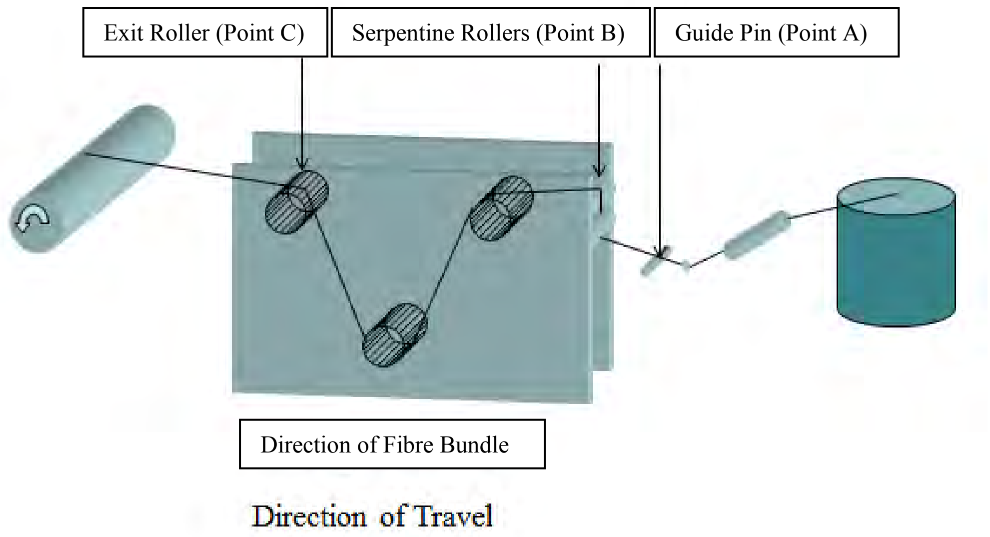


Figure 8b: Schematic diagram of the Prototype-V spreading station with measurement points labelled.

Using the fibre spreading station shown in Figures 8a and 8b, the degree of fibre spreading achievable using various combinations of rollers and profiled rollers was examined in order to determine the optimum configuration. The use of pins was not included in these experiments; previous experiments have shown that the introduction of pins into the system can dramatically increase the tension and affect the normal working of the filament winder. Profiled rollers are rollers which have had a sheet made from ball bearings adhered to the surface; their manufacture is described below. A combination of rollers and profiled rollers was used. Only three rollers/profiled rollers were ever in the spreading station however the ratios were altered; two extreme conditions were used i.e. all rollers or all profiled rollers and the rest involved a combination of the two. A total of seven configurations were used. All other process parameters were fixed. From the results obtained from the Taguchi analysis for the tension release system the optimum values for pull speed and tension were obtained. The pull speed used was 1 m/min and the tension force was 2 N. The diagram below shows the combinations used; the fibre direction is right to left and the circles containing a cross indicate a profiled roller. The width of the fibre was measured at three points along the system; the guide pin, the serpentine roller and the exit roller. Again the fibre was marked at the start of the process so as to ensure no length of fibre was measured more than once. Figure 8b shows the experimental set-up and the measurement points used.

3.3.1 Multi-tow Spreading

Using the results obtained from the spreading experiments with Prototype-V the best combination was obtained; configuration 2. This was then used along with the two extremes (1 and 6) to measure the spreading of multiple tows. The number of tows used was 3, 6, 9 and 12. Each individual tow was measured at the guide pin (Point A), serpentine rollers (Point B) and exit roller (Point C) as in the previous spreading experiments all process parameters were also kept the same.

For the experiments involving more than three tows a second set of serpentine rollers were manufactured in house in order to accommodate the increasing number. The set up was the same other than the serpentine rollers being wider.

3.3.2 Measurement of Tow Twist

As the creel is centre pulled a twist occurs occasionally throughout the length. A short experiment was conducted to determine the effect the twist has on the spread fibres. Using the set-up from the Prototype-V spreading experiments the effect of the twist was measured. Combination 2 was chosen as the configuration for these tests. A total of 20 repeat tests were conducted. The haul off machine was started and the system allowed to run. When a twist occurred the haul-off was stopped when the centre of the twist reached the end of the base plate on which the spreading station was positioned. The distance from the final roller in the spreading station to the end of the base plate is 150 mm. The centre of the twist was then marked. The spread at the final roller was measured. A value of 10 mm was chosen as the critical value and any value below that was deemed as being affected by the twist. The distance between the centre of the twist and the first value below the critical value was measured. A second series of experiments were conducted in order to determine the effect of a twist on neighbouring fibres when multiple tows were being used. To do this 3 tows were used. Each tow was passed through the entire set-up and attached to the mandrel on the haul off winder. The system was then allowed to run. The serpentine rollers were observed constantly; when the centre of a twist was observed going between the two rollers the system was stopped and the tows marked. The system was then allowed to run again until the mark reached the top on the serpentine rollers. Again the system was stopped and the width of each tow was measured and recorded along with noting which tow was twisted. This was repeated a total of 20 times.

3.3.3 Effect of Binder Content on Spreading

Spreading of a single fibre tow was conducted taking note of the point at which the fibre came from the creel through thickness i.e. the inner bore, the middle of the creel or the outside of the creel. The spreading was conducted using the experimental setup illustrated in Figure 8a. Another set of experiments was conducted to measure the effect of where the tow came from in terms of the top, middle or bottom of the inner bore of the creel. The point at which the fibre left the creel was noted and then measured as an as-received value. The tow then underwent the same spreading procedure as mentioned earlier. Finally samples of fibre were taken from the inner bore, centre of the creel and outside of the creel and fibre burn-off tests were conducted according to ASTM D4963/D4963M – 11. Samples were weighed to 5 g and preconditioned for 1 hour at 105 °C. The crucibles were made from steel foil and preconditioned for 30 minutes at 625 °C. Once cooled in a standard atmosphere for 30 minutes the crucibles were weighed. The 5 g of fibre was then added to the crucible and the weight recorded was taken as the tare mass. The crucible containing the fibre was then placed into a furnace at 625 °C for 30 minutes after which it was removed and allowed to cool in a desiccator for a further 30 minutes. After being cooled the crucible and fibre were weighed. Using Equation 4 below the ignition loss of the samples was obtained.

Ignition Loss (%) = 100 x (A/B)/(A/T)

Equation 4; Equation used to determine ignition loss of fibre bundles. Taken from ASTM D4962/D8943M-11

where A is the initial mass of the crucible containing fibre prior to burn-off, B is the mass of the crucible containing glass residue post burn-off and T is the original mass of the crucible.

3.4 Profiled Rollers

Profiled rollers were manufactured in house by members of the Sensors and Composites group at the University of Birmingham. A mould was created in order to align ball bearings (2.38 mm diameter) so as to create a sheet which could be wrapped around existing non-profiled rollers. Once the mould had been filled with bearings a mixture of resin and hardener was carefully injected into the mould using a syringe. When the entire mould had been infiltrated it was part cured and allowed to cool. The reason for only part curing the resin system is that the sheet could be wrapped around the roller without losing any of the ball bearings. The roller was then placed in the oven and the sheet was allowed to cure completely. This created a profiled roller which can be observed in Figure 9.

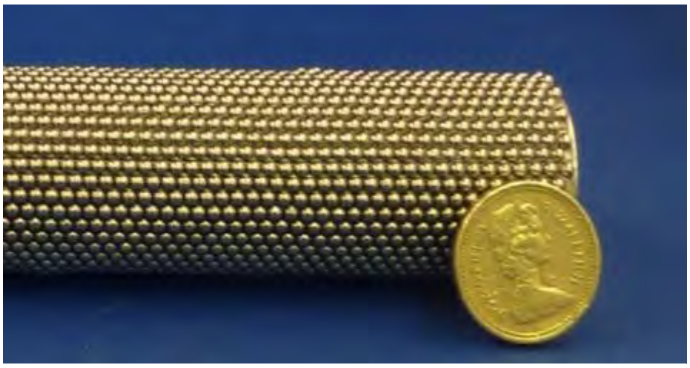


Figure 9: Image showing profiled roller; pound coin is used for scale purposes.

3.5 Impregnation

Impregnation of as received and spread fibre tows was conducted using a novel technique. Two USB microscopes (Veho Discovery VMS-004) were mounted facing each other in a rig.

The lenses of the microscopes were set equidistant from an observation window containing a pair of glass slides between which a 1 mm^2 graticule grid was placed. This allowed the measurement of longitudinal, transverse and through thickness impregnation.

A single drop of NOA 63 UV curing resin was dropped onto the centre of the fibre tow using a syringe (Biohit mLine precision syringe) which was mounted in place to ensure repeatable dispensing. The resin was allowed to impregnate for a set time and then cured using a UV light source. The residence times used for this study were 10, 20, 30, 40, 50, 60, 120, 180, 240, 300 and 600 seconds. Cured samples were cut to shorter lengths and then died using food colouring to enhance the contrast between impregnated and non-impregnated fibres. Images were then taken of the top side and the bottom side of the tow. For these images one slide was removed to enable the tow to be placed directly onto the graticule. The images were then analysed to determine the degree of longitudinal and transverse impregnation and also whether there was any through thickness impregnation. If through thickness impregnation had occurred the approximate area impregnated was calculated.

3.6 Fibre Damage Detection

In order to determine whether fibre tow damage could be visibly detected a short series of experiments were conducted. Lengths of as received fibre tow were prepared and attached to a white light source. Using a CCD camera attached to a binocular microscope (the same as was used for imaging the profiled rollers) images were taken to see if fibre damage was visible. The entire experimental set up was contained in a cardboard box to ensure a dark environment and enhance light detection. Fibre tows were damaged intentionally to measure visibility and determine a critical level of damage required for detection.

3.7 Filament Winding

Two set ups were used for the filament winding. One set of six tubes was hoop wound using the traditional method of a resin bath. The resin and hardener were however carefully measured out to reduce the amount of waste left at the end. The second set of 6 tubes was also hoop wound with a spreading station immediately before the resin bath. This was done to improve the impregnation of the fibre tows. Once a tube had been wound it was left, on the mandrel, to rotate for 24 hours in a mandrel rotation machine to allow the initial stage of curing, gelation, to occur. The mandrel was then removed from the mandrel rotating machine and placed in an oven at 70 °C for 6 hours to allow curing to occur. After the 6-hour cure cycle, the mandrel and filament wound tube were left to cool. Once at room temperature the mandrel was taken from the oven. The mandrel was then removed using a modified log-splitter leaving the filament wound tube.

3.8 Density and Fibre Volume Fraction

Density measurements were conducted on 10 samples from each of the filament wound tubes. Each sample measured 20 mm x 20 mm and was ground down to size after being cut from the tube. Using an Ohaus Analytical Plus mass balance samples were weighed in air then the sample buoyancy is measured by submerging the sample in water. The values from each of the measurements were then put into an equation along with the water temperature recorded at the time and values of density were obtained; the equation used (Equation 5) is shown below.

$$Sample\ Density = \frac{Sample\ Weight}{Sample\ Buoyancy} x\ Density\ of\ Liquid$$

Equation 5; Equation used to determine sample density of filament wound tubes.

The liquid density was determined using a chart provided by the balance manufacturer.

Fibre volume fraction was determined using the resin burn off technique as described in ASTM D171-09 Determination of Constituent Content of Composite Materials. A total of 8 density samples were placed in crucibles, weighed and then placed in a muffle furnace. The samples were heated to 625 ° C for 6 hours. The samples were then allowed to cool for 30 minutes and then the crucibles containing glass residue were weighed again.

3.9 Image Analysis

Density samples not used in resin burn off were potted and mounted to conduct image analysis. A number of samples were mounted in different orientations then ground and polished to an optical standard. The image analysis equipment was used to study fibre volume fraction and void content. A mosaic was taken of the entire sample in order to calculate the FVF and void content.

The experimental work on fibre spreading, binder burn-off, fibre damage and fibre bundle impregnation was conducted in conjunction with Naseem Arar BSc, University of Birmingham.

4.0 Results and Discussion

4.1 Fibre Spreading

With reference to the fibre spreading experiments from the tension-release rig, a total of 18 experiments were conducted using the Taguchi experiment matrix described in Section 4.3. From Figure 10, it is clear to see that the highest spreading values were attained at measurements point-1 (the serpentine rollers) and point-3 (the exit roller). The average values were taken from these two points for each of the 18 experiments and plotted in Figure 10.

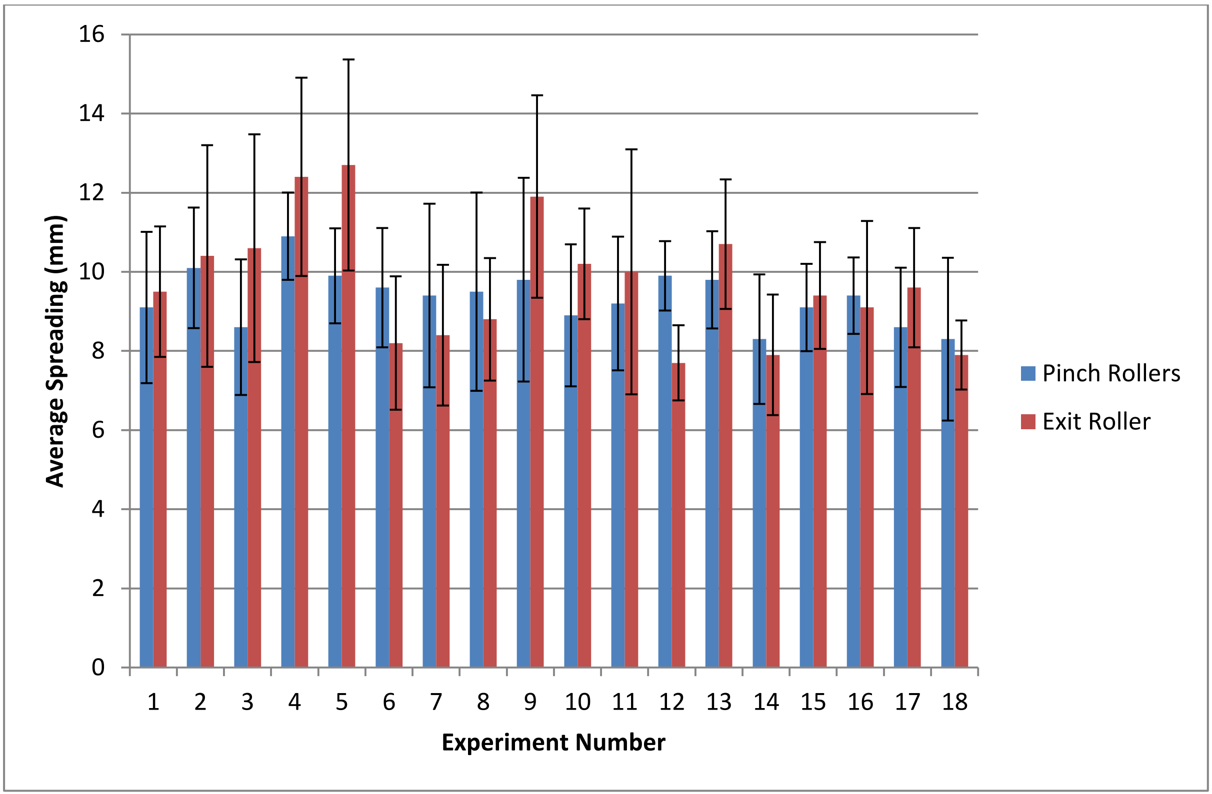


Figure 10: Graph showing the average spreading results and standard deviation for measurements taken at the serpentine rollers and exit roller of the tension-release system.

The highest values are obtained during the spreading experiments were measured at the exit rollers, 12.4 and 12.7. Inspecting the averages for measurements at the serpentine rollers (9.46) and the exit rollers (9.74), it can be seen that there is only a small difference between the two. Therefore, it may be possible that the serpentine rollers are as effective on average as the entire tension release system in spreading a fibre tow. However, it may also be a combined action of the tension-release system and serpentine rollers. This raises the question of whether the tension-release system is necessary when a simple set of serpentine rollers may be able to spread a fibre tow with the same results. The tension release system requires external power, a large amount of space compared to a set of serpentine rollers and it is complicated to change the configuration if necessary. On the other hand the serpentine rollers require no external power, take up minimal space and are easy to adjust if needed. The results from the fibre spreading experiments using the tension-release system were analysed using Taguchi analysis. This was done in order to determine the optimum parameters for the spreading the E-glass fibre tow. Figures 11, 12, 13 and 14 show the trend for each of the parameters; winding speed, pre-tension, disk rotation speed and configuration at the same measurement points. The Taguchi analysis results are more important for the data obtained from the exit rollers. This is because the serpentine rollers are situated prior to any of the parameters in the tension-release rig. The only parameter that will have a definite effect is the winding speed. Disc rotation and roller configuration will not influence the spreading at the serpentine rollers. The pre-tension and general tension in the system may have an effect on the spreading at the serpentine rollers.

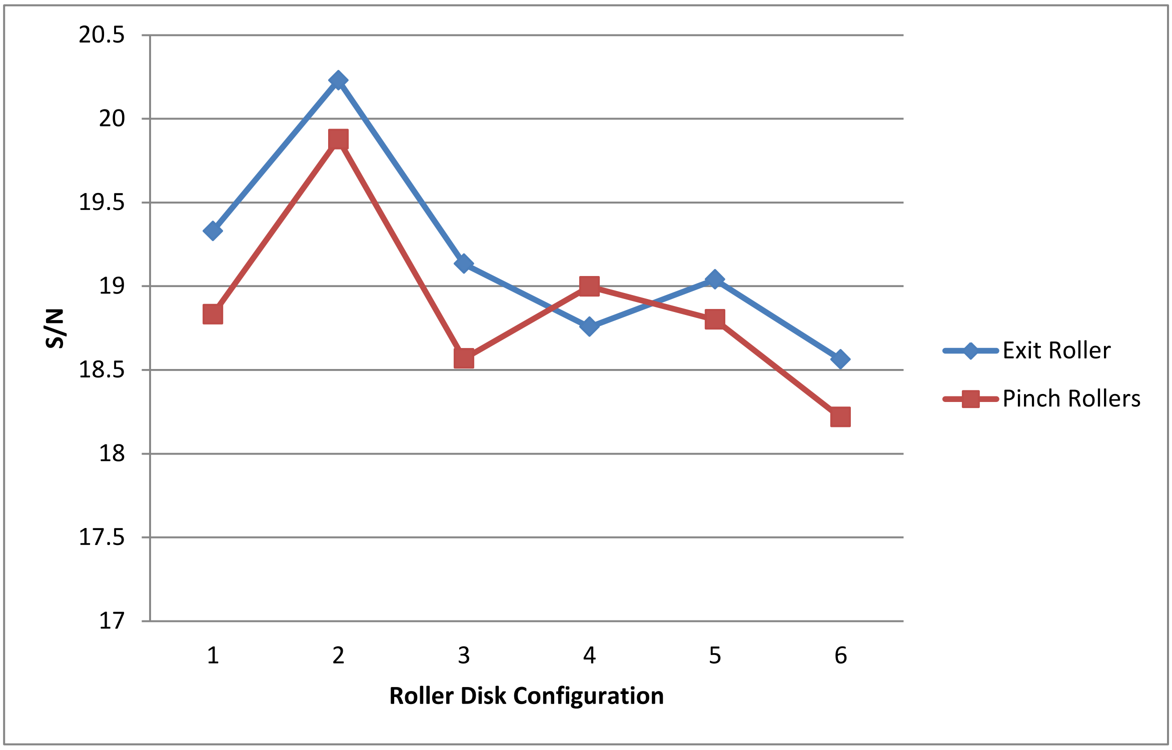


Figure 11: S/N graphs showing the optimum parameters for roller disc configuration.

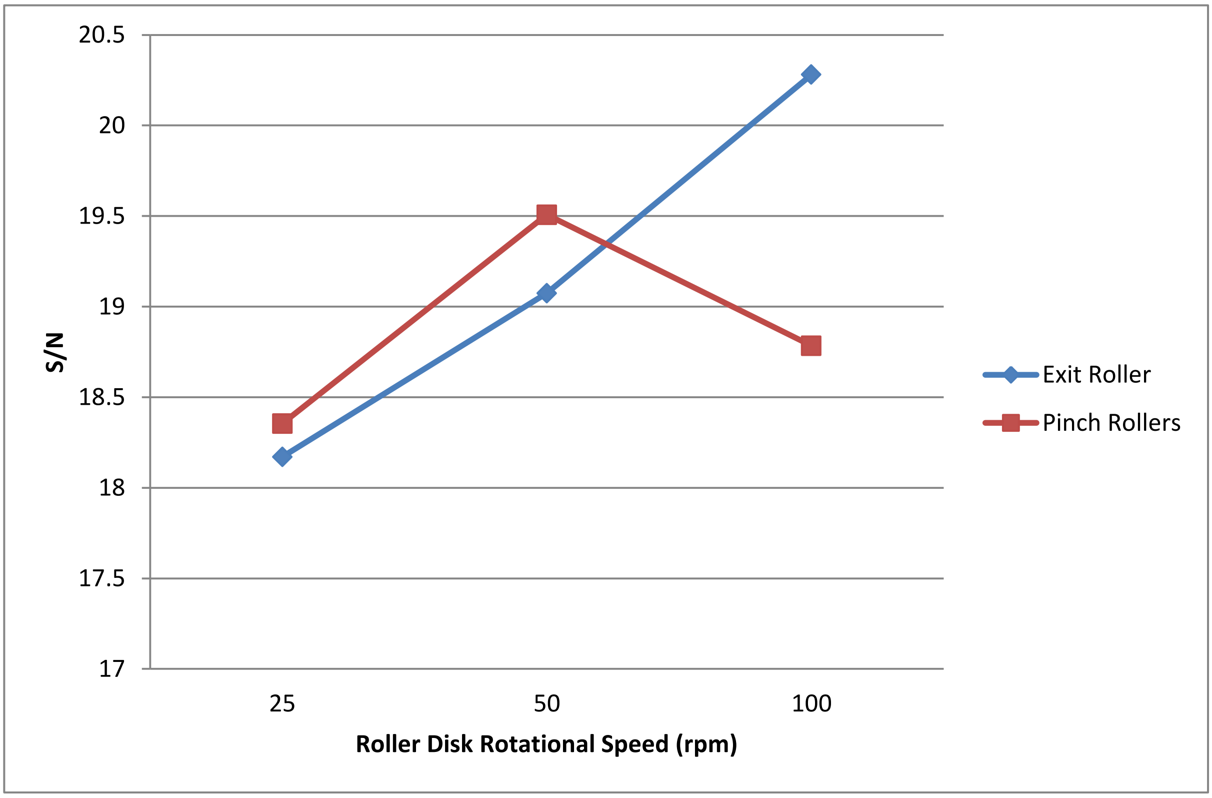


Figure 12: S/N graph showing optimum values for roller disc rotation speed.

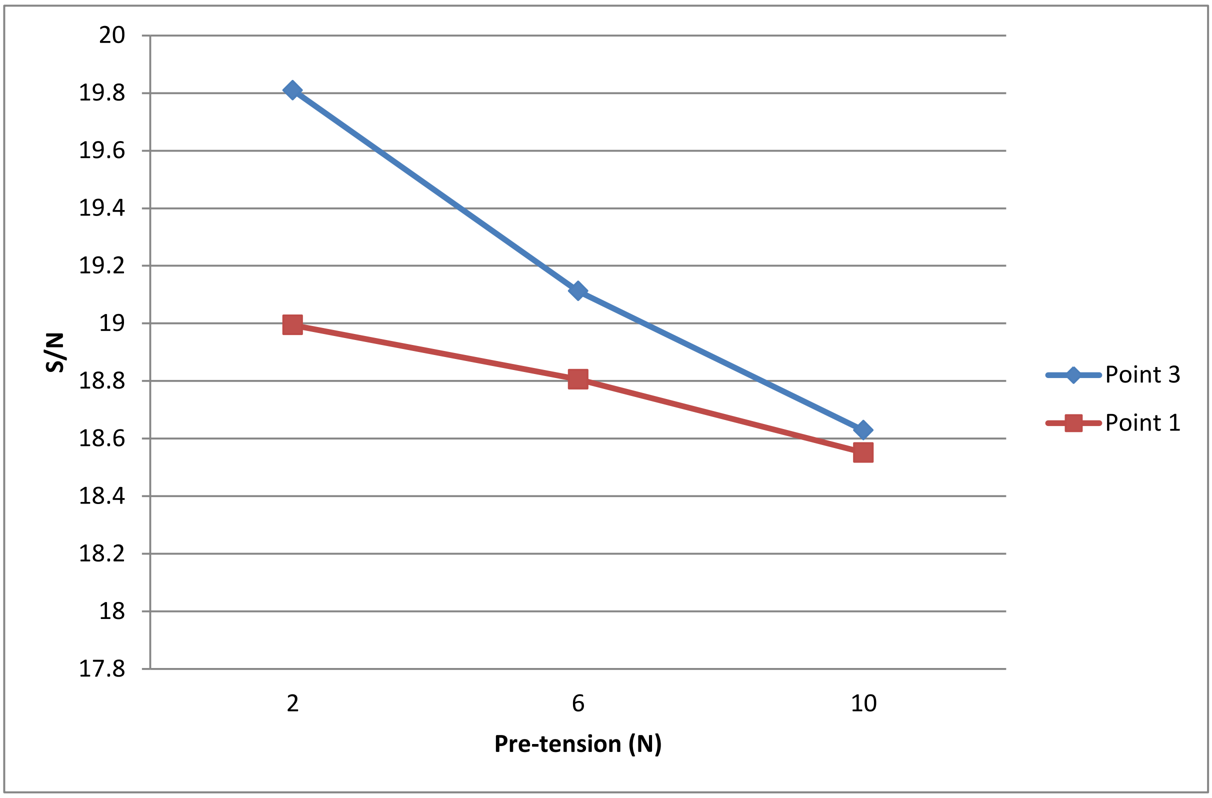


Figure 13: S/N graph showing optimum values for pre-tension.

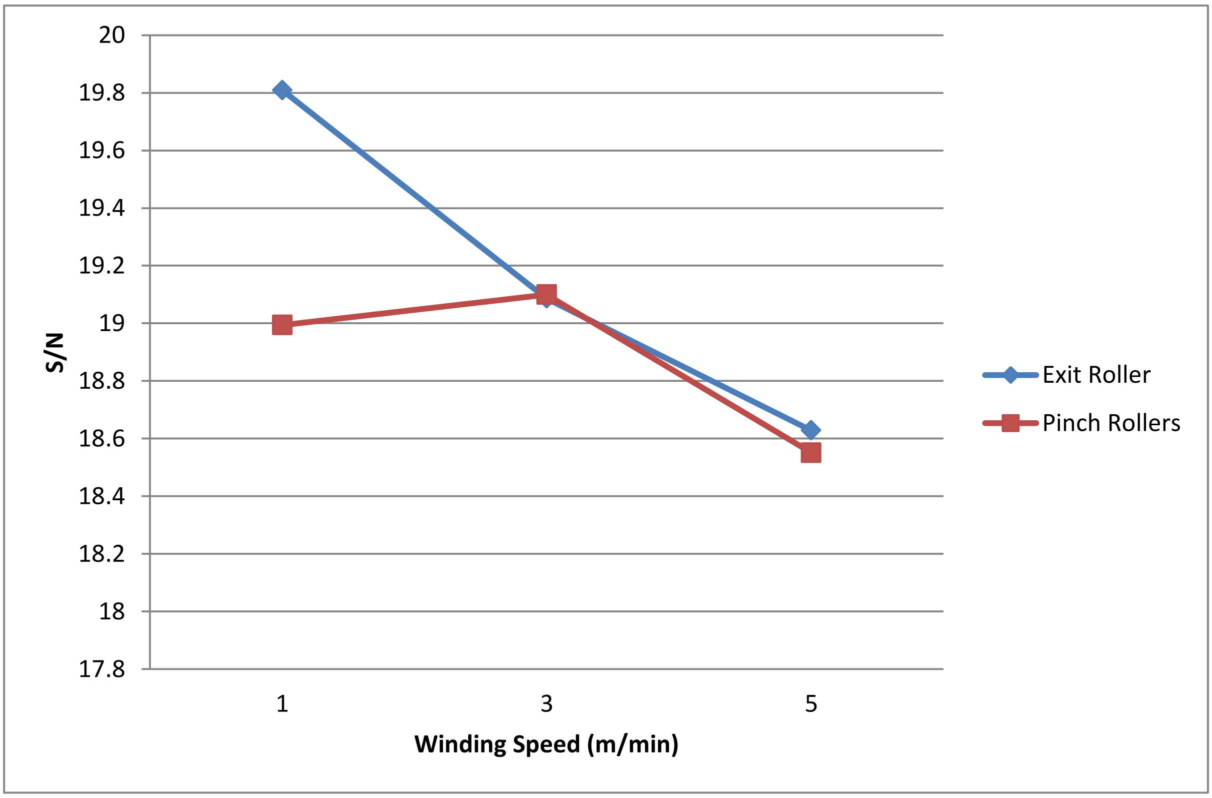


Figure 14: S/N graph showing optimum values for winding speed.

Using each of the S/N (signal-to-noise) graphs the optimum parameters for spreading a fibre tow using the tension-release system were obtained. According to Ross (1995) ‘The S/N (signal-to-noise ratio) is the term that is used in the Taguchi method to analyse the results of the experiments’. S/N represents the degree of variance in the experimental data. A higher S/N ratio is more desirable than a lower one. This is because a higher noise means a lower variability in the parameter being tested. This means that the highest value for each parameter was taken as the optimum condition. Therefore the optimum parameters were shown to be: configuration 2, a disc rotation speed of 100 rpm, a pre-tension of 2 N and a winding speed of 1 m/min. These were expected to be the best values. The low winding speed and high disc rotation allow for maximum tension release to be experienced by the fibre tow. The low pre-tension may act to reduce the overall tension release experienced by the fibre tow however with a higher tension it may be that there is more damage especially with configuration 2. Therefore using a lower pre-tension resulting in less damage may be more desirable. The results of an Analysis of Variance (ANOVA) are shown in Table 1 indicate that the biggest contribution to fibre bundle spreading is from the disc rotation speed. Followed by the configuration and then the tension and winding speed.

Table 1: Table showing results of the ANOVA test for the spreading of an E-glass fibre bundle.

ANOVA						
Factor	DOF	SS	MS	F-cal	F-tab	% contribution
Configuration	5	0.284	0.057	16.725	4.39	18.671
Tension	2	0.235	0.117	34.578	5.14	15.440
Speed	2	0.235	0.117	34.578	5.14	15.440
RPM	2	0.747	0.374	109.976	5.14	49.109
error	6	0.020	0.003			1.340

Total	17	1.521				

By looking at the experiment matrix we can see that the exact combination of optimum parameters was not used. The closest was experiment 4 which consisted of; configuration B (two rollers, see Table 1), a pre-tension of 2 N, a winding speed of 1 m/min and a disc rotation of 50 rpm.

The second set of fibre spreading experiments involved the use of the Prototype-V spreading station shown in Figures 8a and 8b in Section 4.3. The optimum values for tension and winding speed obtained from Taguchi analysis (associated with the tension-release rig) were used. The roller configuration was different because Prototype-V incorporates simple rollers or profiled rollers. Seven configurations were used. There were two extremes; configuration-1 with all plain rollers and configuration-6 with all profiled rollers. The profiled rollers were designed and built in house and their manufacture is described in the experimental methods section. All the other configurations involved a combination of plain and profiled rollers. See Table 2 for the combinations used.

Table 2: Table showing all the configurations used and the type of roller used at each position.

Configuration	Roller One	Roller Two	Roller 3
1	Plain	Plain	Plain
2	Plain	Plain	Profiled
3	Plain	Profiled	Profiled
4	Profiled	Profiled	Plain
5	Profiled	Plain	Plain
6	Profiled	Profiled	Profiled

7	Plain	Profiled	Plain

Figure 15 shows the average fibre spreading results for measurements taken at the serpentine rollers and the exit rollers for the Prototype-V spreading rig. The average spreading at the serpentine rollers for all experiments was 9.64 mm compared to at the exit roller which had an average spreading of 8.92 mm. As with the tension-release system the question is whether a series of serpentine rollers would be a more simple more effective method. Using the graph the optimum configuration for spreading a single fibre tow was chosen.

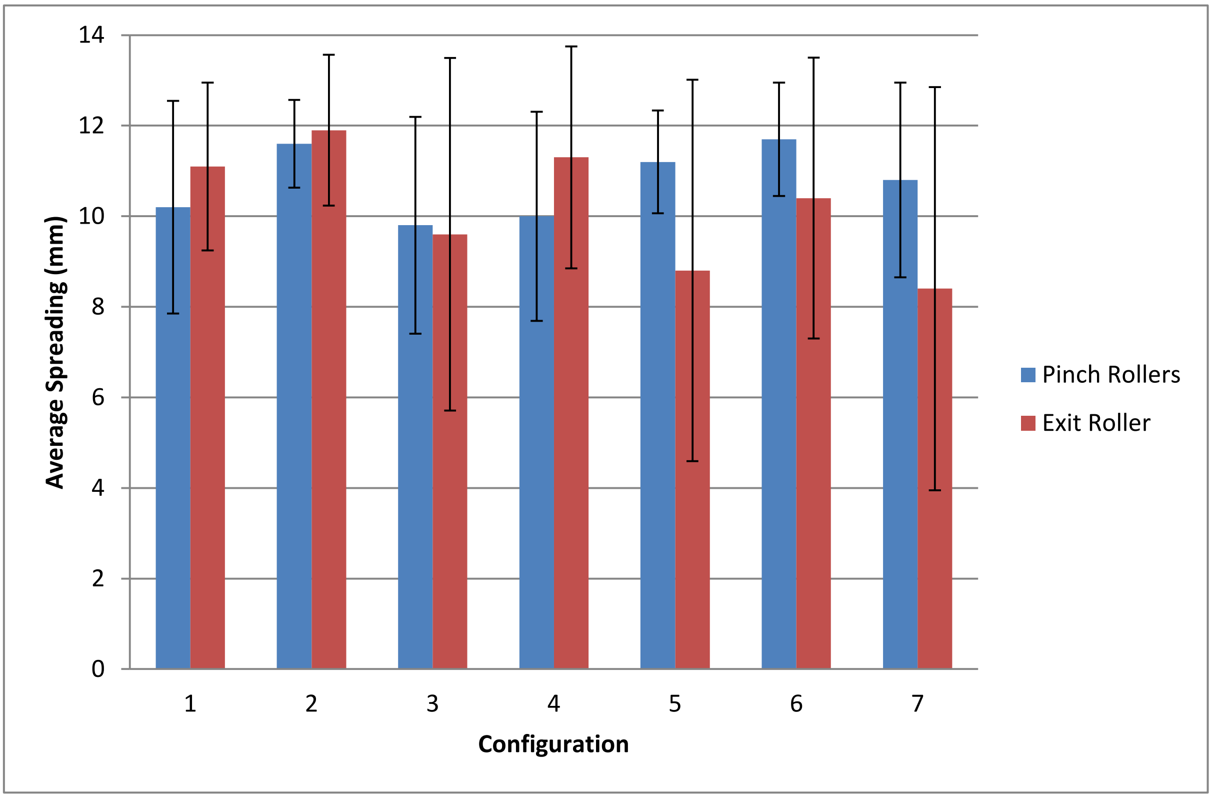


Figure 15: Graph showing the average spreading for measurements taken at the serpentine rollers and exit roller during the Prototype-V spreading station trials.

From the graph it can be seen that the best spreading was achieved using configuration-2. Configuration 1, all plain rollers, also produced 100 % spreading and had lower variance in the results than most others. It is also noted from the graph that the standard deviations for values measured at the serpentine rollers is in general smaller than that for those measured at the exit rollers. This suggests that the serpentine rollers are more consistent for spreading.

There are however fewer influencing factors for the serpentine rollers. Another observation for the serpentine rollers is that they consistently reached 100 % spreading on average when compared to the as-received fibre bundles. With the exit rollers it can be seen that 3 of the 7 configurations recorded an average below 100 % spreading. The large scatter seen for some of the configurations is most likely due to the twist that inherently occurs on occasion with centre-pulled creels.

4.1.1 Multi-tow Spreading

Using the optimised Prototype-V spreading set up experiments were conducted to determine the degree of spreading when multiple tows were used. Three configurations were chosen; two extremes configuration 1 and 6 (all plain or all profiled rollers) and configuration 2 which was deemed to be the most effective during single tow spreading, as discussed in Section 4.1. Initially, 3 tows were used then further experiments were conducted with 6 tows. The reason for these experiments was to determine the effect on the effectiveness of the system in spreading fibre bundles with adding tows. As more tows are added the baseline tension in the system increases which could inhibit spreading if it reaches too high a level. The same method was used as with the previous Prototype-V experiments.

The measurements at the serpentine roller and the exit roller of the Prototype-V system were the two points analysed and compared. Figure 16 shows the results for measurements taken at the serpentine rollers. It can be seen that there is a decrease in spreading in all configurations from 1 tow to 6 tows. This is most likely due to the increase in tension at the serpentine rollers caused by adding more fibre tows to the system. However it is important to note that even though there is a decrease in average spreading, the error bars show for most of the configurations that 100 % spreading, from the as-received width, is still achievable.

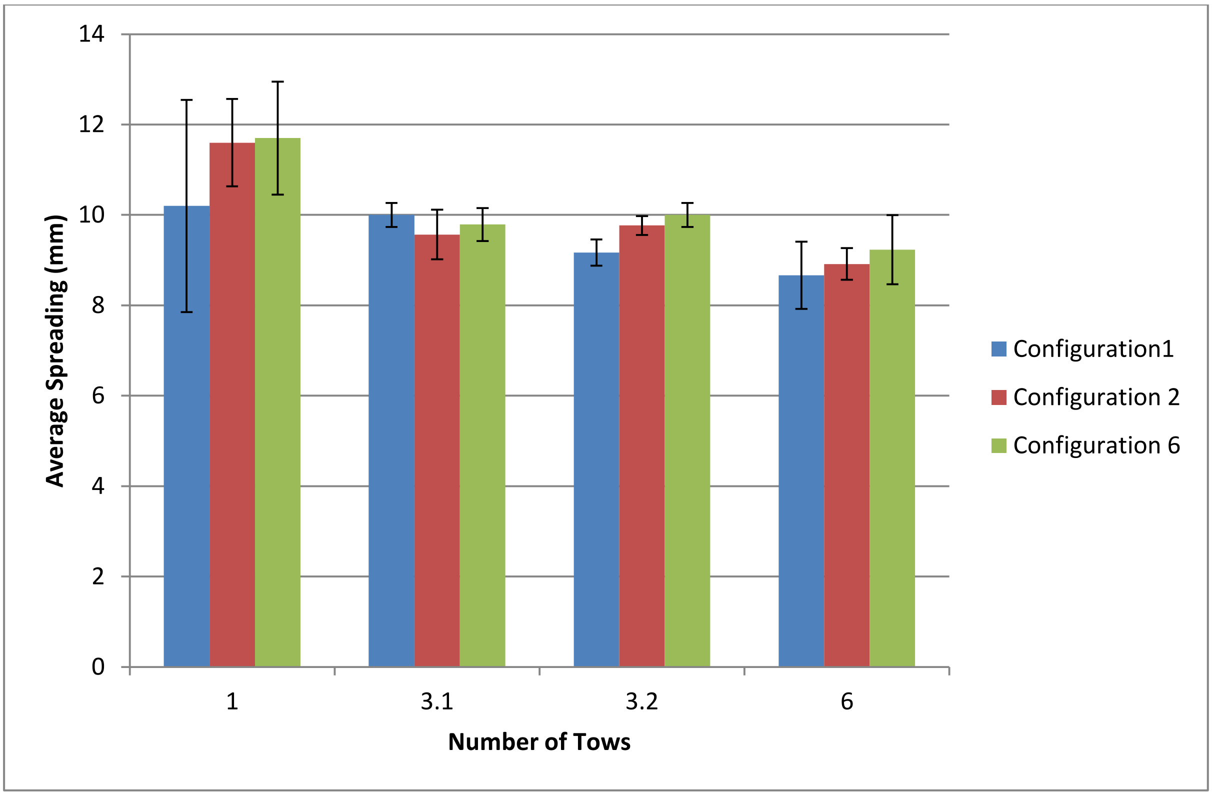


Figure 16: Graph showing average spreading at the serpentine rollers for trials with 1, 3 and 6 tows. Two trials were conducted with 3 tows, the first number refers to the number of tows, the second to the trial number i.e. 3.1 is 3 tows, trial number 1.

The increase of the tow width is sufficient for an improvement in through thickness impregnation. The evidence for this will be discussed in the impregnation section. In the literature it has been suggested that by spreading the fibre tow it is possible to increase tow width whilst decreasing tow thickness which aids impregnation (Wilson, 1997). By decreasing the tow thickness the impregnating liquid has less distance to travel. Bates *et al* 2000 also showed that the presence of a pin or bar increases impregnation through an increase in pressure at the contact point.

Figure 17 shows the results for measurements taken from the exit roller of the system. As with the serpentine rollers it can be seen that for each configuration there is a decrease in the average spreading recorded from one tow when more tows are added. However for these results the percentage spreading has also decreased and there are fewer measurements reaching 100 % spreading. The most likely reason for the decrease in average spreading as more tows are added is again most likely due to the increase in tension (tension increased from an average of 3 N to 5 N from one tow to three tows). This will be greater at the exit roller due to the increased tension both at the serpentine rollers and in the spreading station itself. The results for configuration 1 do not fit the same trend as for the other configurations. One possible reason for this is that during the one tow experiments there were more twists observed which would drop the average spreading below that when 3 tows were used. The twists in the creel are unavoidable due to the tow being centre pulled. The occurrence of the twists does not appear to have any relation to the area of the creel the tow is coming from. There does not seem to be any regularity to the appearance of the twist or the influence of the twists on the spreading as has been shown in a previous section.

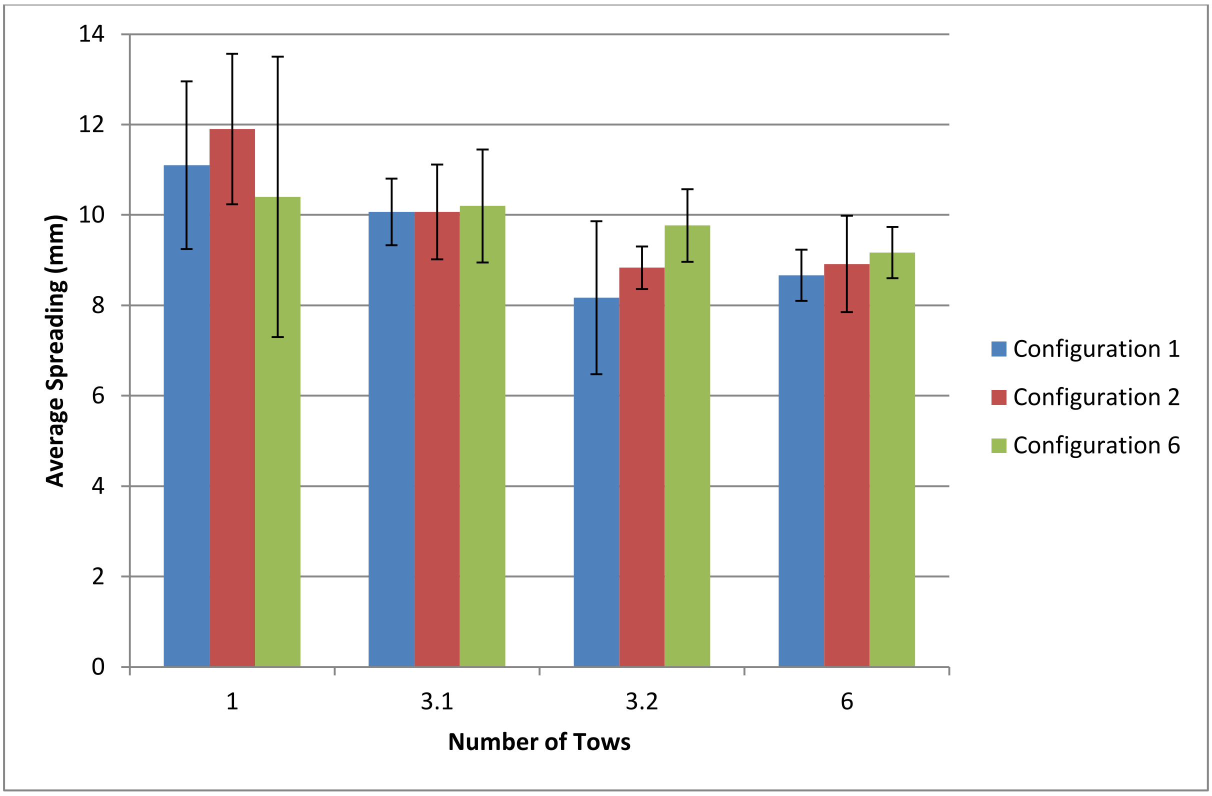


Figure 17: Graphs showing average spreading for measurements taken at the exit roller using 1, 3 and 6 tows.

Another important observation in from the data is that the average data for the serpentine rollers is in similar to the average data from the exit roller. This trend has been observed in the tension release system. As well as this, by looking at the standard deviation it can be seen that there appears to be less variance in the measurements. Especially when looking at the two experiments involving 3 tows. Therefore it is proposed for further work that a bank of serpentine rollers in series should be tested to determine the degree of spreading achievable with such as set-up.

4.1.2 Measurement of Tow Twist

As the tow is centre pulled from the creel a twist can occur periodically throughout the tow. The occurrence of a twist is a regular occurrence coming from the creel, however whether or not that twist remains twisted as it enters the system would appear to be random. It was also noted that when a twist does enter the system the effect on the spreading would also appear to be random. The extent to which this twist affects the fibre spreading was therefore analysed and these are presented in Figure 18.

The graph shows the spread measured at the final roller and the length of fibre tow affected by the twist. A critical value of 10 mm was set and any value under that was said to have been affected by the twist. The spread at the final roller is relatively consistent with values ranging from 10-12 mm with the average spread being 11.15 mm. However it appears that the effect of the twist is much more irregular with values ranging from 75 mm to 130; the average was 106.45 mm. The twist will affect the impregnation of the fibre tow which is undesirable.

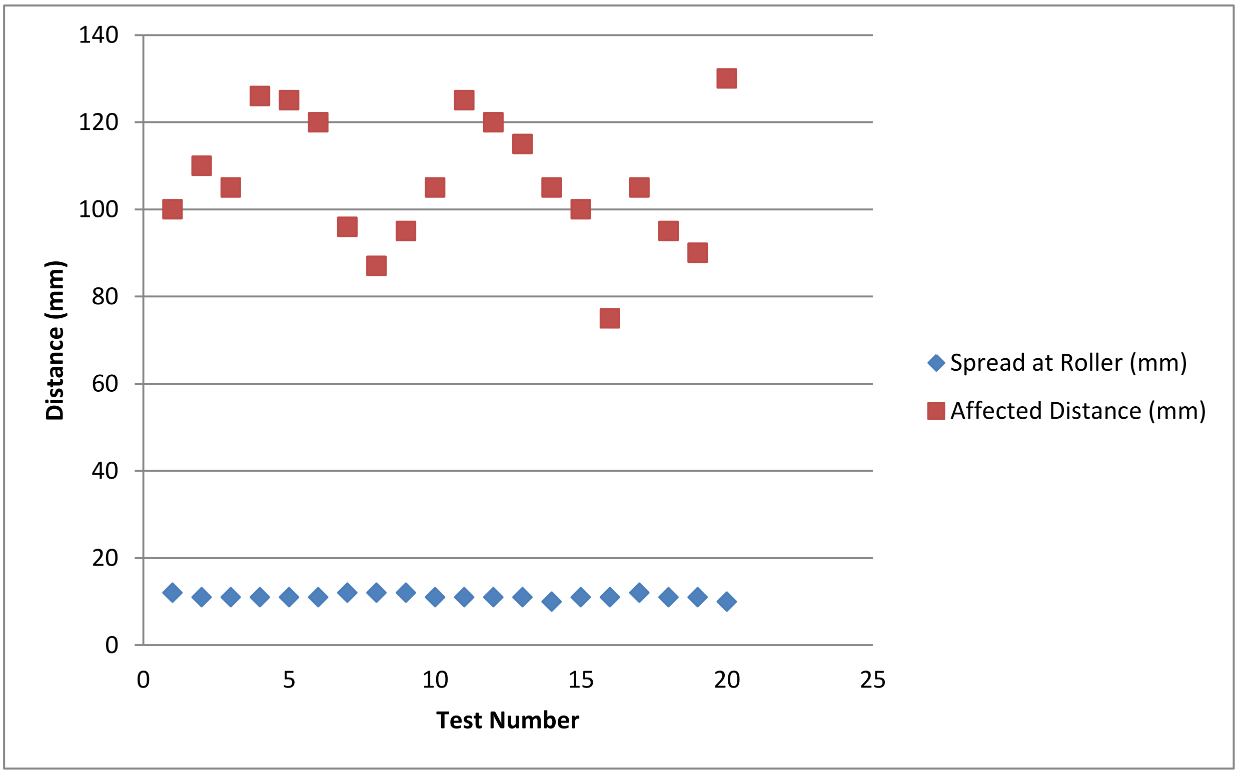


Figure 18: Graph showing the spreading at the serpentine rollers and the length of the tow affected by the twist.

A second series of experiments were conducted to determine whether a twist in the tow has an effect on neighbouring tows during multi-tow spreading. When a twist occurred at the serpentine rollers the width of all 3 tows was measured and recorded. Table 3 shows the results. Values in red boxes highlight a twisted tow.

Table 3: Table showing measured values of spreading when a twist occurs in one or more tows. Twisted tows are highlighted in red cells. The experiments were conducted using the Prototype-V spreading rig with a 3 E-glass fibre bundles.

Twist 3 Tows	1	2	3
1	4	9	12
2	12	7	11
3	11	6	9
4	10	5	10
5	4	9	11
6	11	9	7
7	12	9	6
8	13	10	5
9	11	11	5
10	12	5	11
11	11	6	10
12	5	8	11
13	5	9	10
14	4	11	10
15	11	6	5

16	5	6	9
17	12	12	6
18	5	11	6
19	5	10	6
20	9	4	12

Some of the time two tows were twisted. The lowest spreading measured in a non-twisted tow is 8 mm which is 60% spreading from the as received value of 5 mm. The highest spread measured in a non-twisted tow was 13 which is a 160% increase in tow width.

From the above results it appears that when there is a twisted tow, the other two tows tend to reach 100% or near 100% spreading. This can also be said for when there are two tows twisted. Out of four measurements where two tows were twisted only one was less than 100% increase in tow width and this was still 80% spreading.

4.1.3 Effect of Binder Content on Spreading

Binder is added to fibres during the manufacturing process. It helps to protect the fibres and maintain the bundle preventing fraying. It is therefore important during spreading to reverse this by breaking up the binder. However in doing this it is also important to keep fibre damage to a minimum. To determine the effect of the binder content on the spreading of a fibre tow two sets of experiments were conducted.

The first experiment had two parts. Firstly spreading experiments were conducted where the fibre was taken from a different part of the creel in the through-thickness direction i.e. inner bore, the centre of the creel or the outside of the creel. The results are shown below in Figure 19.

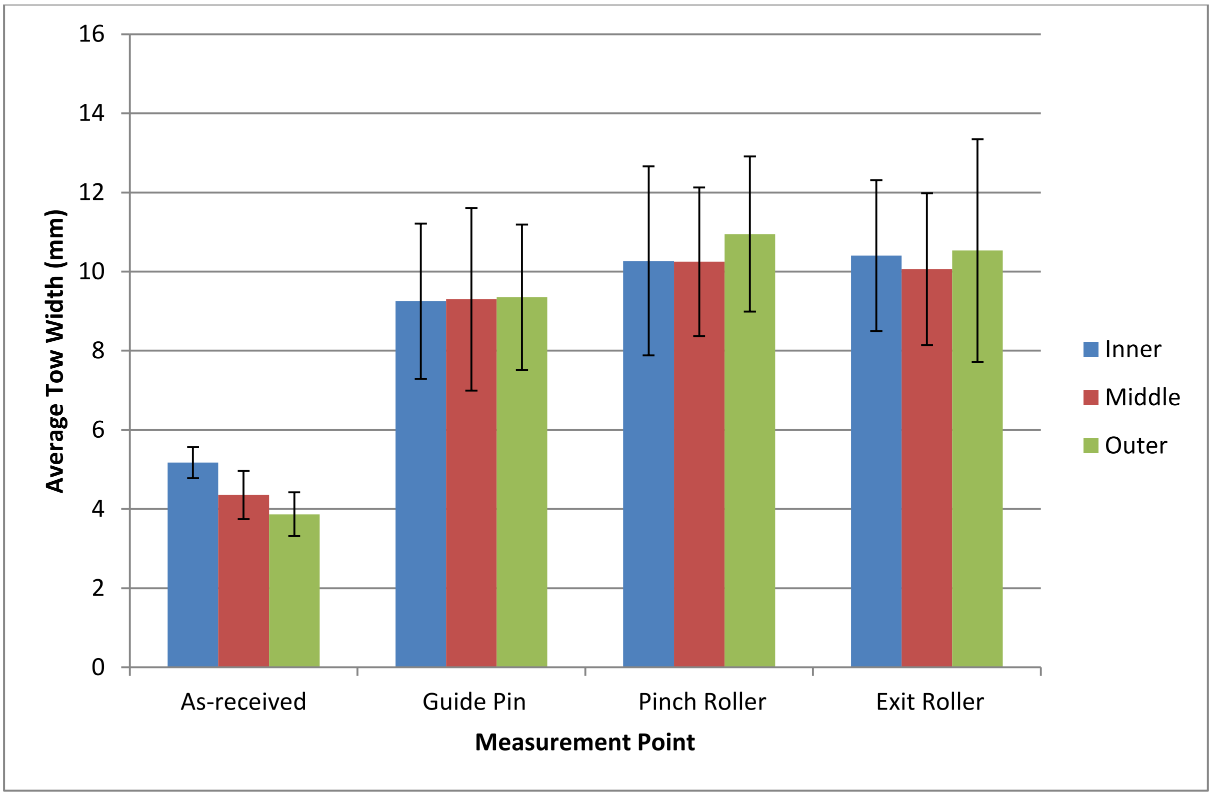


Figure 19: Graph showing the change in spreading at different regions of the creel (through-thickness). Inner bore, middle of the creel and the outer section.

As can be seen from the graph most of the measurements showed 100 % spreading throughout the thickness of the creel. The measurements at the serpentine rollers and exit roller are all over 100 % with a small difference between results for the different areas of the creel. The biggest difference is in the as-received measurement of the tow. There is a decrease of 1 mm from the inner bore to the outer section of the creel. To determine a possible reason for this a second test was conducted for this part of the experiment. Samples of as-received fibre from each of the 3 sections were kept. This was to allow fibre burn-off tests to be conducted, according to ASTM D4963/D4963M – 11. The results for this are shown in Table 4.

From the table it can be seen that the binder content does vary however there isn't any apparent relationship between the position from which the fibre comes and the loss on ignition of the fibre. The highest loss on ignition was found for samples taken from the middle of the creel, 0.744 and 0.671 were the two highest recorded values. However, the other values obtained from the middle of the creel were 0.490 and 0.566 which are similar to values obtained from the other creel positions. It would appear therefore that the binder content does not affect the as-received width of the tow. As is shown previously the fibre near the inner bore of the creel had an average as-received width of 5.278 mm compared to 4.201 mm and 3.877 mm for as-received width at the centre and outside of the creel respectively. From the loss on ignition results it is not possible to link the width of the as-received tow with binder content and position in the creel. One possible explanation for the change in tow width is an increase in tension as the tow is wound onto a creel. As the creel becomes thicker the tension in the tow being wrapped around the creel may increase causing the variance in tow width. The highlighted data in the table refers to anomalies in the data. All the other results are relatively similar. No explanation for this has been determined so far.

Table 4: Results of the ignition loss tests of E-glass bundles taken from different regions of the creel through-thickness. Inner bore, middle of the creel and outside of the creel. R refers to work conducted by the author, Richard Murray, N refers to work conducted by Naseem Arar. I, M and O refer to the inner, middle and outer sections of the creel respectively.

Test	Fibre	Crucible	Fibre and Crucible	Post Burn-Off	Ignition Loss %
R-I	5.12	15.30	20.42	20.49	-1.31
R-I	5.08	16.80	21.94	21.86	1.48
R-M	5.08	15.30	20.39	20.35	0.67
R-M	5.51	16.80	22.32	22.29	0.49
R-O	5.59	15.30	20.89	20.86	0.56
R-O	5.52	16.80	22.31	22.28	0.57

N-I	5.12	15.30	20.42	20.39	0.55
N-I	5.08	16.80	21.88	21.85	0.54
N-M	5.10	16.30	20.41	20.38	0.74
N-M	5.03	16.80	21.83	21.80	0.57
N-O	5.24	15.30	20.54	20.51	0.57
N-O	5.14	16.80	21.94	21.91	0.61

4.2 Profiled Rollers

As described in the experimental methods section profiled rollers were manufactured in house and used in the Prototype-V spreading experiments. To determine the quality of the rollers image analysis was conducted. Images were taken along the length of the roller at four different points. This was done in order to determine the regularity of the ball bearings and the resin level.

4.2.1. Image Analysis

From the images it can be seen that there is a regular distribution of ball bearings on the surface of the rollers. There is however a difference in the resin level around the roller. This could occur when the roller undergoes the second stage of curing. The resin could pool at the lowest part of the roller. To counter this in future a rotation device could be incorporated so that the rollers remain rotating throughout the cure cycle.

4.3 Impregnation

Impregnation experiments were conducted using two different glass fibres both in the as received and spread conditions. Each individual experiment was filmed and the samples were imaged top and bottom post cure. Due to a software issue the films were not of a high enough standard to determine impregnation rate in real time as was the plan. Therefore using the top and bottom images of the samples measurements of impregnation were taken in the longitudinal, transverse and through thickness direction. Using the top image longitudinal and transverse measurements were made and through thickness was measured as an estimated area using the bottom image. From the measurements graphs were compiled showing the range of results from 10 seconds to 10 minutes. During analysis of the graphs it was found that with an increase in impregnation time there was in increase in longitudinal impregnation. However transverse impregnation remained relatively constant. The biggest change was with through thickness impregnation. During shorter impregnation times, similar to those experienced by a fibre during filament winding, there was no observable through thickness impregnation. For as received sample of fibre type 1 there was no observed through thickness impregnation until an impregnation time of 50 seconds which is much longer than would be normal during a manufacturing process. A similar trend is seen for fibre type 2 where there isn't consistent through thickness impregnation until an impregnation time of 2 minutes. However there was some through thickness impregnation observed at 30 and 50 seconds. This could have been due to splitting in the fibre bundle prior to the impregnation allowing the resin to pass through the bundle. During analysis it was decided to concentrate on the results for impregnation times of 0-120 seconds. This range is closer to the times experienced by a fibre tow during a real filament winding process.

As well as as-received samples spread samples were made and impregnated as well. The spreading was done using the Prototype-V spreading station using the optimal parameters found during the spreading experiments. Samples were spread to 8 mm in width and then impregnated using the same method and procedure as with as received samples. During analysis it was found that there was both and increase in longitudinal and through thickness impregnation with an increase in impregnation time. Similar to what was seen with as received fibres the transverse impregnation remains relatively constant with an increase in impregnation rate.

From the graphs it can be seen that spreading the fibres has two main effects. Firstly the through thickness impregnation occurs at lower impregnation times. For example for fibre type 1 through thickness impregnation is apparent at 30 seconds for spread samples whereas for as received samples this does not occur until 50 seconds. Secondly, the spread fibres have a greater area of through thickness impregnation compared to as received. From the fibre type one results it can be seen that after 30 seconds the measured through thickness impregnated area is greater for spread samples compared to as received samples. There is one result that does not fit this however the difference in area between the spread and as received sample is only 2 mm. The reason for through thickness impregnation occurring more quickly and having a larger area in spread samples is due to the effects of the spreading process. During spreading the fibre bundle becomes thinner, therefore there is less distance for the impregnating liquid to travel to fully penetrate the fibre bundle in the Z direction. Another observation during analysis was the lower longitudinal impregnation for spread samples when compared with as received samples. One possible reason is that the greater through thickness impregnation effects the overall longitudinal impregnation. The increased driving force created in the z-direction by having a thinner bundle will inhibit the longitudinal flow of the liquid on the surface of the fibre. The effect is more apparent with a greater area of through thickness impregnation.

Longitudinal impregnation occurs throughout the fibre bundle on each level. Initially the impregnating liquid will flow across the surface of the bundle. In an as received bundle the flow is quick across the surface as there is little through thickness impregnation. With a spread fibre the through thickness impregnation increases but the available channels for the resin to flow in in both X,Y and Z directions has increased meaning reduced flow in the longitudinal, X, direction.

4.4 Fibre Damage Detection

Prepared fibre bundles were imaged using an optical microscope with a CCD camera. Using a white light source it was determined that it is possible to detect fibre damage in a bundle. A comparison between as received fibre bundles and fibre bundles that had been passed through serpentine rollers was conducted. Initial observation showed that fibre damage was visible in both samples however the cut was brighter in the as received fibres, for the same light intensity. This is most likely due to the fibres being more closely packed in the bundle compared to the fibres in a bundle that has been spread. Figure 20 shows an as received fibre bundle, a damaged as received bundle, a spread fibre bundle and a damaged spread fibre bundle. The specks of light are caused due to surface illumination of dirt on the bundle. Samples were cut at different distances from the light source. It was found that the further away from the light-source the damage was the less light escaped from the cut. However, even at a distance of 15 mm the damage was still visible at the same light intensity used for 5 mm.

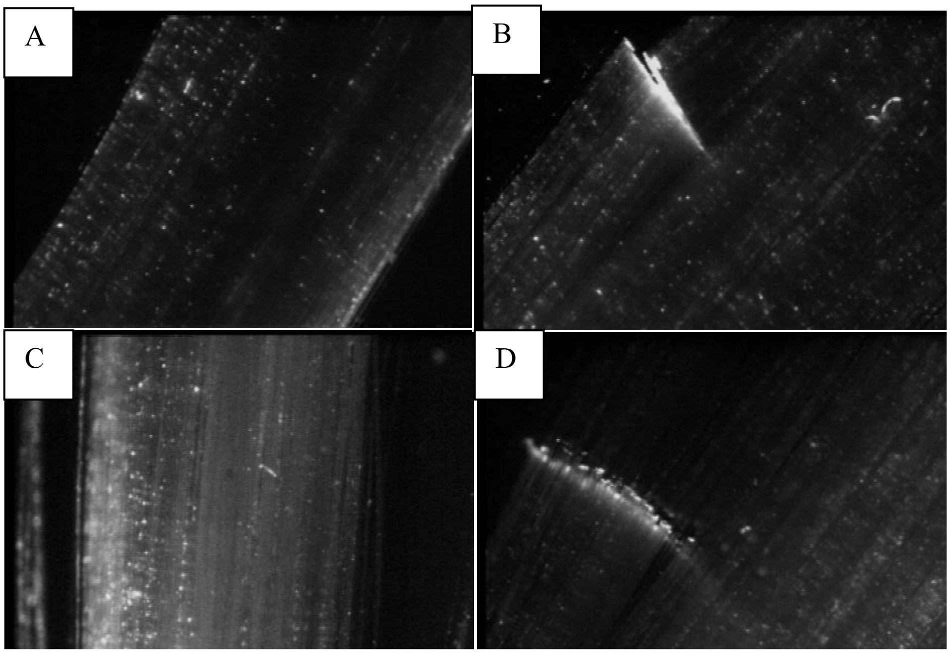


Figure 20: Images of fibre damage detection studies. a) As-received bundle b) Damaged as-received bundle c) Spread bundle d) Damaged bundle.

4.5 Density and Fibre Volume Fraction

Using ASTM D792-08 samples from tubes wound using only the resin bath and tubes wound using the spreading station in addition to the resin bath were measured for density. Figure 21 shows the results for both sets of samples. From Figure 21 it can be seen that the samples taken from the tube wound using a resin bath have a higher density. The average densities for all the samples across all 6 tubes wound were 1.87 and 1.80 for the resin bath tubes and the spreading tubes respectively.

It can also be seen that there is slightly less variation in the densities of the tubes wound using the spreading station. The average standard deviation for the densities of the spread tubes is 0.01 whereas for the tubes wound just with the resin bath the average standard deviation is 0.04.

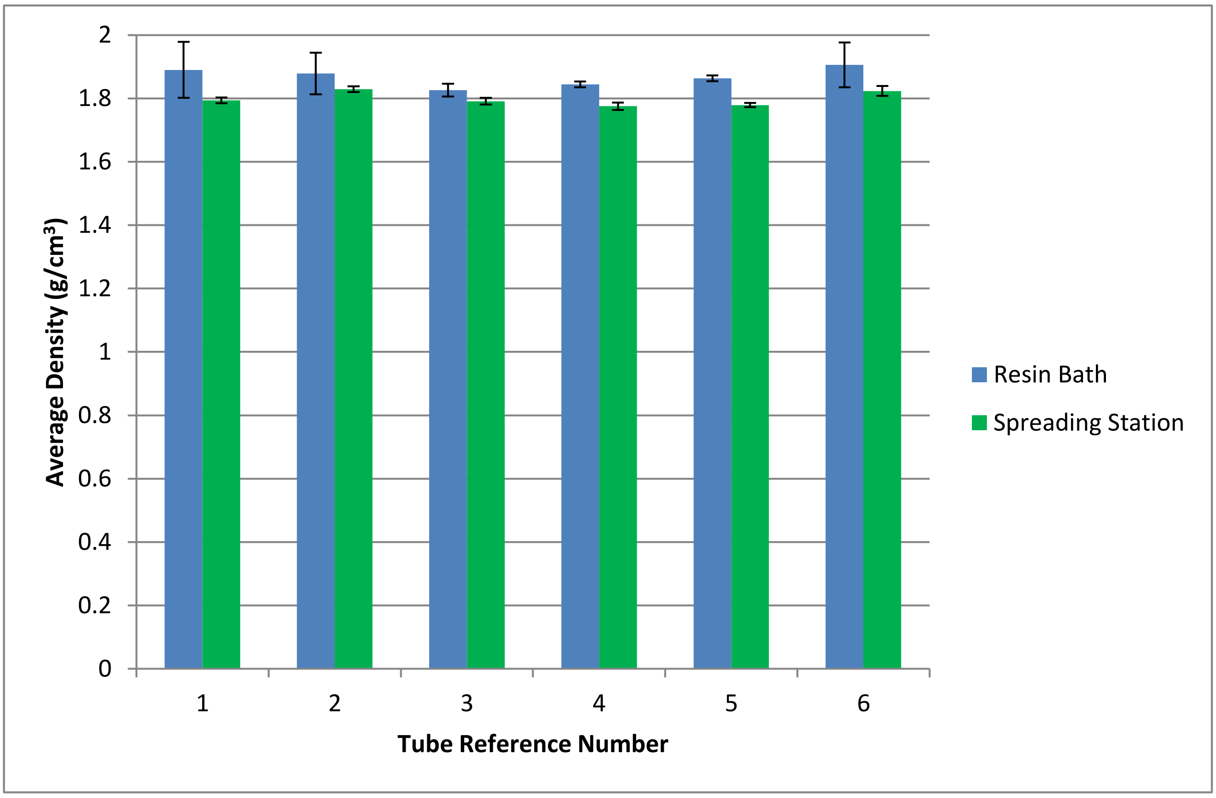


Figure 21: Graph showing average density measurements for samples wound using just the resin bath and those wound using the spreading station prior to the resin bath.

The fibre volume fraction shows a similar trend in that the tubes wound using only the resin bath have a higher volume fraction than those incorporating the spreading station. However the difference between the two sets of data is more significant than seen for the density. Figure 22 shows the data for the burn-off experiments described in the experimental methods section.

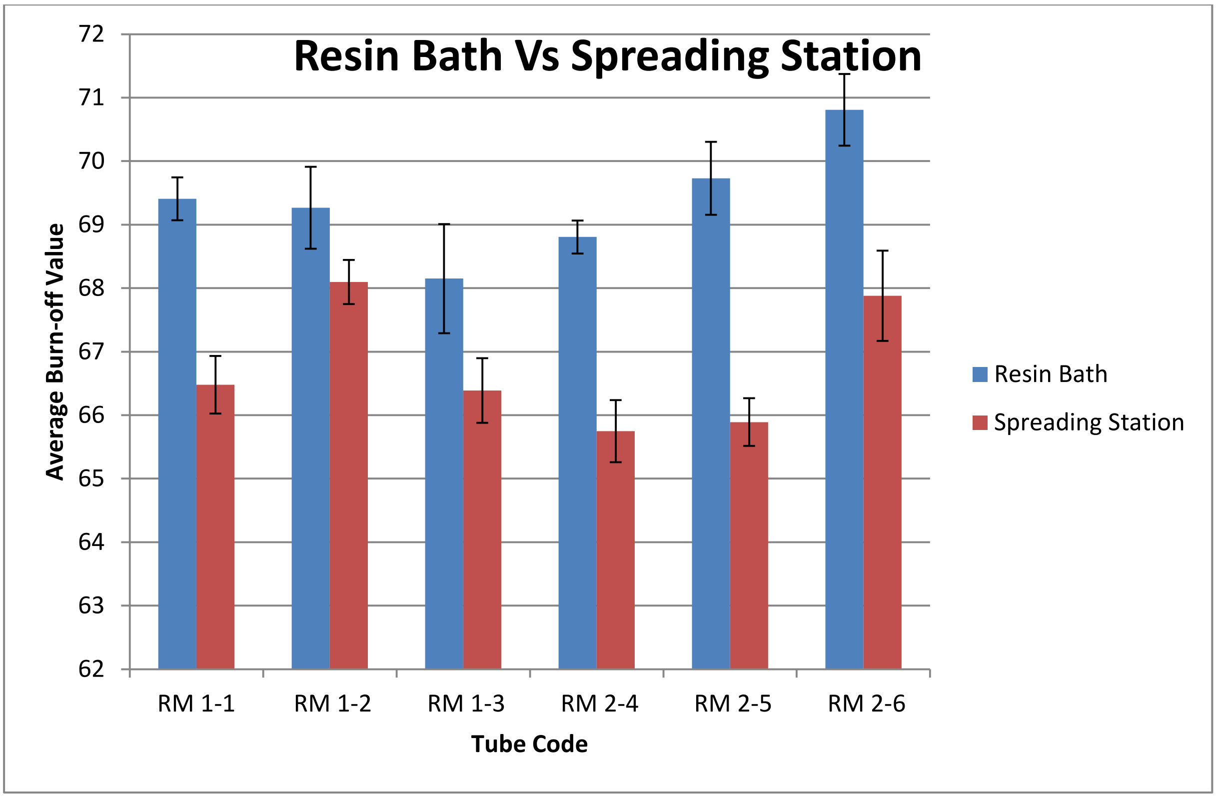


Figure 22: Graph showing the average FVF of samples wound using only the resin bath and those wound using both the resin bath and spreading station.

From the graph it is clear to see that the tubes wound using the resin bath have on average a greater volume fraction. The average volume fractions for the two data sets are 69.36 and 66.74 for the tubes wound using the resin bath and those with the spreading station respectively. This drop in FVF can be explained by a drop in tension associated with using the spreading station. With the resin bath it is necessary to use an extra pre-tension system between the creels and the bath. Using this system the tension is approximately 30 N at the extremes of the mandrel and approximately 25 N at the centre. In contrast when using the spreading station no extra pre-tension is required. Due to the spreading station being located directly in-line with the bath there is a drop in tension. With this system the tension is constant at 16 N across the entire mandrel. Previous studies as mentioned in the literature review section have shown that an increase in winding tension results in an increase in the

FVF of the final product. For example Mertiny & Ellyin (2002), Chen & Chiao (1996) and Kugler & Moon (2002) all found that an increase in winding tension generally resulted in an increase in the FVF.

4.6 Image Analysis

A selection of samples from each filament wound tube were mounted, ground and polished for image analysis. Images were taken a 5x, 10x and 20x magnification.

The dark regions that can be seen in the images are voids in the sample. These images only give a snap shot of the tube as a whole. It appears that there are more voids in these sample than would be suggested by the void content obtained using resin burn-off. However the void content obtained using resin burn-off is a more accurate representation.

During analysis of the images of tubes wound using the resin bath and those wound using the spreading station there didn’t appear to be a large difference in the appearance. For the resin bath tubes the fibre bed was more compacted at the mandrel edge than the spreading station samples. However, closer to the surface there appeared to be little difference in the fibre compaction.

Both sets of samples exhibited a more ordered and uniform edge, the edge in contact with the mandrel, and a less ordered edge, the outside edge.

This pattern as mentioned earlier is to do with which side was in contact with the mandrel but also the tension that occurs. As more layers are wound onto the tube the tension in the outer layers increases. The increase in tension results in resin being forced through the fibre bed as well as the fibre bundles becoming more compacted.

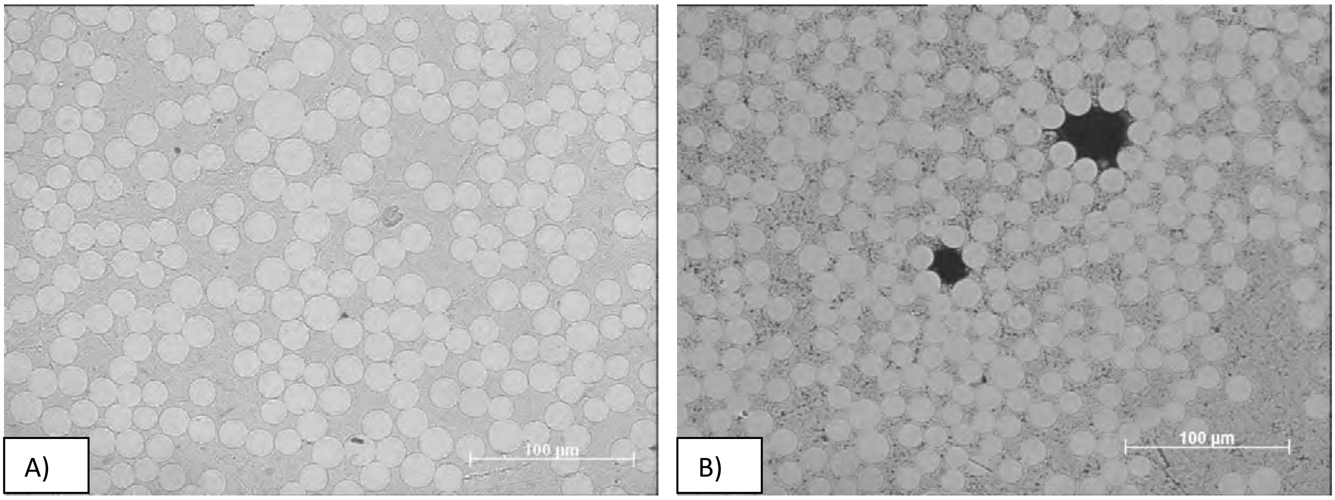


Figure 23: a) Image of fibres in sample wound using resin bath; b) Image of fibre in sample wound using resin bath and the spreading station. Both images were taken at 20x magnification.

Figure 23 shows images of fibres in both resin bath tubes and spreading station tubes. Despite the presence of voids in the second image (spreading station) the fibre beds look relatively similar. They are both relatively compact with little room between fibres. This suggests that even though the tension is lower in the spreading station tubes the fibre compaction isn't affected as much as FVF and void contact appear to be. It may be that closer to the mandrel there is an increased tension improving fibre compaction but closer to the surface resin pools due to the lack of tension. This could explain the lower FVF and higher void content in those tubes wound using the spreading station in conjunction with the resin bath.

5.0 Conclusions

The main conclusion to be drawn from this study is that the mechanical approach is an effective method for the spreading of an E-glass fibre bundle. It is also important to note that using a series of serpentine rollers may be more cost-effective whilst producing the same degree of spreading. However more research is required to validate this hypothesis.

It has also been shown that the spreading of an E-glass fibre bundle is an effective method for improving the speed of through-thickness impregnation. This improvement in through-thickness impregnation did result in a decrease in the longitudinal impregnation. However this issue is more apparent in the laboratory settings used here. In a manufacturing process the improvement in through-thickness impregnation would be much greater than the reduction in longitudinal impregnation.

On analysis of tubes wound using a resin bath compared to those using both a resin bath and spreading station it was found that the density and FVF was slightly lower in tubes wound using the spreading station. It was also noticed that there was a slight increase in void content for tubes wound using the spreading bath. This is most likely due to the decrease in winding tension when using the spreading station. The addition of the spreading station negates the requirement for a pre-tension system that is needed when winding solely with the resin bath. Further work is required to determine the effect of increased winding tension when using the spreading station.

While the physical properties do not appear to be significantly affected by the addition of a spreading station further work needs to be conducted to determine the effect of spreading the fibre bundles on the mechanical properties of filament wound tubes.

6.0 Future Work

The analysis of the filament wound tubes in this study is all to do with physical properties. It is therefore important that future work be conducted on mechanical properties. This would be achieved using the split-ring tensile experiment as described in ASTM D2290-08. The original plan was to conduct split-ring tests however due to a recent refurbishment in Metallurgy and Materials the required equipment was not available. A more detailed analysis on the effect of tension on the properties of filament wound tubes could also be conducted.

This study showed that using the spreading station reduced fibre tension and fibre damage however in the literature higher tension resulted in better mechanical properties.

Further work on the spreading of fibre tows could be conducted on different fibre types. For example only two types of E-glass fibres were used in this study. Other fibres such as Carbon, Kevlar and Polyethylene could also be tested. The effect of spreading these fibres could be compared to those discovered in the current study.

Other further work would include SEM analysis of the fracture surfaces of the split-ring specimens to determine failure loads. More analysis on the effect of binder content on fibre architecture and fibre spreading is needed.

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