

Design and Development of a New Class of Intra-filament Hybrid Composite



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ABSTRACT

A primary aim of this research project was to develop a technique to enable the efficient spreading of as-received 2400 Tex E-glass and 12K carbon fibre bundles where the resultant preform exhibited uniform fibre dispersion with minimum segmentation and damage. Two distinct automated fibre spreading techniques were designed and developed: (i) mechanically-assisted spreading and (ii) vacuum-assisted spreading for the as-received E-glass and carbon fibre bundles respectively. A post-processing method for the spread E-glass preform was developed to create a single-layer of filaments; this has not been reported in the literature. The spreading of E-glass fibre bundles achieved using this method enabled an average increase in the fibre bundle width of 956%. The vacuum-assisted spreading process for carbon fibres enabled a degree of spreading to the order of 1121%. This surpasses anything reported in the literature. Specific procedures were developed to impregnate the spread fibre preforms whilst maintaining the spatial architecture.

Tensile testing was undertaken on as-received and spread dry fibre bundles. It was found that an increase in gauge length, from 50 mm to 100 mm, resulted in a reduction in the tensile failure stress and the Weibull survival probability for as-received and spread fibre bundles respectively. For E-glass fibre bundles the average reduction in tensile failure stress, with an increase in gauge length, was 74 MPa and 88 MPa for as-received and spread fibre bundles respectively. With respect to carbon fibre bundles an increase in gauge length resulted in an average reduction in tensile failure stress of 261 MPa and 164 MPa for as-received and spread fibre bundles respectively. The effect of spreading was determined to be statistically significant at a gauge length of 100 mm.

However, in contrast the effect of spreading at a gauge length of 50 mm was determined to not be statistically significant for both fibre types.

The physical and mechanical properties of mono-fibre and hybrid composites manufactured using as-received and spread fibre bundles were analysed and compared. It was found that by using the spread fibre bundles, a significant reduction in the average thickness of the composite was achieved when compared to those manufactured using as-received fibres. The greatest reduction in thickness when using spread fibre bundles to manufacture a composite was 84% (0.238 mm to 0.037 mm). The overall average reduction in thickness when manufacturing composites using spread fibre bundles was 78% when compared to the thickness of composites manufactured using as-received fibre bundles. The degree of mixing of the two reinforcing fibre bundles achieved in the current study is greater than has been reported to date in the literature. With reference to the hybrid composites manufactured in this study, an apparent enhancement of the initial failure strain of carbon fibre was observed, for as-received and spread hybrid composites compared to mono-fibre carbon composites. The greatest enhancement of 43% was observed in both the [GCG] hybrid composites manufactured using as-received and spread fibre bundles. The overall conclusion from this study is that the utilisation of spread E-glass and carbon fibre bundles can be used as a means for enhancing the apparent failure strain of carbon fibre composites.

This thesis is dedicated to

my late father

*(his breadth and depth of knowledge still inspires me, and I am forever grateful for the
lessons he gave, sometimes without my realising)*

my mother and two sisters

*(their continuing strength and laughter throughout our journey has kept me hopeful and
smiling)*

my girlfriend

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1. Introduction

1.1 Background

Fibre reinforced composite materials are made up of a polymer matrix, for example epoxy, and a reinforcing fibre such as glass or carbon (Hull & Clyne, 1996). Hull (1981) provides a comprehensive definition of composite materials:

- (i) it consists of two or more physically distinct and mechanically separate materials;
- (ii) it can be made by mixing the separate materials in such a way that the dispersion of one material in the other can be done in a controlled way to achieve optimum properties; and
- (iii) the properties are superior, and possibly unique in some specific respects, to the properties of the individual components.

A variety of different resins are used in the manufacture of composites. These can be broadly split into two categories; thermosetting resins and thermoplastic resins; in the current study only thermosetting resins were considered. Thermosetting resins once cured remain in that state. A chemical cross-linking reaction occurs between the resin and a catalyst creating a brittle solid network of polymer chains (Hull, 1981). The resultant properties of thermoset resins depend on the degree of cross-linking within the material. The degree of cross-linking can be influenced by the processing method. Examples of thermoset resins include epoxy and polyesters. These two resin types also have many variations within their class. Within these two groups the properties, both physical and mechanical, can vary greatly.

Composite materials can be manufactured using a variety of techniques such as filament winding, pultrusion, autoclave processing, compression moulding, resin transfer moulding and wet lay-up. The method chosen for manufacture will depend on the part that has been designed for manufacture.

For example, filament winding creates composite tubes or pipes which have strength in the axial plane; other uses include over-winding pressure vessels with impregnated reinforcing fibres to improve their pressure burst resistance. The resultant properties of the composite will depend not only on the constituent materials but also on the winding parameters. For example both winding pattern and winding tension have been known to influence the physical and mechanical properties (Rousseau, Perreux & Verdiere, 1999; Chen & Chiao, 1996; Mertiny & Ellyin, 2002). In composites the fibre volume fraction and void content are critical physical properties.

A new method of filament winding, known as clean filament winding, has been developed by a team at the University of Birmingham. An explanation of this can be found in Pandita *et al.* (2012). In this process the resin bath has been removed and replaced with a custom-built impregnation head. Instead of being premixed the resin and hardener of choice are stored separately and pumped on demand by dedicated precision pumps to a static mixer. The two liquids are then intimately mixed until being impregnated directly onto the reinforcing fibres. The fibres are then wound onto a rotating mandrel. This process has a number of advantages over conventional filament winding. For example, it allows the use of fast-curable resins reducing processing time from manufacture to post-process curing. In addition it reduces waste and reduces the amount of solvent required for cleaning post production.

The compression moulding, resin transfer moulding and wet lay-up techniques produce composite laminates. Laminates consist of a number of individual layers of fibre bundles or pre-impregnated (prepreg) sheets or tapes. The properties of laminates can be influenced by the material and resin choice but also by the fibre direction in each lamina and the stacking sequence of the laminate. The stacking sequence can be unidirectional $[0]$, cross-ply $[0/90]$, angle ply $[0/+45/-45/0]_x$ or multi-directional $[0/+45/-45/90/-45/+45/0]_x$. The stacking sequence can also be symmetric or asymmetric.

It is well known, that composite materials offer improved specific strength and stiffness, factors that can be influenced by the materials used and processing method, compared to metals (Swolfs, Gorbatiuk & Verpoest, 2014). As well as this, composites also provide improved corrosion resistance and fatigue behaviour (Cantwell & Morton, 1991). While carbon fibre composites have good specific strength and stiffness, they are susceptible to impact damage, and sudden brittle catastrophic failure due to their relatively low failure strain. The safety factor, when designing a composite material, often restrains the material to a low percentage of its ultimate failure strain (Czél & Wisnom, 2013).

Due to the sensitivity of carbon fibre composites to impact damage, a range of techniques have been used to improve its damage tolerance. Hybridisation has been proposed and used extensively in the literature to improve the general properties of fibre reinforced composites. Carbon fibres have a relatively low failure strain whereas E-glass and Kevlar® fibres have higher failure strain. Hence these fibres have been mixed with carbon fibres to alter the failure characteristics of the composite.

Hybridisation involves the combination of two or more reinforcing fibres in a single matrix. Common combinations include: carbon and glass, carbon and Kevlar®, glass

and Kevlar®, carbon and polyethylene and glass and polyethylene (Bunsell & Harris, 1974; Gustin *et al.*, 2005; Park & Jang, 2000; Peijis & DeKok, 1992; Datta, Basu & Banerjee 2004). There are also a number of different methods of hybridising, and types of hybrid composite. Inter-ply, intra-ply, inter-tow (also known as intra-filament) composites and combining thermoplastic fibres with reinforcing fibres, known as commingling, are methods reported in the literature. These will be discussed further in the literature review section.

The main advantage of hybrid composites is that through careful selection of the fibres and matrix, as well as design and manufacture, a composite with the desired properties can be manufactured. The principal, is that the disadvantages of one fibre, such as relatively low failure strain, are counteracted, through synergistic effects, by the advantages of the other fibre type and vice versa.

A number of studies have reported on the influence of hybridisation on the tensile behaviour of composites (Bunsell & Harris, 1974; Manders & Bader, 1981; Czél *et al.*, 2012; Diao *et al.*, 2012; Czél & Wisnom, 2013; Diao *et al.*, 2014). In addition, the behaviour of hybrid composites under fatigue loading (Peijs *et al.*, 1993; Shan & Liao, 2001; Shan *et al.*, 2001) and during impact loading (Peijs *et al.*, 1990; Dutra *et al.*, 2000; Naik *et al.*, 2001) has been studied.

The magnitude of the reported effect of hybridisation varies in the literature. In a review by Swolfs, Gorbatiikh & Verpoest (2014), the authors stated that reported hybrid effects for the tensile properties of hybrid composites range from 10-50%. No unified explanation for the existence of the hybrid effect is given in the literature. The effect of hybridisation on the composite properties has been attributed to thermal residual stress,

due to the elevated processing temperature and different coefficients of thermal expansion, (Bunsell & Harris, 1974; Czél & Wisnom, 2013), as well as synergistic effects and statistical effects such as the influence of strength distribution, relative fibre volume fractions and degree of dispersion of the two fibre types (Manders & Bader, 1981).

A number of models have been proposed to predict the magnitude of the hybrid effect. They have progressed from early studies, such as Zweben (1977) in which a simple 2D-array of alternating carbon and glass filaments were modelled, to more complex 3D models such as that proposed by Swolfs *et al.* (2015).

A common theme in the models of hybrid composites reported in the literature, is the effect of the dispersion of the two reinforcing fibres within the composite. In general, it is believed that alternating the fibre types at the filament level would result in the largest hybrid effects. The early studies into hybrid composites, however, predominantly used inter-layer or intra-layer hybrids. In other words, the fibre type in each layer alternated or the fibre bundles were alternated within each layer.

In order to create a hybrid in which the two fibre types are mixed intimately and uniformly, it is necessary to spread the respective as-received fibre bundles. Ideally, the fibre bundles would be spread to a mono-layer of filaments. This would enhance the chances of the filaments mixing in the desired fashion.

The first reported use of a spread fibre bundle in a composite was in Manders & Bader (1981), in which, a spread carbon fibre bundle was sandwiched between two plies of as-received glass composite. More recently, this construction has been studied by Czél *et al.* (2012), Czél & Wisnom (2013) and Fotouhi *et al.* (2016). Although the central

carbon layer in these studies was spread, there was little intermixing of the carbon and glass filaments and the composites can best be described as inter-ply.

Diao *et al.* (2014) reported a hybrid effect for an intra-tow (intra-filament) hybrid in which spread hybrid fibre bundles of carbon and glass were manufactured. To date this is the closest example to an ‘idealised’ hybrid. This construction can be considered intra-filament, as the reinforcing fibres were mixed at the filament level. However, upon microscope analysis it was seen that the filaments were not alternating one after the other. Furthermore, they were present in large clusters of the same fibre type; increasing the chance of critical crack development.

Swolfs *et al.* (2015) determined using a computational model that random dispersion of the fibre types would not result in the largest hybrid effect. The model suggested that the optimum configuration for a hybrid composite was alternating layers of the reinforcing fibre bundles that were present in mono-layers. Put simply, each layer of fibre would be one filament thick.

In the current study, the previous short comings in manufacturing an idealised hybrid were considered. To overcome the above mentioned short comings it was necessary to develop a number of new techniques. Firstly, two individual techniques for spreading E-glass and carbon fibre bundles to their idealised state were designed and developed. Secondly, appropriate techniques were developed to impregnate the spread fibre preforms whilst maintaining the spatial architecture of the filaments. In order to assess the effect of the spreading method on the tensile properties of E-glass and carbon fibre bundles, fibre bundle testing was undertaken in tandem with acoustic emission monitoring.

This was followed by an evaluation of the fibre volume fraction and evaluation of the tensile failure behaviour of composites manufactured using as-received and spread fibre bundles.

1.2 Aims of the Current Study

The primary aim of this research was to develop an intra-filament hybrid composite; a type of idealised hybrid that, at the time of writing, had rarely been reported in the literature. The specific aims of this study were as follows:

- (i) To modify a fibre spreading rig to enable the spreading of E-glass and carbon fibre bundles to their optimum state.
- (ii) To determine the effect of fibre spreading on the tensile properties and Weibull survival probabilities of the two fibre types.
- (iii) To determine the effect of fibre spreading on the properties of mono-fibre composites compared to as-received composites.
- (iv) To determine a baseline for the effect of hybridisation on the properties of as-received mono-fibre composites compared to as-received hybrid composites.
- (v) To determine the effect of using spread fibre bundles in the production of hybrid composites.

1.3 Structure of the Thesis

Chapter 2 is the review of the literature. This chapter covers the main topics relating to this project including: fibre spreading, fibre bundle tensile testing and hybrid composites; with specific focus on the statistical models and tensile properties.

Chapter 3 presents the experimental method. In this chapter the designs of the fibre spreading rigs are described and explained. The method of tensile testing fibre bundles and composites are outlined. In addition, the manufacture and analysis of as-received and spread composites (mono-fibre and hybrid) is explained in detail.

Chapter 4 presents the results obtained using the experimental method in Chapter 3 and provides a discussion relating to these results. There are three sub-sections: fibre spreading, fibre bundle tensile testing and composite manufacture and testing.

Chapter 5 highlights the conclusions of the current study and, furthermore, provides recommendations for future research into the specific areas covered in the thesis.

2. Literature Review

This chapter is concerned with a review of the scientific literature with regards to the following key topics: fibre spreading, strength distribution in reinforcing fibres, and hybrid composites; including the types, the ‘hybrid effect’, modelling hybrid composites and their properties.

2.1 Fibre Spreading

The following section presents a review of the patent and scientific literature on fibre spreading. The spreading of reinforcing fibre bundles is an area in which most of the information is found within the patent literature. There are only a handful of experimental studies in which the spreading process is fully defined in terms of the mechanism(s) of spreading and the degree of spreading achieved.

In order to evaluate a fibre spreading technique, the criteria for the assessment need to be considered. For example: (i) the magnitude of the apparent damage that is induced on the filaments, including appropriate methods for assessing the damage; (ii) the extent of spreading desired and the criteria for determining this, with or without segmentation, and homogeneity of the extent of spreading.

A search of the patent literature highlighted five different techniques designed to spread a reinforcing fibre bundle; these are listed below:

- (i) mechanical;
- (ii) electrostatic;
- (iii) pneumatic;
- (iv) vibration; and
- (v) acoustic.

Each of these methods will be described in detail with a review of the relevant prior art and scientific literature.

2.1.1 Mechanically Induced Fibre Spreading

In principal, mechanical spreading involves a fibre bundle being drawn over a single rod or a series of rods. These rods can be set as pins or allowed to rotate freely around their central axis i.e. act as rollers. Van Den Hoven (1981) proposed a mechanical method for spreading continuous fibre bundles that incorporated a grooved pin; this is illustrated schematically in Figure 2.1.

With reference to Figure 2.1, the roller consisted of a central axis (i), and a roller (ii) around the circumference of which were a series of grooves (iii) that had a gradual change in width from the minimum (N) to a maximum width (W). It was claimed that as the fibre bundle traversed across the roller and interacted with the grooves the filaments began to separate and move in the direction perpendicular to the direction of fibre bundle traverse. It was also claimed that through rotation of the pin, a selection could be made on the desired fibre bundle width. No claim was made on the degree of fibre spreading that could be achieved. The patent stated that the extent of spreading was determined by the width of the grooves that the fibre bundle contacted as it traversed. In other words, a greater spread fibre bundle width could be achieved if the fibre bundle traversed across the widest area, W, compared to N in which the grooves were less far apart. In addition, there was no mention of the magnitude of damage, or any control measures in place to reduce the risk of damage. If there were misaligned filaments within the bundle, it is possible that they could become tangled as they traversed. This could potentially result in damage to the fibre bundle.

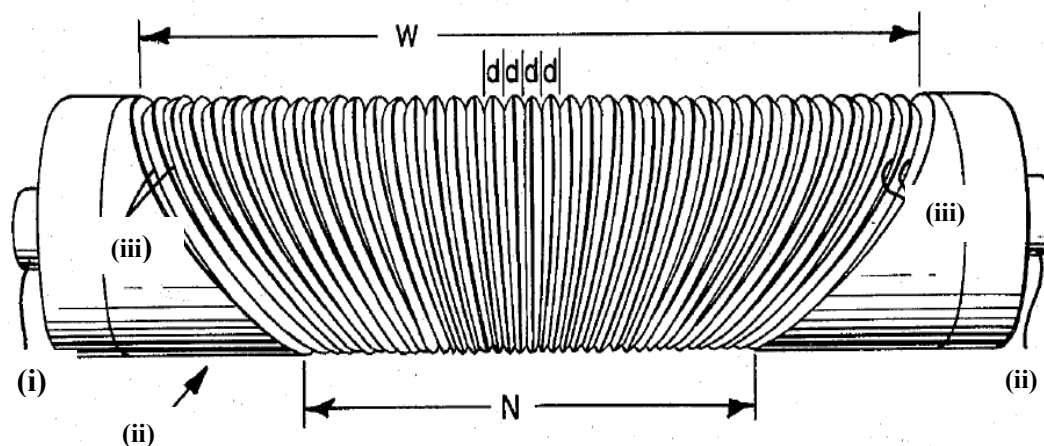


Figure 2.1 A schematic illustration of the roller proposed by Van Den Hoven *et al.* (1981). The numbered items are as follows: (i) the central drive shaft or axis, (ii) the grooved roller and, (iii) the grooves. W is the maximum width of the grooves, N is the minimum width of the grooves, d is the distances between neighbouring grooves.

Nakagawa *et al.* (1992) proposed a technique utilising a number of convex shaped rods that could be utilised as rollers or pins, positioned around a central axis. The entire assembly was then rotated, resulting in each individual convex roller intermittently coming into contact with the fibre bundle. Figure 2.2 presents a schematic illustration of the design showing the central rotating axis (i) around which the concave rollers (ii) were positioned inside the roller assembly (iii).

The claim was that the bevelled surface would induce lateral movement of the filaments in the bundle with different radii of curvature, thus creating differing degrees of fibre spreading. It was noted, however, that too great a radius of curvature would result in individual filaments slipping off the edge of the rollers. If a number of slipped filaments became entangled and built up within the roller assembly then damage to the fibre bundle could occur.

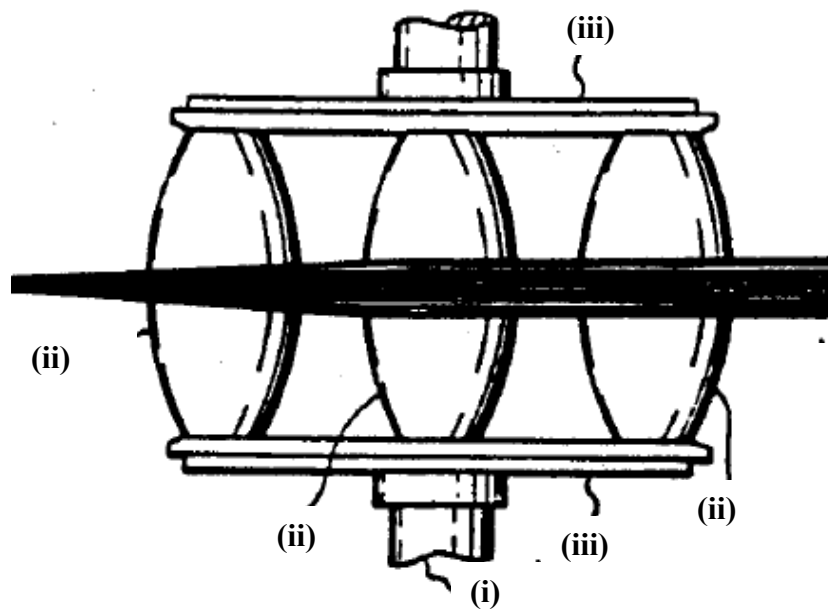


Figure 2.2 A schematic illustration of the roller hub assembly proposed by Nakagawa et al (1992). With reference to the illustration the labelled parts are: (i) the central drive shaft, (ii) the roller hub and, (iii) the convex rollers.

A study by Marissen, van der Drift & Sterk (2000) recognised this damage mode as a potential issue after observing filaments breaking during impregnation in a resin bath. The solution (discussed in Figure 2.6) was to use conical rollers supported only at one side. The roller tapered to a thin point away from the support. This meant that if any filaments broke or slipped they would drop off the roller altogether into the impregnation bath. The set-up can be seen in Figure 2.6. A more detailed review of the study is discussed later in this section.

Lifke *et al.* (2000) proposed a system for spreading reinforcing fibre bundles where a number of evenly spaced expandable bands, tubes or foam, were stretched between two angled support discs. The chosen expandable components had a cylindrical cross-section. A schematic illustration of the spreader proposed by Lifke *et al.* (2000) can be seen in Figure 2.3.

The authors stated that with their invention, the degree of fibre spreading could be controlled through alterations to the support discs; no claim was made on the homogeneity of the spreading or degree of segmentation. With reference to Figure 2.3, the angle of the discs (iii) influenced the ‘stretch’ in the expandable components (iv), and concurrently changed the shape of the roller assembly. Using this method it was possible to create different shapes with the assembly and mimic systems such as a bevelled roller as utilised in Nakagawa *et al.* (1992). Furthermore, a series of spreader assemblies could be used to continuously spread the fibre bundle to a desired width. A potential cause of damage in this instance would be snagging of the fibre bundle on the expandable component. The patent did not state a method with which to ensure minimal friction between the expandable band and fibre bundle. There could also be danger of broken filaments becoming entangled around one of the expandable bodies during rotation of the spreading unit.

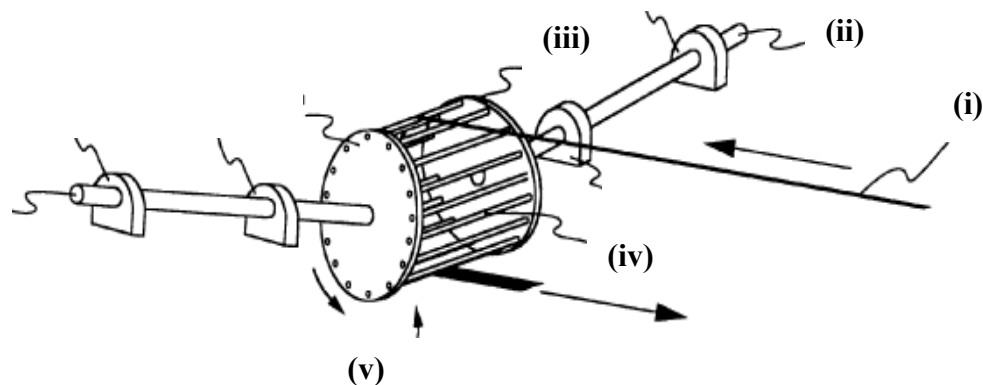


Figure 2.3 A schematic illustration of the rotating fibre spreader invented by Lifke *et al.* (2000). The numbered items are as follows; (i) input fibre bundle, (ii) rotating axel or motor, (iii) supporting disc, (iv) expandable member (cylindrical band), and (v) spread fibre bundle.

In 2001, Krueger proposed a mechanical method (illustrated schematically in Figure 2.4) to spread a fibre bundle (i) utilising a rotating assembly (ii) supporting a series of smaller discs (iii) positioned perpendicularly to the sides. Each of these smaller discs had a series of pins (v) protruding from the surface. The pin spacing on each small disc was different from the others and the pin orientation and height also varied. This hub (ii) rotated around a central axis (iv) so that as the fibre bundle (i) traversed through the spreading machine it came into contact with each series of pins around the hub. The distance between the pins varied around the rotating disc.

In principal, this was a good method as the pins would split the bundle aiding the separation of individual filaments, reducing the bundle thickness and increasing the width. However, in practice it is likely that the pins could induce damage in the fibre bundles. The friction between the fibre bundle and the pin could cause filaments to break or induce damage, such as scratches, to the filament surface. This could in turn have a detrimental effect on the properties of the fibre bundle when reinforcing a composite and placed under load.

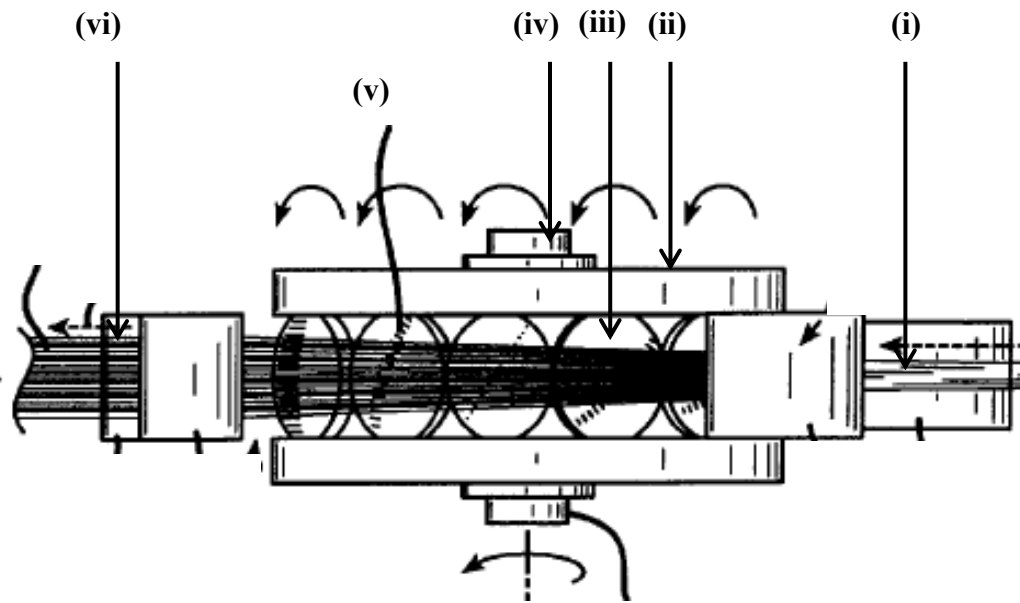


Figure 2.4 Schematic illustration of the mechanical spreader proposed by Krueger (2001). The numbered items are as follows: (i) an as-received fibre bundle, (ii) the rotating hub, (iii) small disc, (iv) the central axis, (v) series of pins located in small discs and, (vi) the spread fibre bundle.

Guirman *et al.* (2005) suggested a system with in which fibre bundles were initially spread using a series of pins and then subjected to an air-jet to enable further spreading of the fibre bundle. Figure 2.5 shows a schematic illustration of the invention; the numbered items are: (i) the fibre bundle creel, (ii) the initial spreading pins, (iii) the guide pin and, (iv) the air-jet used to further increase the fibre bundle width.

The fibre bundle(s) (i) were traversed across a series of initial spreading pins (ii) positioned in such a way that the fibre bundle always came into contact with the convex side of the pin; this resulted in the width of the fibre bundle gradually increasing; similar to the bevelled roller in Nakagawa *et al.* (1992). In addition, the serpentine arrangement would induce more friction between the fibre bundle and the pin resulting in lateral movement of the filaments. After traversing through the pins the fibre bundle

passed over a larger diameter guide pin (iii) before traversing downwards in a vertical fashion. The fibre bundles were then subjected to a traversing air-jet directed at an angle perpendicular to the traverse direction of the fibre bundle; this air-jet resulted in filament vibration; as the filaments vibrated, movement would occur and filaments experiencing a momentary tension decrease would drop into the interstitial spaces between neighbouring filaments.

An advantage of this method is the ability to spread multiple fibre bundles at the same time; it was designed to form a spread fibre sheet from multiple fibre bundles. A series of air-jets could also be utilised to aid control of the degree of fibre spreading. Due to the traversing nature of the air-jet nozzle a number of fibre bundles could be traversed through individual sets of spreader pins before meeting on the guide roller. With respect to the disadvantages, no discussion was made on the uniformity of the spreading achieved. With numerous fibre bundles being spread at the same time, it could be difficult to maintain uniform spreading among all of them. As their respective widths increased they could begin to impinge on one another.

The air-jet could also result in the fibre bundle splitting; there could be an increase in the segmentation of the fibre bundle. Each time the air-jet passes that region the segmentation could worsen.

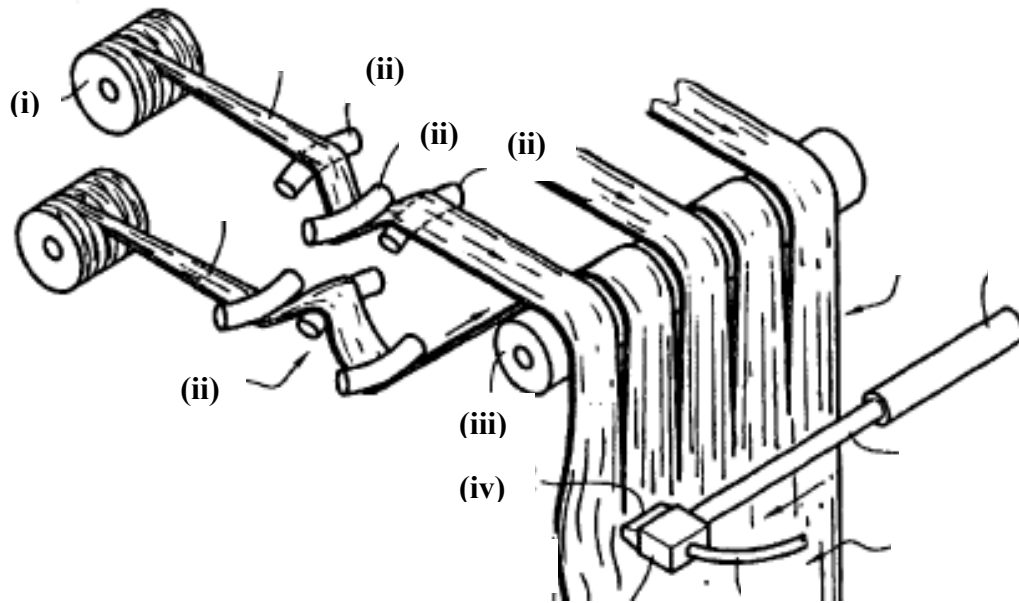


Figure 2.5 A schematic illustration of the invention proposed by Guirman *et al.* (2005) to spread multiple fibre bundles. The numbered items are: (i) fibre creel, (ii) curved spreader pins arranged in serpentine fashion, (iii) guide pin and, (v) the traversing air-jet nozzle.

Broyles *et al.* (1997) used mechanical spreading during the sizing process of carbon fibres in an experimental study. A sizing (or binder) is a chemical solution added to the surface of reinforcing fibre during manufacture and has a number of functions ranging from adding protection to the fibre bundle during handling to influencing the interface properties between the fibre and matrix. A carbon fibre bundle was dipped into sizing solution and drawn over a series of rollers; therefore in this case the fibre bundle was lubricated. In the previously discussed patents no mention was made of whether the fibre bundle was dry or lubricated. The spreading was controlled through the use of tension in the fibre bundle; the tension was controlled by “a nip roller that was connected to a magnetic brake”. The break in turn was part of a feedback control-loop with a load-cell which controlled the tension of the fibre bundle between 0-130 N. The

authors reported that the spreading could be controlled up to 150 mm however no empirical evidence was given to support this statement.

Marissen *et al.* (2000) also used mechanical spreading with a wet fibre bundle when trying to improve the impregnation time during the pultrusion process. In pultrusion, dry fibre bundles are impregnated by traversing them through a resin bath. The authors added convex rotating rollers (item (i) in Figure 2.6) to their resin bath in order to promote spreading of the fibre bundle (item (ii)) and hence reduce the thickness of the bundle. As the fibre bundle became wider and thinner, the through-thickness impregnation became more efficient. During manufacture it was noticed that occasionally filaments broke and became entangled around the rollers, in some cases causing further significant damage. In order to stop this occurring conical rollers supported only at one side were used. If a filament broke off from the bundle instead of becoming wrapped around the roller it slipped off the edge into the resin bath. The rollers, at the point which the fibre bundles were in contact with the surface, had a diameter of 41 mm. No information on the change in fibre bundle width as it traversed was given.

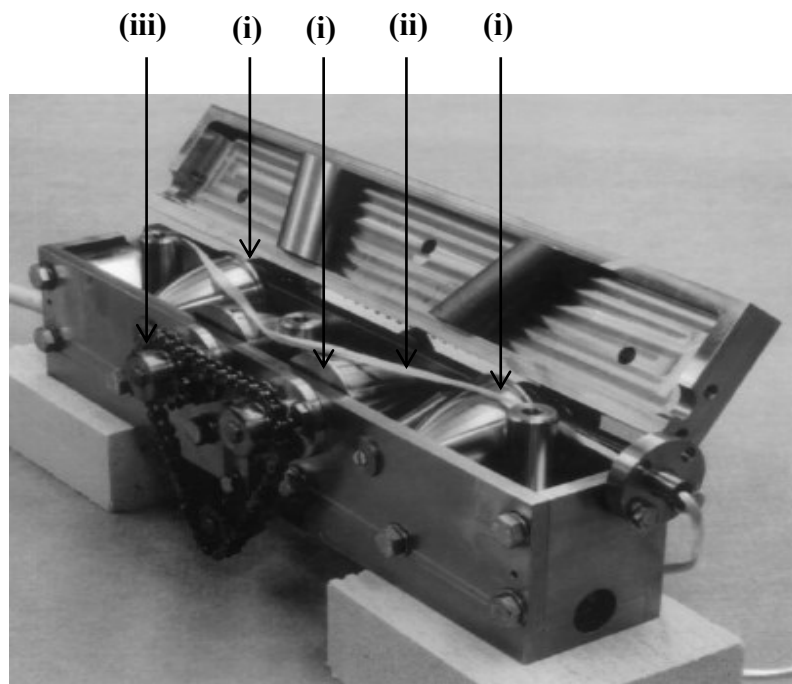


Figure 2.6 The fibre bundle impregnation unit utilised by Marissen *et al* (2000) showing: (i) convex conical rollers supported at one side only, (ii) the fibre bundle and, (iii) one of the gears used to power the roller rotation.

A number of mechanical techniques have thus far been reviewed, with the main theme occurring being the use of rotating assemblies utilising some form of rod either as a pin or roller. Convex rollers were said to induce lateral movement of the filaments within a bundle, however there can be issues with filaments slipping off the roller edge. The intermittent contact with a fibre bundle during the rotation of an assembly would induce intermittent periods of reduced tension where the fibre bundle relaxed and this may promote filament movement. It is important to ensure with mechanical spreading that the friction between rods and the fibre bundle does not induce abrasion damage which can be a detriment to fibre properties. This is an issue that could be counteracted through careful selection of the parameters such as tension in the fibre bundle and the rotation speed of the rotating assemblies. Incorporating rollers instead of pins is another way to reduce the potential for damage as a result of rod/fibre friction.

2.1.2 Electrostatic-assisted Fibre Spreading

Electrostatic-assisted fibre spreading involves inducing a charge onto a reinforcing fibre bundle, and then passing through an environment with a different charge. For example, Niina *et al.* (1967) sprayed water onto reinforcing fibre yarns before passing them through an electrode. This electrode was coupled to a power source which, the inventor stated, should have provided a charge of 5000 V. This created a repulsive force within the fibre bundle resulting in the filaments moving away from each other.

In another invention, proposed by Uchiyama *et al.* (1972), a fibre bundle was ‘*charged*’ by passing through an electrode. The fibre bundle was then passed through a second electrode, the sides of which diverged outwards. This second electrode was grounded and the fibre bundle spread due to the repulsive force experienced.

Other examples include the use of corona discharge electrodes (Sternberg, 1976) and traversing a fibre bundle, supported by an electrically conductive sheet, under an electrode (Peritt, Everett & Edelstein, 1993).

The uniformity of the fibre spreading which is achievable using these techniques is unclear. No information is given on the width of the fibre bundle after spreading or the degree of splitting or segmentation in the bundle. The control of the width of the fibre bundle is also unclear. To ensure the optimum chance of achieving uniform spreading it would be necessary to ensure that the fibre bundle was charged uniformly. Each method states it would produce a uniformly spread tow but no quantification of ‘uniform’ is given.

2.1.3 Pneumatic Methods for Fibre Spreading

A number of patents exist in which inventions for the pneumatic spreading of a fibre bundle have been disclosed. Summaries of these inventions will be described in this sub-section.

One method proposed by Daniels (1974) relied on the Venturi effect. This phenomenon is characterised by a pressure drop as a gas or other fluid medium passes through a constricted region. A single fibre bundle was passed through two individual slot-type Venturi systems, denoted a “pre-blower” and “spreader”. As the fibre bundle traversed through this first pre-blower Venturi, the air-flow was in the same direction as the fibre bundle traverse. The initial spreading was a result of the air and fibre bundle converging upon passing through the “throat” of the Venturi, a region thinner than the inlet and exit. Upon exiting the “throat” the air diverged towards the sides of the Venturi which caused the fibre bundle to “expand” and the filaments in the bundle to also move laterally. The spread fibre bundle architecture was not uniform upon exiting the pre-blower. It was the second Venturi spreader that was used to form a uniform spread fibre tape. In contrast to the pre-blower, the air-flow direction was in the opposite direction to that of the fibre bundle traverse. Upon entering the throat of the Venturi the air-flow above and below the fibre bundle resulted in the filaments being aligned in the vertical, not horizontal, direction. The width of the fibre bundle was controlled by the width of the exit of the Venturi spreader. I.e. the maximum spread fibre bundle width was the same as the width of the exit of the spreader.

A potential problem with this method could be the control of the width and homogeneity of the fibre bundle. As the fibre bundle spread, more filaments would move outwards towards the edges of the Venturi. If the only control is the width of the

Venturi itself then there is no control over the uniformity of the spreading in the horizontal plane. There doesn't seem to be any way of preventing the fibre bundle splitting into two strands as the filaments try to move to the extreme side of the Venturi in closest proximity. When filaments moved away from the centre to the edges segmentation or fibre bundle splitting may occur. This could cause the final spread bundle to be non-uniform in the horizontal plane. The inventors specify that the spreader Venturi only aligned the filaments in the vertical plane.

Chung *et al.* (1986) proposed a pneumatic spreading method (shown schematically in Figure 2.7) for uniformly spreading carbon fibre bundles for the manufacture of thermoplastic reinforced composites. The as-received carbon fibre bundle was passed through a "gas box", item (i) in Figure 2.7, into which compressed air was fed at a pressure between ~ 275 kPa and ~ 620 kPa. The top of the box had one or more V-shaped air outlet ports, item (ii) in Figure 2.7, the point of the 'V' being directed in the direction of traverse of the bundle, which resulted in the gas impinging on the fibre bundle separating the filaments. McMahon *et al.* (1989) utilised the same design but intermixed thermoplastic fibre with the carbon fibre and passed the two over rollers in a serpentine arrangement to induce intermixing. Additionally a much lower pressure range of 3 – 68 kPa was used in the gas box.

In both cases there is little mention of the degree of spreading achievable using this method and the level of control of fibre bundle width.

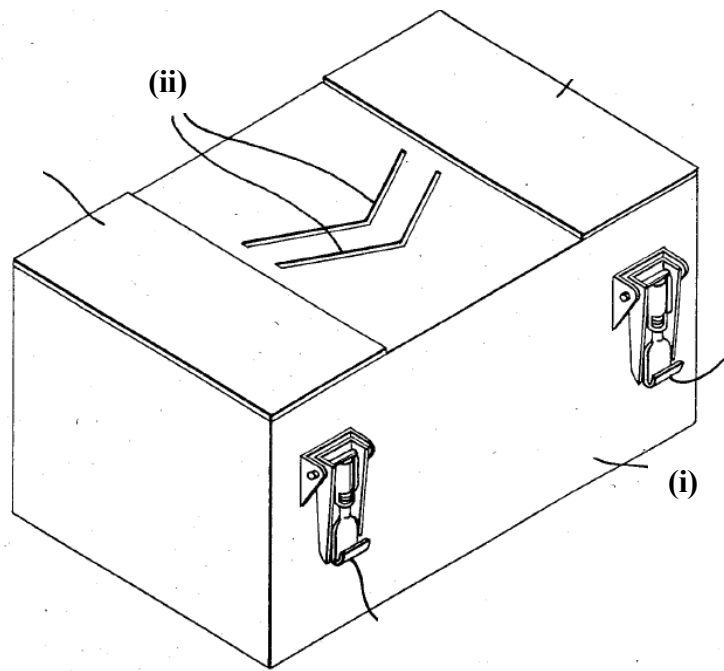


Figure 2.7 A schematic illustration of the pneumatic spreader for carbon fibre bundles invented by Chung *et al.* (1986) and McMahon *et al.* (1989). The numbered items are as follows; (i) “gas box” and (ii) V-shaped exit ports.

Baucom *et al.* (1991) used a vacuum induced air-flow technique to ‘pull’ the filaments in the fibre bundle laterally in the horizontal plane, thus increasing the width of the fibre bundle. The proposed invention can be seen in Figure 2.8.

With reference to Figure 2.8, from the creel (i) the as-received fibre bundle (ii) was traversed through an inlet (iii) to spreading system the inside of which diverged in width. The diverging sides (iv) had air outlet ports through which air was drawn via two vacuum manifolds (v), one on either side positioned directly opposite one another. The action of the air moving laterally towards the manifolds induced a pressure gradient, with lower pressure at the sides of the spreading rig, that resulted in the filaments of the fibre bundle following and expanding laterally from a region of high pressure to the

lower pressure region. The fibre bundle then exited the spreading system in its final spread state (viii).

Baucom *et al.* (1991) also suggested that the width of the spread bundle could be controlled through the use of the tension in the line and the degree of vacuum pressure applied. If the tension was increased the filaments would not move as far in the horizontal plane. The converse was also true i.e. if the tension was decreased more lateral movement could be achieved. The opposite is true for the vacuum pressure; an increase would result in more lateral filament movement with a decrease resulting in less lateral movement.

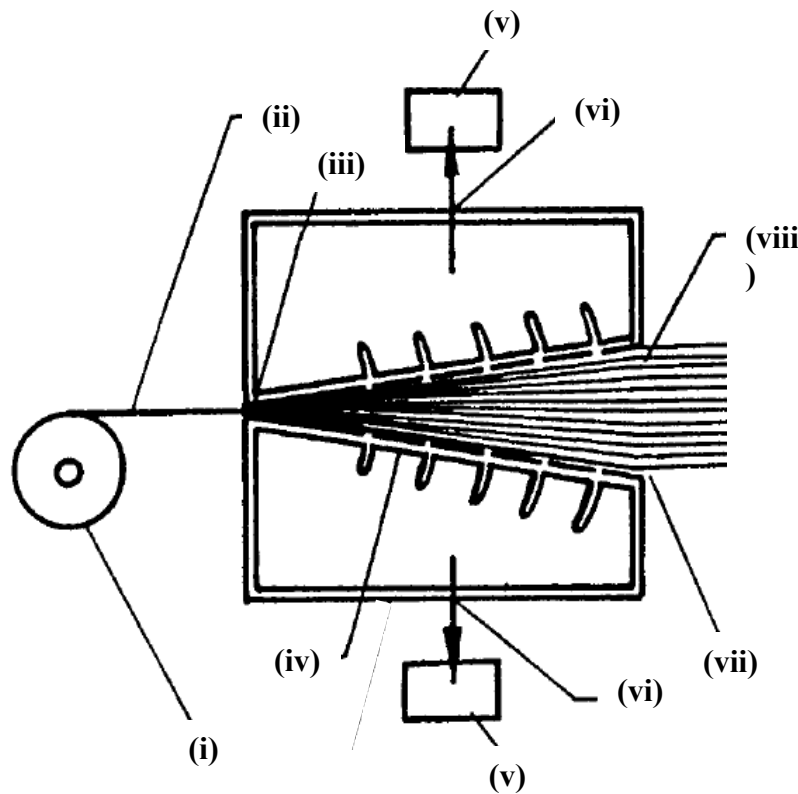


Figure 2.8 A schematic illustration of the spreading system invented by Baucom *et al* (1991). The numbered items are as follows; (i) the fibre creel, (ii) the as-received fibre bundle, (iii) the inlet of the spreading system, (iv) diverging sides of the spreading system with outlet ports, vacuum manifold used to draw air out of the chamber, (vi) the direction of air-flow out of the chamber, (vii) the exit of the spreading system, and (viii) the spread fibre bundle.

Each of these spreading methods had disadvantages and advantages. However, on the whole pneumatic spreading appears to have a lack of control over the width of the spread fibre bundle, especially with regards to the potential segmentation. The only main method of control is the use of tension which can have a significant effect on the spreading (Murray, 2013).

A Venturi system has been reported in the literature by Newell & Puzianowski (1999). They used Kevlar®-based carbon fibre (Kevlar® fibre that had been subjected to a carbonisation process) in their spreading rig; presented in Figure 2.9. They discovered that high tension in the fibre bundle was inhibiting the spreading. In order to counteract the high tension, two sets of rubberised pinch rollers (i) positioned at the entrance to spreader one (ii) and the exit of spreader two (ii), were used to create an area of lower tension where it was easier for the fibre bundle to spread laterally. Using this system a spread fibre bundle width of 3-4 inches (76.20-101.60 mm) was reported. This spread width is lower than that reported by Broyles *et al.* (1997) however in that study carbon fibre bundles with a very high filament count were used. Information on the Kevlar-based carbon fibres used by Newell & Puzianowski (1999) was not outlined.

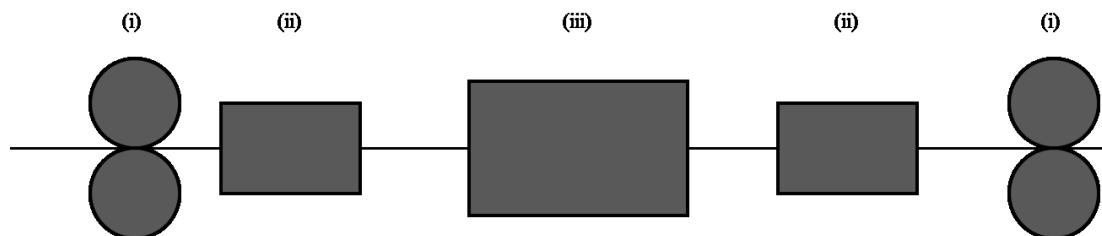


Figure 2.9 A schematic illustration of spreading system used by Newell & Puzianowski (1997); consisting of two sets of pinch rollers (i), two fibre spreaders (ii) and a chemical vapour deposition unit (iii).

The images in Figure 2.10 show the as-received fibre (i) and an example of the final “spread” state (ii) of the fibre bundle from Newell & Puzianowski (1999). Whilst there has been an increase in the fibre bundle width it can be seen that the “spreading” is not uniform. The filaments are not aligned in a uniform manner and the width is different along the length of the fibre bundle. The degree of segmentation was also extensive. Based on these images it would be difficult to suggest that this is a suitable technique for uniformly spreading a fibre bundle.

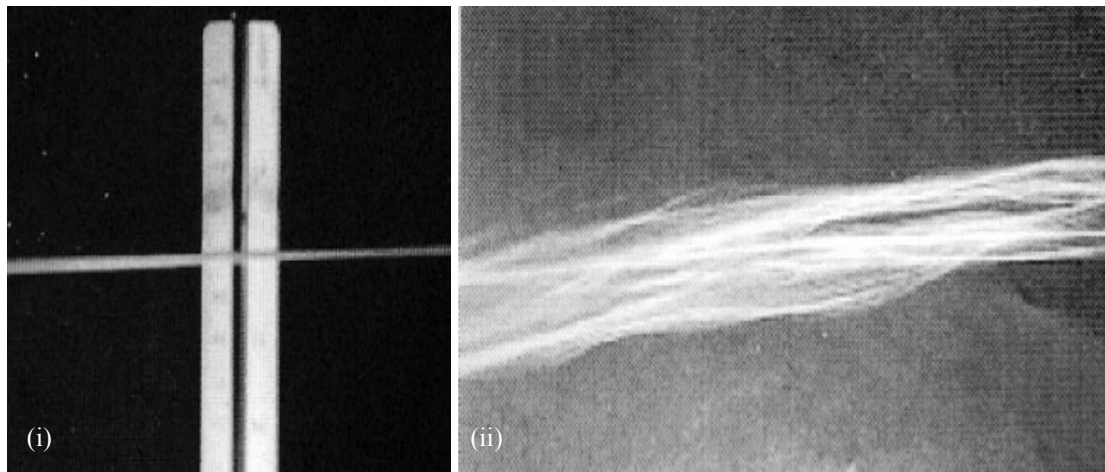


Figure 2.10 Images showing the fibre bundle in the (i) as-received state and (ii) spread state; Newell & Puzianowski (1999).

Sihn *et al.* (2007) conducted a study spreading carbon fibre bundles (Torayca Ltd T800-24K) using a commercially available pneumatic fibre spreader. In contrast to other pneumatic techniques, in which air was blown out through a slot or through a chamber, in this instance a vacuum was applied and air was drawn downwards. The carbon fibre bundle was traversed across an air-duct. The fibre bundle supported at the entrance and exit of the air-duct by a roller. Figure 2.11 shows the experimental configuration. As the

bundle traversed across the air-duct, the air-flow induced by the vacuum resulted in the fibre bundle relaxing into the air-duct; the authors called this a “tension-free state”.

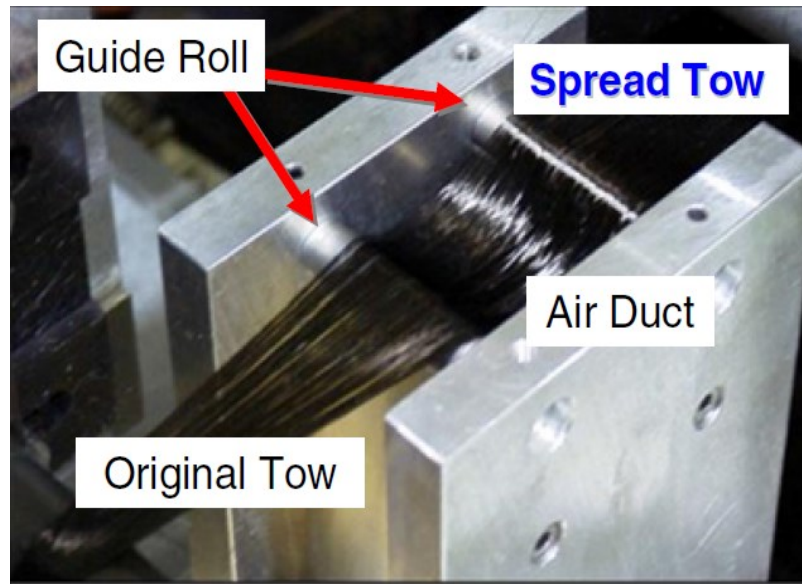


Figure 2.11 Spreading rig used by Sih *et al.* (2007) a fibre bundle is passed over an air duct with a vacuum applied. The bundle is supported at both side of the air duct by guide rollers creating a 'tension-free' state temporarily.

Sihn *et al.* (2007) also gave an explanation for the mechanism of spreading when using a vacuum to draw air through a fibre bundle. They stated that a pressure differential existed due to varying air-flow velocities across the air-duct and around the fibre bundle. The authors suggest that the air-flow velocity varies across the slot width and around the fibre bundle. The difference in air-flow in close proximity to the bundle compared to further away creates a difference in the pressure at these points. According to the authors ‘the pressure difference creates an aerodynamic force that helps the filament fibres to lose tension momentarily’. As the fibre bundle becomes wider the air-flow would begin to penetrate the bundle creating more regions of differential pressure.

Figure 2.12 shows a schematic illustration of the authors' explanation of air-flow around a fibre bundle during spreading.

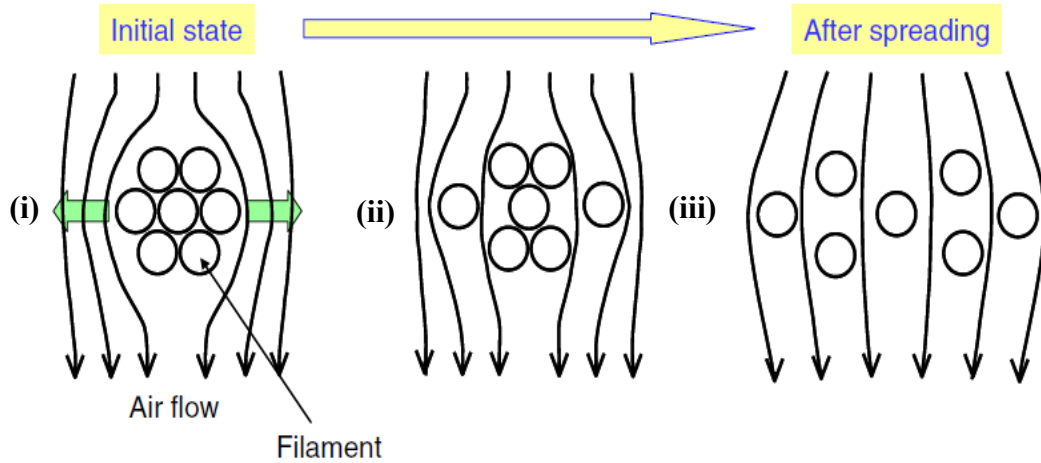


Figure 2.12 Sihh *et al.* (2007) schematic illustration of air-flow patterns (i) around the fibre bundle, the arrows show the pressure differential and the lateral movement of the fibre bundle, (ii) as the fibre starts to spread, and (iii) the final spread state.

The as-received average width of the carbon fibres used in this study was 6 mm. Two spread fibre bundle widths were achieved, 12 mm and 20 mm respectively. Sihh *et al.* (2007) reported a decrease in the thickness after spreading from 0.14 mm to 0.04 mm; the spread fibre bundle is just over 3 times thinner than the as-received bundle. Previous work (Bogonez, 2014; Wait, 2016) has highlighted that reducing the thickness of a fibre bundle can have an advantageous effect on the impregnation, particularly in the z-axis (through-thickness direction). Figure 2.13 shows the as-received (i), 12 mm spread (ii) and 20 mm (iii) spread carbon fibre bundles.

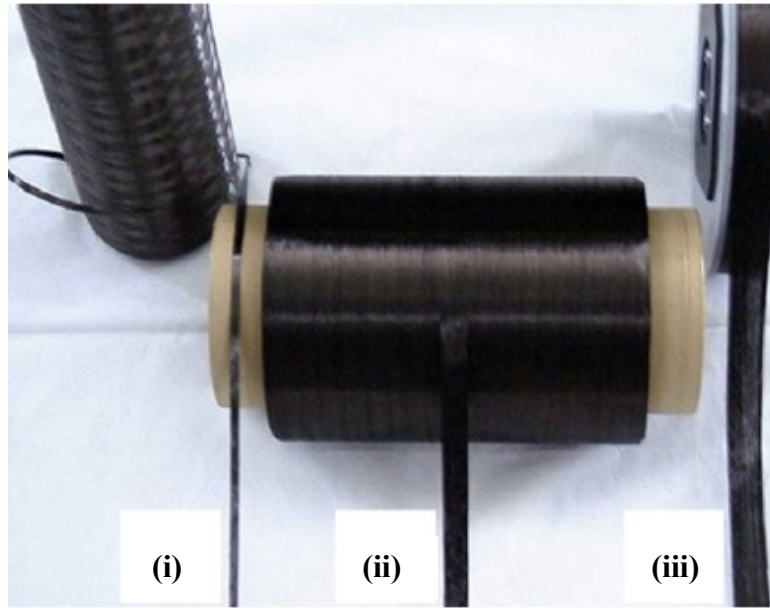


Figure 2.13 Photograph of the (i) as-received, (ii) 12 mm spread and (iii) 20 mm spread carbon fibre bundles from Sihm et al (2007).

Another study incorporating a ‘tension-free’ state was conducted by El-Dessouky & Lawrence (2013). In this study the same commercially available pneumatic spreader was used as in Sihm *et al.* (2007); Figure 2.14 shows the experimental set-up for El-Dessouky & Lawrence (2013). As with Sihm *et al.* (2007), an air-duct coupled with a vacuum was utilised, however, in this case two changes were made. Firstly, a horizontal bar was introduced perpendicular to the fibre bundle traverse (denoted by the arrows under ‘spreader 1’ and spreader ‘2’ in Figure 2.14), across the air-duct. Secondly, two spreaders were utilised in series. The horizontal bar oscillated in a back-and-forth motion. The speed of the air flow was controlled by a regulator (no operating parameters were given) to ensure no damage was induced in the fibre bundle. The same as-received carbon fibre bundles (Torayca T700-12K) were used by El- Dessouky & Lawrence (2013) as were used in the current study. The average width of the as-received fibre bundle was measured at 5 mm; through the use of this pneumatic

spreading system this was increased to 25 mm, this is 5 mm wider than that reported by Sihni *et al.* (2007). The authors stated that the increase in width resulted in a decrease in the layer thickness of the fibre bundle from 24 to 6 layers; the filaments in the fibre bundle had an average diameter of 7 μm .

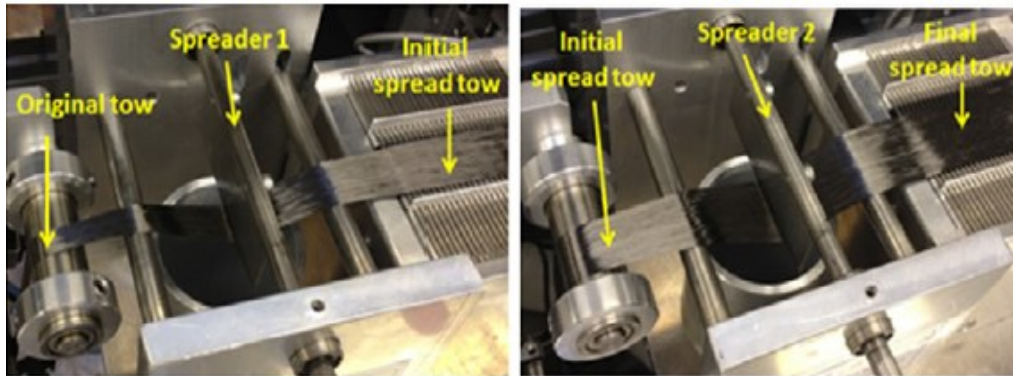


Figure 2.14 Photograph showing the increase in the width of the original tow, through the first and second fibre bundle spreaders to its final spread state (El-Dessouky & Lawrence, 2013).

The technique used by Sihni *et al.* (2007) and El-Dessouky & Lawrence (2013) seems to be an effective method for uniformly spreading a fibre bundle; Figure 2.13 shows that it was possible to spread to fibre bundle to at least two distinct widths from as-received width.

2.1.4 Vibration/Acoustic Methods for Spreading

Vibration and acoustic spreading generally make use of a vibrating medium through or over which a fibre bundle is traversed. Sager (1990) used a series of highly polished cylindrical rods and the fibre bundle traversed through these in a serpentine fashion. The rods all vibrated about their longitudinal axis, resulting in the fibre bundle spreading laterally as it traversed. Akase *et al.* (2000) also incorporated vibrating rods into their

spreading device. In this invention the rods vibrated in the axial direction compared to the longitudinal direction as in Sager (1990). It was also suggested that a pair of rods could be utilised with one being fixed and non-vibrating whilst the other would be vibrating and able to rotate freely about its axis.

Tanaka *et al.* (2004) presented a spreader, shown schematically in Figure 2.15, in which a fibre bundle (i) was traversed through a series of support rollers (ii). This system also incorporated a vertically moving roller (iii/iiia), called a “base-body” by the authors. This base-body had two states: in contact with the bundle and not in contact with the bundle; the vertically linear travel is denoted by (iv) in Figure 2.15. As the roller moved in and out of contact with the fibre bundle it induced cyclic periods of high and low tension in the fibre bundle, when in contact and when not in contact respectively.

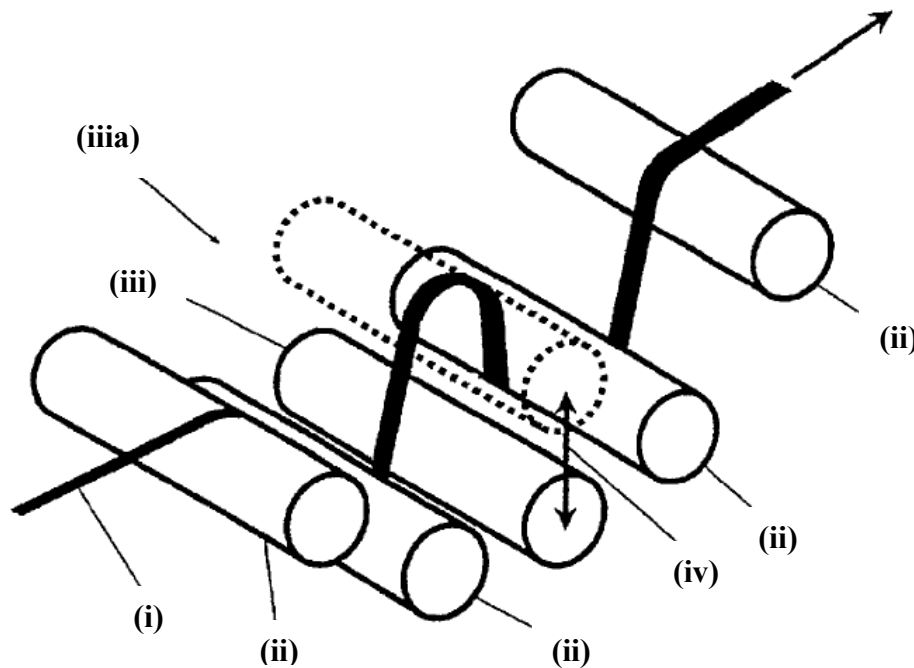


Figure 2.15 A schematic illustration of the device used to induce a cyclic tension in a fibre bundle (Tanaka *et al.*, 2004). The numbered items are as follows; (i) as-received fibre bundle, (ii) support rollers, (iii) low position of base-body, (iiia) upper position of base-body, (iv) indication of movement of base-body in a vertically linear fashion.

Iyer & Drzal (1991) utilised vibration of a gaseous medium as a spreading technique. An illustration of the technique for fibre spreading as proposed by Iyer & Drzal (1991) is shown in Figure 2.16. In the invention a fibre bundle (i) was traversed across a series of rods (iia) connected to roller bearings (iib) in a bearing housing (iic). These rods were therefore able to act as rollers and were positioned perpendicular to the direction of fibre bundle traverse. The array of rods were located above a loud speaker (iiia) positioned in a speaker housing (iiib). The loud speaker was attached to a signal generator and amplifier to create a vibrating gaseous medium through which the fibre bundle passed as it traversed in a serpentine fashion through the rods.

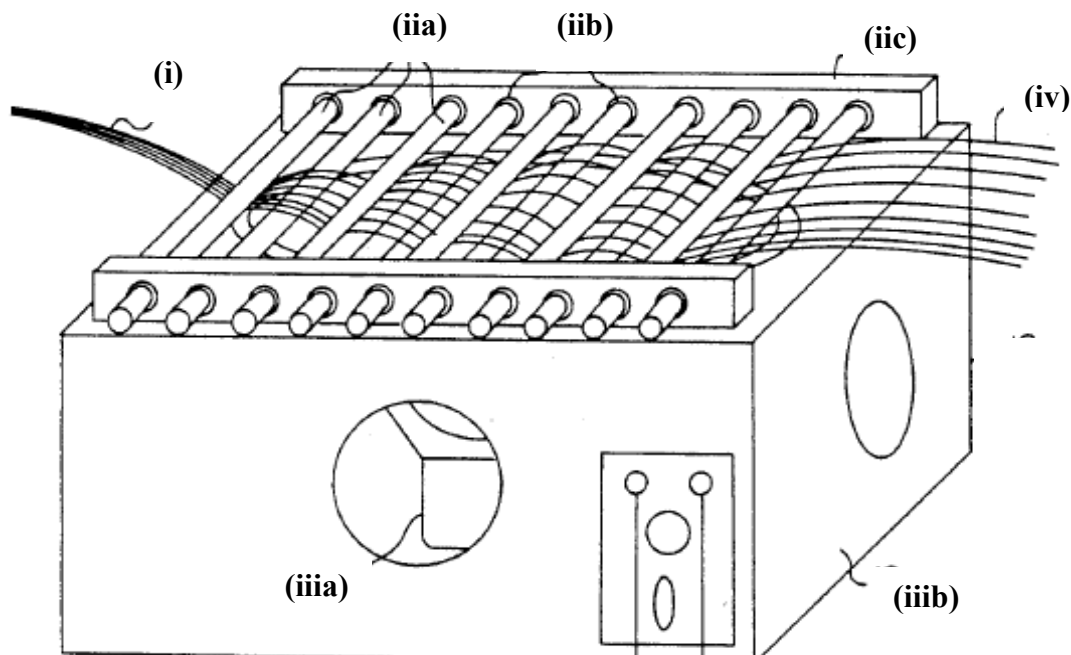


Figure 2.16 Acoustic spreading system designed by Iyer & Drzal (1991) for spreading; numbered items are as follows; (i) as-received fibre bundle, (iia) rollers, (iib) roller bearings, (iic) roller housings, (iiia) speaker, (iiib) speaker housing, (iv) spread fibre bundle.

A number of techniques have been reviewed in this section. In the patent literature there was insufficient information given on the assessment criteria defined here. The degree of fibre damage and the mitigation of such damage is not presented. Many of the inventors claim their invention does not induce fibre damage but no quantification is given. Furthermore, the information provided on the homogeneity of fibre spreading achieved using each technique is lacking. Newell & Puzianowski (1999) reported spread fibre bundle widths of 76.20 mm to 101.60 mm. However, on inspection of photographic evidence of the fibre spreading it was apparent that there was severe segmentation. Sihn *et al.* (2007) and El-Dessouky & Lawrence (2013) provide evidence for as-received and spread fibre bundle widths. They reported widths of 5 mm and 6mm for the as-received fibre bundle. This was increased to 20 mm and 25 mm respectively.

After reviewing the literature, it is believed that mechanically assisted or controlled pneumatic spreading (as seen in Sihn *et al.*, 2007 & El-Dessouky & Lawrence, 2013) are the most appropriate methods of fibre spreading.

2.2 Strength Distribution in Reinforcing Fibres

The following section is a review of the scientific literature on the following topics: the strength distribution in reinforcing fibres, the use of acoustic emission (AE) in conjunction with tensile testing and the use of the Weibull distribution model to determine survival probability.

2.2.1 Manufacture of Reinforcing Fibres

Carbon fibres are formed using one of three precursors; polyacrylonitrile (PAN), rayon, or pitch (mesophase). In each case a similar system of a stabilising treatment,

carbonisation and high temperature treatment (graphitising) is used (Goodhew, Clarke & Bailey, 1975).

For PAN-based fibres the initial heat treatment is conducted in air at around 220 °C. This is followed by carbonisation at 1000-1500 °C in an inert atmosphere and finally graphitisation at 3000 °C. In order to reduce the losses of molecular order in the fibre structure the ramp rate of the temperature is low. The properties of PAN-based fibres can be controlled with changes in the temperature used during the graphitisation stage. For example Goodhew, Clarke & Bailey (1975) state that a higher final heat treatment temperature will result in fibres with a greater elastic modulus. This is a result of an 'improvement of the fibre texture' and 'spontaneous improvement of the orientation of graphite crystallites' (Goodhew, Clarke & Bailey (1975). Tanaka *et al.* (2014) used PAN-based fibres that had been subject to different heat treatments, resulting in varying Young's moduli between sample groups. The authors reported that, higher temperatures during carbonisation resulted in the amorphous phase of the carbon fibre structure becoming crystalline. In addition, as the structure became more crystalline the Young's modulus became greater.

The production of glass fibres differs from the process for carbon fibres. The basis of glass fibre is SiO₂, with a number of additional oxides such as boron, calcium, sodium and iron (Hull, 1981). There are different types of glass fibre each of which has its own prefix; for example E-glass is predominantly made up of oxides of silicon, calcium, aluminium and boron; where-as S-glass is predominantly produced using oxides of silicon, aluminium and magnesium. A detailed explanation of the production of glass fibres is presented by Ifran *et al.* (2013).

Silica and the inorganic oxides for the desired glass are mixed in the required proportions, prior to being fed into a furnace. Irfan *et al.* (2013) describe the furnace as having three distinct regions. The first operates at temperature between 1370 – 1400 °C; it is in this region that the inorganic oxides melt. In the second region, denoted as the ‘refiner’, the melt is filtered and any adsorbed gases, moisture and products of decomposition are removed. It is important that excess moisture is removed as it can adversely affect the fibre properties (Brown *et al.*, 2005; R’Mili, Moevus & Godin, 2008). The final region of the furnace, the ‘foreharth’, is where a process called “*fibrizing*” takes place. At this stage the molten material is drawn through a ‘*bushing*’ with a series of holes of the desired filament diameter. Upon drawing through the bushing, the fibres are cooled in a controlled manner using cooling fins and quenching; this is achieved using a fine mist of water. Once cooled a ‘*sizing*’ or ‘*binder*’ is applied to the fibres. According to Irfan *et al.* (2013) this binder contains a number of components including, but not limited to: coupling agents, lubricants and a binding medium which holds individual filaments together.

Issues with the homogeneity of the application of the binder and its effects on fibre spreading, impregnation and composite properties have been reported by Irfan (2013) and Wait (2016).

2.2.2 Strength Distribution in Reinforcing Fibres

It is known that the strength of reinforcing fibres is governed by inherent flaws within the material. The inherent flaws generally occur during the manufacturing and or handling of the fibres. The degree to which these flaws influence the fibre strength varies due to factors such as their different size, shape and location within, or on the surface of the fibres (Foray *et al.* 2012). Thomason (2013) stated that due to these flaws

or defects, the strength of reinforcing fibres can be related to the weakest link theory; that is, that a material will fail at its most severe flaw.

For carbon fibres, the flaws are generally introduced during the manufacturing process. They are inherent to the microstructure of the material itself. Different types of flaws exist. Pardini & Manhani (2002) and Naito *et al.* (2012) reported that common flaws in carbon fibres include fibrillar misalignments and micropores or microvoids.

Furthermore, a review, by Goodhew, Clarke & Bailey (1975), highlighted four types of flaws that have been observed in PAN-based fibres. These were: inorganic inclusions, organic inclusions, irregular voids from local rapid coagulation, and cylindrical voids formed by dissolved gasses. Zhong, Bian & Wang (2016) describe carbon fibres as consisting of crystalline carbon layers, an amorphous region and needle-like microvoids. Figure 2.17 presents an illustration of these regions; with reference to the Figure (i) is a model of a carbon filament and (ii) is an illustration of the carbon structure. The structure consists of amorphous regions (ii.a), highly ordered crystalline regions (ii.b) and microvoids in the material (ii.c).

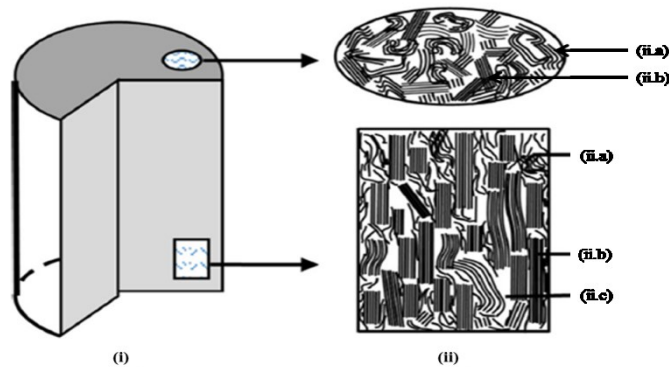


Figure 2.17 A schematic illustration of a carbon filament: (i) the model carbon fibre, (ii) the structure of carbon fibre highlighting, (ii.a) the amorphous regions, (ii.b) the crystallites and (ii.c) the microvoids. Zhong, Bian & Wang (2016).

In contrast to carbon fibres, glass fibres are more sensitive to surface defects (Oskouei & Ahmadi, 2010; Foray *et al.* 2012). These defects can occur during manufacture and handling, and through hydrolytic degradation (Brown *et al.* 2005). Hydrolytic degradation is characterised by moisture interacting with the metal oxides in the glass fibre, leading to defects formed through corrosion mechanisms. R'Mili, Moevus & Godin (2008) reported that water molecules weaken the bonds in the glass structure leading to localised stress concentrations under loading. The sizing added to glass fibres during manufacture aims to reduce the chance of damage through abrasion damage (during handling). Brown *et al.* (2005) reported that the type of sizing can also influence the failure behaviour of the fibre bundles. It was found, that fibre bundles with an epoxy-based sizing were less susceptible to water damage compared to those with a starch-based sizing. Hydrolytic degradation was greater in the fibres with starch-based sizing with an increase in humidity levels. By contrast, the failure behaviour of fibre bundles with an epoxy-based sizing was independent of the humidity level.

2.2.3 Determining the Strength of Reinforcing Fibres

2.2.3.1 Test Method

A number of methods exist for the determination of the tensile strength of reinforcing fibres. Two of the most common methods are the single-filament test (SFT) and the fibre bundle test (FBT).

The single-filament test (SFT) involves the careful removal of a single filament from a reinforcing fibre bundle. Once separated from the bundle this filament is mounted, often in a card window frame (illustrated in Figure 2.18), and tested in tension (Hitchon & Phillips, 1979; Farrow, Hughes & Darby, 1994; R'Mili, Bouchaour & Merle, 1996;

Tagawa & Miyata, 1997; Jihan, Siddiqui & Sweet, 1997; Pardini & Manhani, 2002; Andersons *et al.*, 2002; and Naito *et al.*, 2012). With reference to Figure 2.18, a single filament (i) is carefully extracted from a fibre bundle. This filament is then mounted in a card window frame (ii). The frame is then mounted into the chosen tensile testing machine, and gripped at the extreme ends (iii). Once the sample is mounted, the window frame is cut to ensure that only the filament contributes to the tensile loading. The cut is represented by the dashed line (iv).

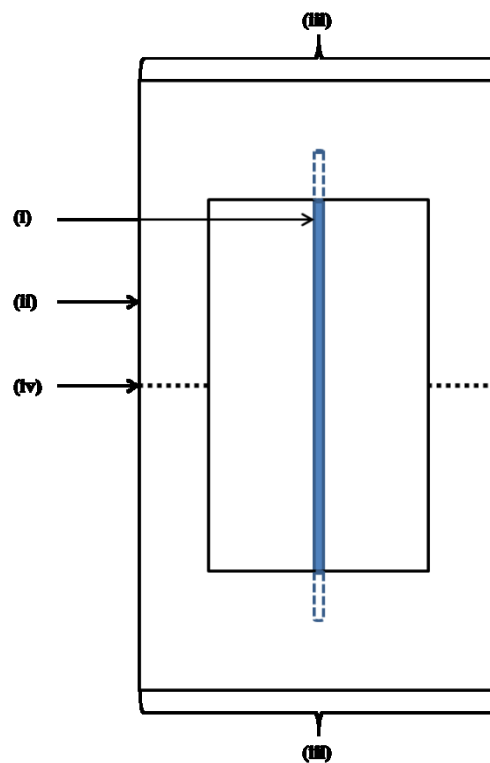


Figure 2.18 A schematic illustration of the single filament tensile test sample.

One of the major disadvantages of this method is the likelihood of censoring the data. It is possible that during sample preparation a filament might break during removal from the bundle, during mounting in the window frame or even during loading in the tensile test machine. Only the weakest of the filaments would likely fail in this way.

Consequently only the strongest filaments in the bundle would ever be tested. The resulting strength distribution could be skewed in favour of these stronger filaments.

One way to overcome these issues inherent to the SFT is through the use of the fibre bundle test (FBT). An advantage of this method over the SFT is that all of the filaments in a bundle are tested at once. Using this method is faster and samples can be produced more easily with less risk of weaker filaments failing during sample manufacture or handling prior to testing. The filament alignment in the longitudinal direction of the bundle can be an issue (Andersons *et al.*, 2002; Oskouei & Ahmadi, 2010); this will be discussed later. Another potential problem with the FBT is the premature failure of filaments due to inter-fibre friction (Hill & Okoroafor, 1995; R'Mili, Moevus & Godin, 2008).

The influence of friction on the tensile properties of reinforcing fibre bundles has been reported by Hill & Okoroafor (1995) and R'Mili, Moevus & Godin (2008). Hill & Okoroafor (1995) reported that dry fibre bundles, of carbon fibre and 600 Tex E-glass fibre, failed at a lower tensile strength than when the bundles were lubricated.

Figure 2.19 presents representative load/displacement traces for the dry and lubricated bundles of carbon and E-glass fibre respectively (Hill & Okoroafor, 1995). The failure stress and strain of dry E-glass fibre bundles were 14.5% and 16.5% lower, respectively, compared to lubricated E-glass fibre bundles. It was also observed that filament failure occurred earlier in the dry bundles. The authors reported that an increase in inter-fibre friction resulted in the reduction in tensile strength and earlier failure of filaments in the dry fibre bundles. Failures events were determined using acoustic emission (AE) sensors.

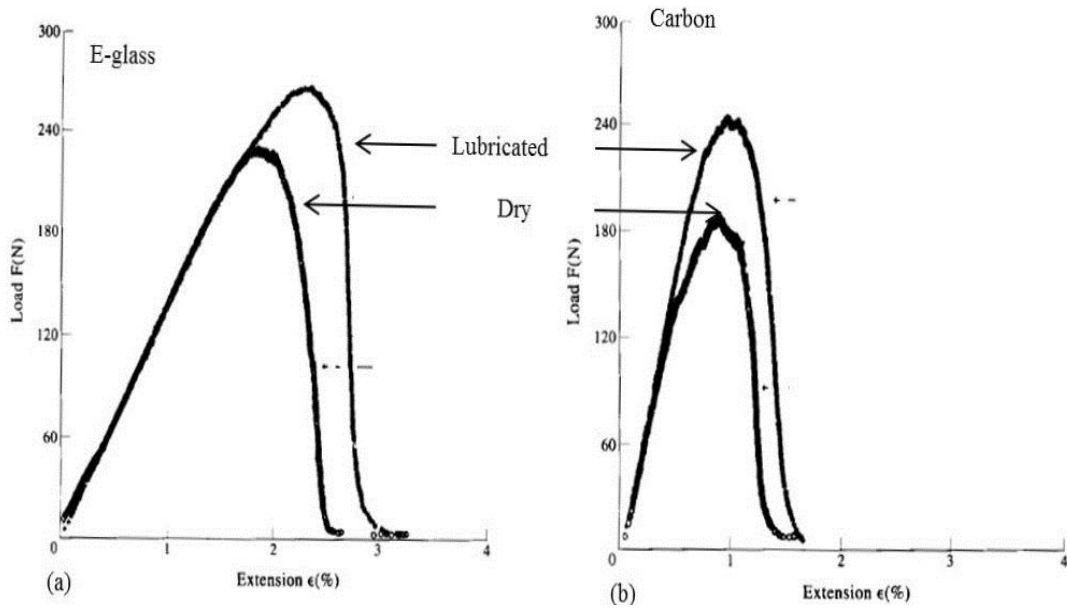


Figure 2.19 Load-extension curves for dry and lubricated E-glass and carbon fibre bundles respectively. Hill & Okoroafor (1995).

R'Mili, Moevus & Godin (2008) also found that dry bundles failed at lower loads than lubricated bundles. In their study, E-glass fibres with ~ 2000 filaments were tested at gauge lengths of 30, 60 and 100 mm, with a cross-head displacement rate of $2 \mu\text{m}/\text{minute}$. In addition, it was determined that the viscosity of the lubricant also influenced the fibre bundle strength. The dry fibre bundles exhibited the lowest tensile strength; the most viscous lubricant, Vaseline-oil, was found to result in failure similar to that observed in the dry fibre bundles. Representative load/strain traces, for fibre bundles with different lubricants tested at a gauge length of 60 mm, are presented in Figure 2.20.

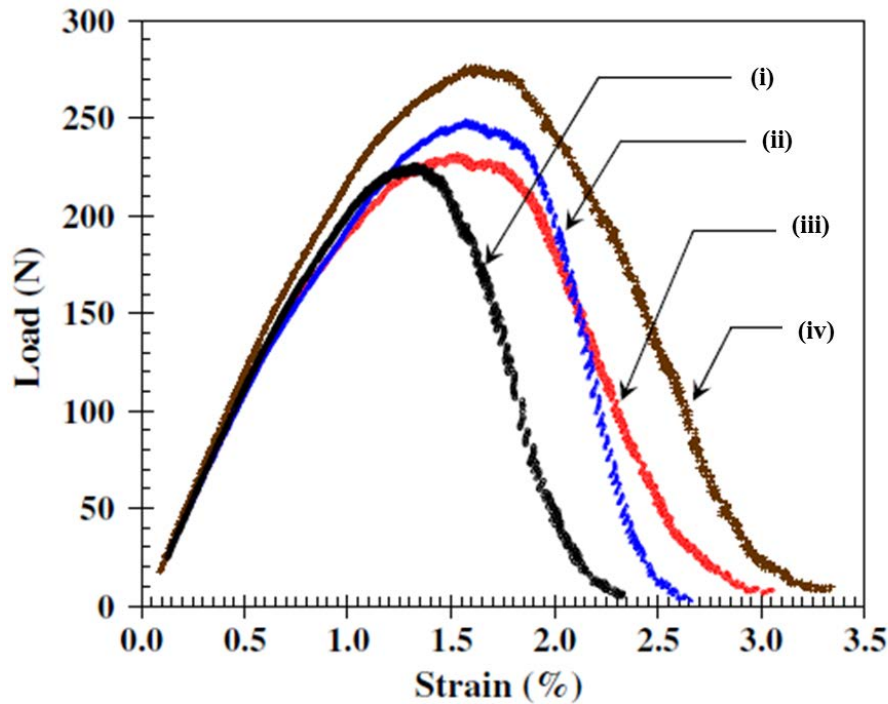


Figure 2.20 The reported representative load/strain curves for E-glass fibre bundles tested at a gauge length of 60 mm; (i) dry, (ii) petrol-oil, (iii) Vaseline-oil and (iv) light-oil. R'Mili, Moevus & Godin (2008).

Work by a number of authors has determined that there is gauge length dependence for reinforcing fibre bundle strength i.e. the testing gauge length influences the tensile behaviour of reinforcing fibres. R'Mili, Bouchaour & Merle (1996) reported a mean tensile strength of 2950 MPa for a Thornel 300 carbon fibre filament tested at a 30 mm gauge length. The tensile strength was observed to reduce to 2700 MPa at gauge length of 60 mm. Naito *et al.* (2012) showed gauge length dependence for a range of carbon fibre types. In each case, an increase in the gauge length resulted in a reduction in the average tensile failure stress. Pardini & Manhani (2002) reported average tensile failure stress values of 2.90 GPa, 2.70 GPa, 2.66 GPa and 2.54 GPa, at gauge lengths of 25, 50, 75 and 100 mm respectively, for PAN-based 400 dTex AS4-GP carbon fibres. They

also reported average tensile failure stress values of 2.58 GPa (25 mm), 2.27 GPa (50 mm), 2.43 GPa (75 mm) and 2.18 GPa (100 mm) for 750 dTex E-glass fibres.

Pickering & Murray (1999) reported that the change in tensile failure stress of Tenax 800 Tex carbon fibres reduced even with an increase of 1 mm. The SFT was used and the average tensile failure stress of 4749 MPa, at a 1 mm gauge length, reduced to 4577 MPa at a gauge length of 2 mm. At a gauge length of 500 mm the average tensile failure stress was reported to be 2206 MPa.

This gauge length dependence is related to the distribution of flaws along the length of the filaments in a fibre bundle. As the length of the fibre bundle increases the probability of flaws within that length also increases.

2.2.3.2 Acoustic Emission (AE)

By attaching AE transducers to the end-tabs of a fibre bundle sample it is possible to record the ‘energy released as an elastic wave when a filament breaks’ (Okoroafor & Hill, 1995). To ensure efficient recording of the AE, it is important to ensure the material is coupled effectively to the transducer. This is achieved using a couplant; a common example of a couplant is silicone grease (Hill & Okoroafor, 1995; R’Mili, Moevus & Godin, 2008).

The stress wave recorded by an AE transducer can be produced by a number of events, ranging from filament fracture, inter-fibre interaction (such as friction) and background mechanical noise (Hill & Okoroafor, 1995). It is possible, through post-processing of the recorded data, to filter the data in such a way that specific events can be analysed. If the load is used as a parametric input to the AE system it is also possible to match each filament break with a unique failure load (Oskouei & Ahmadi, 2010).

Figure 2.21 (Oskouei & Ahmadi, 2010) shows an example of a wave form recorded when reinforcing filament fractures in a fibre bundle tensile test. Waveforms associated with filament failures generally have high amplitude, quick rise time (time taken to reach peak amplitude) and a rapid decay (time taken for signal to return to 0).

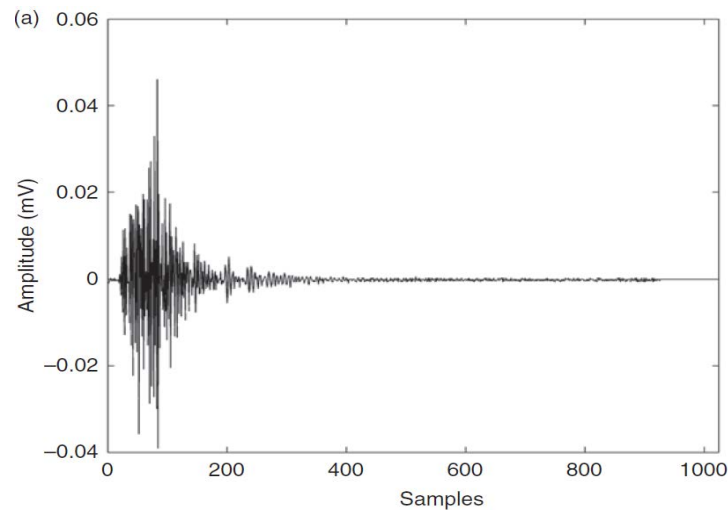


Figure 2.21 An example waveform recorded using AE when a filament fails under tensile loading. Oskouei & Ahmadi (2010).

In cases where the FBT has been utilised, two distinct distributions in the AE events, have been observed. In the case of E-glass, Jihan, Siddiqui & Sweet (1997), R'Mili, Moevus & Godin (2008) and Oskouei & Ahmadi (2010), have reported the observation of two distinct amplitude distributions during tensile testing. One distribution is of high amplitudes events with values around 80-95 dB associated with fibre breaks. The second lower amplitude event distribution, around 50 dB, is associated with inter-fibre interaction (Jihan, Siddiqui & Sweet, 1997; R'Mili, Moevus & Godin, 2008; Oskouei & Ahmadi, 2010)

Figure 2.22 presents examples of the two distinct AE amplitude distributions at two different gauge lengths reported by R'Mili, Moevus & Godin (2008). It is interesting to note that at the shorter gauge length there is pronounced distribution at 50 dB where as

in the longer gauge length data there is a wider amplitude distribution between 40-60 dB; this is because at longer gauge lengths there is more inter-fibre friction, as mentioned previously.

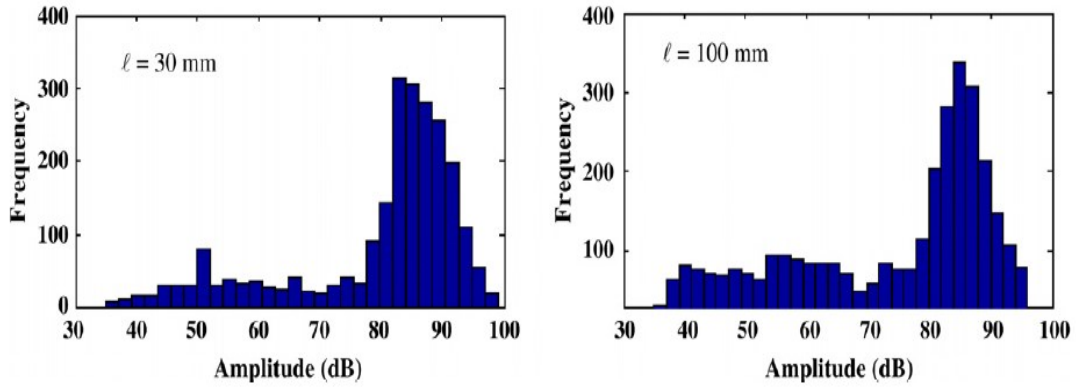


Figure 2.22 Amplitude (dB) vs frequency distribution histograms for fibre bundles tested at 30 mm and 100 mm gauge lengths. R'Mili, Moevus & Godin (2008).

Oskouei & Ahmadi (2010) also observed two distributions in E-glass bundles with a gauge length of 100 mm; a large distribution of high amplitude hits and a second smaller distribution of lower amplitude hits. From Figure 2.23, it can be seen that the higher amplitude fibre failures were distributed in an amplitude range between 75-95 dB whereas noise due to inter-fibre friction was in an amplitude distribution ranging from 40-55 dB.

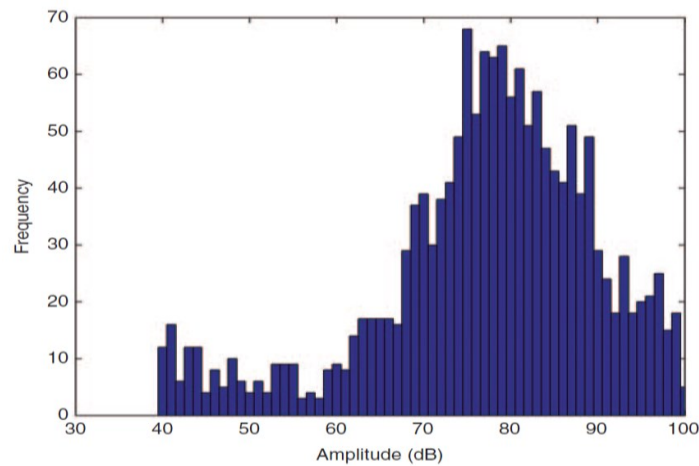


Figure 2.23 A typical amplitude distribution histogram for E-glass reinforcing fibre. Oskouei & Ahmadi (2010).

Okoraofor & Hill (1995) and Jihan, Siddiqui & Sweet (1997) described the first amplitude distribution as a group of weaker filaments that fail prior to peak load whilst the other distribution was the strongest filaments failing after peak load. The filaments failures associated with a lower amplitude hit would be failing at a lower strain and therefore releasing less energy. Jihan, Siddiqui & Sweet (1997) stated that the weakest filaments failed prior to peak load with an amplitude range of 53-73 dB, and the strongest filaments failed after peak load with an amplitude range of 73-95 dB.

Figure 2.24 presents an example of the amplitude distribution as the applied tensile stress increased. It is clear to see that at a lower stress, <1.0 , the filament failures resulted in lower amplitudes. There was then a transition closer to, and after, peak load where the amplitude distribution increased.

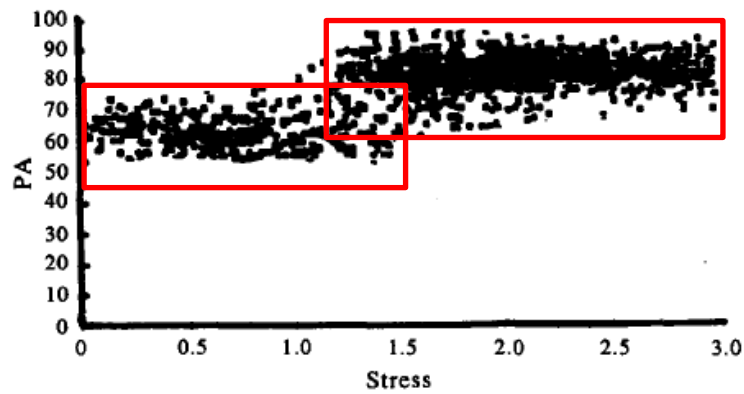


Figure 2.24 Amplitude (PA refers to peak amplitude) vs stress during tensile testing of E-glass fibre bundles containing up to 4000 filaments; AE data recorded during loading. Jihan, Siddiqui & Sweet (1997).

2.2.3.4 The Weibull Distribution

The Weibull distribution has been deployed by researchers looking at all types of fibres; from carbon (Hill & Okoroafor, 1995; Naito *et al.*, 2012), to E-glass (Hill & Okoroafor, 1995; R'Mili, Bouchaour & Merle, 1996; Andersons *et al.* 2002) and even Kevlar® (Hill & Okoroafor, 1995; Okoroafor & Hill, 1995).

The most common method used to determine the Weibull parameters is the two-parameter Weibull distribution (Equation 2.1).

$$P = \exp[-L(\alpha/\alpha_0)^m] \quad \text{Equation 2.1}$$

where α is the scale parameter, which can be considered the failure strain (Hill & Okoroafor, 1995), m is the shape parameter (sometimes referred to as Weibull modulus), which can be considered a measure of the flaw size distribution as well as the coefficient of variance, and L is the normalised fibre length.

For fibre bundle testing there are some assumptions for the Weibull model these are (R'Mili, Moevus & Godin, 2008; Oskouei & Ahmadi, 2010):

- (i) All of the filaments in the fibre bundle are a constant length.
- (ii) The stress/strain relationship under load follows Hooke's law up to failure.
- (iii) There is equal load sharing (ELS) among the filaments in the bundle i.e. when a bundle fails the load that it was carrying is redistributed equally among the surviving filaments.

With respect to the above assumptions, Andersons *et al.* (2002) stated, that determination of the Weibull parameters from the results of FBT can sometimes be inaccurate. The issues arise from the variability of filament length within the bundle and the potential for inter-fibre friction resulting in local load sharing (LLS), not ELS.

R'Mili, Moevus & Godin (2008) tried to reduce the occurrence of variable filament length, a potential issue with regards to assumption (i). Using a thermos-retractable sheath, one end of the fibre bundle sample was '*pinned*'. Resin was then introduced to the area and cured to lock the filaments in place. Once one end was secured the other was prepared in the same fashion.

In the case of assumption (ii) some authors have recorded an initial non-linear portion of the load-displacement trace (Calard & Lamon, 2004; Oskouei & Ahmadi, 2010). This was stated as evidence of different filament lengths or uneven tension within the gauge length. There is also an inherent issue with the tensile test known as system compliance, in which the initial portion of the curve is observed to be non-linear. The method of determining the system compliance for a given machine is presented in ASTM C1557-14. Figure 2.25 shows an example of this from Oskouei & Ahmadi (2010). After the initial non-linear portion of the curve, the stress/strain relationship did exhibit linear behaviour up to final failure. Oskouei & Ahmadi (2010) stated this was due to uneven

tension in the bundle. Along with system compliance it is possible that the specimen was not under uniform tension at the start of the test.

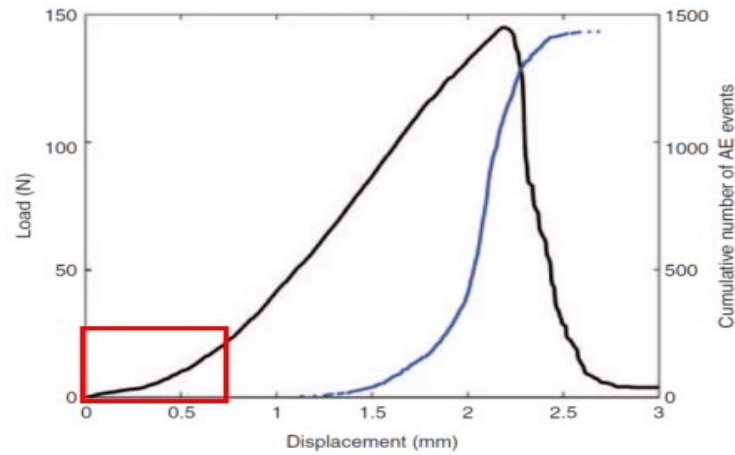


Figure 2.25 A typical load-displacement curve showing initial non-linear behaviour (red box) during tensile testing of E-glass fibre bundles. Oksoueï & Ahmadi (2010).

With regards to assumption (iii), the ELS rule will only apply if there is no interaction between the filaments in the bundle; the influence of inter-fibre friction has been discussed already (Hill & Okorafor, 1995; R'Mili, Moevus & Godin, 2008). If there is inter-filament interaction, such as friction which leads to load transfer, then local load sharing (LLS) is a more realistic assumption. In this instance, when a filament breaks the load it was carrying is transferred to any of its neighbours that are in intimate contact (Calard & Lamon, 2004).

Pardini & Manhani (2002) tested both carbon and E-glass single filaments selected at random from 400 Tex and 750 Tex fibre bundles respectively. The single-filaments were tensile tested at a cross-head displacement of 2.5 mm/min, at gauge lengths of 25, 50, 75 and 100 mm. They reported Weibull moduli, at a gauge length of 25 mm, of 3.28 and 5.76 for the carbon and E-glass fibres respectively.

In Pardini & Manhani (2002), a unimodal flaw distribution, a distribution where only one type of flaw exists, was observed for carbon fibres. By contrast, some other researchers have observed a bimodal distribution. Hitchon & Phillips (1979) found a bimodal flaw distribution for carbon fibre bundles. They attributed this finding to the possible presence of two unimodal flaw distributions.

Bimodal flaw distributions have also been observed in glass fibres. Jihan, Siddiqui & Sweet (1997) and Oskouei & Ahmadi (2010) both found bimodal flaw distributions. Jihan, Siddiqui & Sweet (1997) used this distribution to determine upper and lower limits for fibre bundle strength. Similarly Oskouei & Ahmadi (2010) were able to split their flaw distribution into a group of weaker fibres failing prior to the peak load and stronger group of fibres that failed at or beyond the peak load. Figure 2.26 shows that the flaw distribution could be fitted by two straight lines. Oskouei & Ahmadi (2010) reported that this indicated a bimodal flaw distribution. They also suggested it provided upper S_u and lower S_l limits for strength of the fibre bundle.

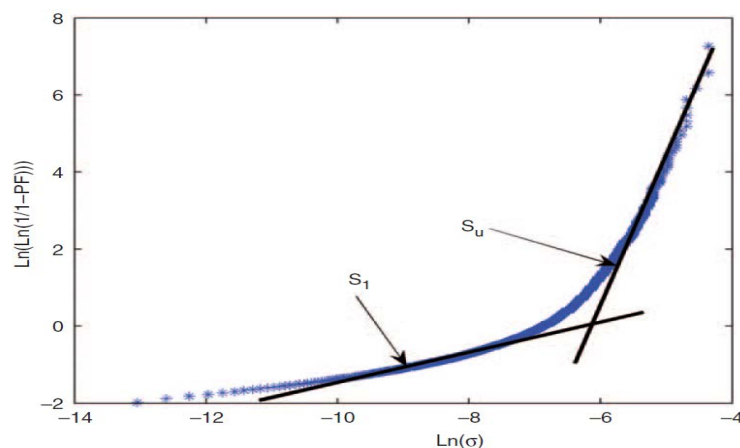


Figure 2.26 A flaw distribution graph showing two linear fit lines for upper and lower limits for strength. Oskouei & Ahmadi (2010).

Presented in Table 2.1 are values reported for the Weibull shape and scale parameters for carbon fibre and E-glass fibre. Information is given on the type of testing, the gauge length and the Weibull parameter.

A search of the literature has highlighted that there have been varying reports for the shape and scale parameters of carbon fibres and E-glass fibres. With reference to Table 2.1, it can be seen that the scale parameter has been reported using different definitions. For example, Hill & Okoroafor (1995) reported scale parameters of 2.437 GPa and 1.243 GPa for dry E-glass and carbon fibre bundles. By contrast, the scale parameters reported by R'Mili, Moevus & Godin (2008) for E-glass fibre bundles were reported as strain (2.07-2.15%). R'Mili, Bouchaour & Merle (1996), Gurvich, DiBenedetto & Ranade (1997), Gurvich, DiBenedetto & Pegoretti (1997) and Andersons *et al.* (2002) all reported scale parameter values in MPa.

The reported shape parameters are all within a more reasonable range. It has been observed that, as with tensile failure strength, there is an influence on the shape parameter with a change in the testing gauge length. However, it does not always follow that an increase in gauge length results in a decrease in the shape parameter. For example, R'Mili, Bouchaour & Merle (1996) reported an increase in shape parameter, obtained from E-glass fibres, from 5.5 to 7.6 after doubling the gauge length from 30 mm to 60 mm. Whereas, Andersons *et al.* (2002) reported shape parameters for E-glass tested at 80, 160 and 320 mm of 5.38, 3.98 and 4.37.

This non-linear trend was also reported for carbon fibres by Pardini & Manhani (2002). Shape parameters of 3.25, 3.56, 3.14 and 3.10 were obtained from gauge lengths of 25, 50, 75 and 100 mm, when using the SFT, for PAN-based 400 dTEX carbon fibres.

Andersons *et al.* (2002) also reported values for SFT and FBT using E-glass fibres. The common gauge length for both tests was 80 mm. The shape and scale parameters obtained using SFT and FBT were 5.38 and 4120 MPa, and 5.18 and 4440 MPa respectively. This was the only direct comparison of Weibull parameters obtained using the two different test methods discovered during the literature search.

Hill & Okoroafor (1995) reported a change in Weibull parameters for the FBT for E-glass fibre and carbon fibre tested in the dry and lubricated state. For carbon fibre there was a very small change in the reported shape, 4.5 and 4.25, and scale, 1.243 GPa and 1.424 GPa, parameters for dry and lubricated fibre bundles respectively. By contrast, the obtained shape and scale parameters for E-glass fibres were affected by the testing state. The shape and scale parameters were 9.4 and 6.4, and 2.437 GPa and 3.074 GPa for dry and lubricated bundles respectively.

The effect of sizing (Gurvich, DiBenedetto & Ranade, 1997; Gurvich, DiBenedetto & Pegoretti, 1997), manufacturer Gurvich, DiBenedetto & Pegoretti, 1997) and humidity (Brown *et al.*, 2005) have also been reported.

Table 2.1 A compilation of reported values for the Weibull shape and scale parameters, obtained from SFT and FBT of a range of carbon fibres and E-glass fibres at varying gauge lengths.

Author(s) (Date)	Test	Fibre Type: Gauge Length	Shape parameter (m)	Scale parameter (α) (GPa)
Hill & Okoroafor (1995)	FBT	E-glass fibre: 70 mm Dry (Lubricated)	9.4 (6.4)	2.437 (3.074)
		Carbon fibre: 70 mm Dry (Lubricated)	4.5 (4.25)	1.243 (1.424)
Okoroafor & Hill (1995)	FBT	Lubricated E-glass fibre 70 mm:	6.7	3.07
		Lubricated carbon fibre (9007C) 70 mm:	4.5	1.62
Ma & Sines (1995)	SFT	Pitch-based carbon fibres		
		E130:		
		1.5 mm	5.74	-
		3 mm	6.07	-
		6 mm	4.66	-
		12 mm	5.42	-
		24 mm	4.68	-
		C700:		
		1.5 mm	-	-
		3 mm	4.81	-
		6 mm	4.82	-
		12 mm	4.88	-
		24 mm	-	-
R'Mili, Bouchaour & Merle (1996)	SFT	T300 carbon fibre:		
		30 mm	5.5	3200 (MPa)
		60 mm	7.6	2970 (MPa)

Gurvich, DiBenedetto & Ranade (1997)	SFT	S2-glass fibres, 25.4 mm:		
		463 AA epoxy sizing	4.52	2644.8 (MPa)
		933 AA PEEK sizing	5.32	3009.9 (MPa)
		Starch-sizing	3.96	1434.5 (MPa)
Gurvich, DiBenedetto & Pegoretti (1997)	SFT	E-glass fibres (various suppliers and sizing):		
		14.8 µm Ø: 20 mm	3.18	2020
		15 mm	5.13	1793
		10 mm	6.61	1768
		5 mm	4.16	2017
		14.7 µm Ø: 20 mm	7.07	2565
		15 mm	7.76	2558
		10 mm	6.85	2640
		5 mm	5.52	2628
		25.1 µm Ø: 40 mm	2.76	4218
		25 mm	6.47	2341
		10 mm	8.14	2207
		5 mm	5.65	2184
		19.9 µm Ø: 20 mm	7.94	2602
		15 mm	6.50	2703
		10 mm	9.38	2742
		5 mm	8.74	2400
		16.8 µm Ø: 20 mm	4.44	2146
		15 mm	3.67	3220
		10 mm	3.17	3364
		5 mm	3.44	2777

		Carbon fibres μm 7 Ø: 25 mm	5.72	3764
		20 mm	5.80	3967
		10 mm	6.00	3945
		5 mm	9.81	3765
Pickering & Murray (1999)	SFT	12k HTA 5131 800 Tex carbon fibre:		
		1 mm		-
		2 mm	5.65	-
		5 mm	6.06	-
		20 mm	6.67	-
		200 mm	7.86	-
		500 mm	6.29	-
			6.95	-
Pardini & Manhani (2002)	SFT	E-glass 700 dTex fibres:		
		25mm	6.56	-
		50 mm	4.74	-
		75 mm	5.63	-
		100 mm	5.89	-
		PAN-based 400 dTex carbon fibres:		
		25 mm	3.25	-
		50 mm	3.56	-
		75 mm	3.14	-
		100 mm	3.10	-

Andersons <i>et al.</i> (2002)	FBT	E-glass fibre: 80 mm	5.38	4120 (MPa)
		160 mm	3.98	5660 (MPa)
		320 mm	4.37	5280 (MPa)
	SFT	E-glass fibre: 5 mm	5.12	3380 (MPa)
		10 mm	5.48	3620 (MPa)
		20 mm	5.50	3810 (MPa)
		40 mm	5.54	3880 (MPa)
		80 mm	5.18	4440 (MPa)
Moser <i>et al.</i> (2003)	FBT	T300 carbon fibres	15	3.5
Brown <i>et al.</i> (2005)	FBT	Epoxy-sized Glass Fibre 25 mm:		
		10% humidity	13	-
		40% humidity	14	-
		80% humidity	14	-
		100% humidity	17	-
R'Mili, Moevus & Godin (2008)	FBT	E-glass fibre:		
		30 mm	3.0	2.75(%)
		60 mm	3.6	2.14(%)
		100 mm	2.8	2.07(%)

This section of the literature review has highlighted a number of key points. A number of test techniques exist for determining the strength distribution known to exist in reinforcing fibres. The FBT provides a quick accurate way of measuring fibre bundle strength. In comparison to the SFT it is less likely that sample censoring will occur and it is a way of getting strength data for a whole fibre bundle at once. It is still possible to introduce flaws or induce filament fracture during sample preparation and handling. The selection of the testing gauge length(s) is important as it is known that the strength distribution has a dependence on the gauge length.

The use of AE is a powerful tool to interpret the data and in conjunction with the Weibull model it is possible to gain further insight into the strength distribution behaviour of fibre bundles. Accurate recording and analysis of the AE data is important in order to draw accurate conclusions. The assumptions of the Weibull model can result in discrepancy between predicted and experimental values.

From the literature reviewed there was no observation of the effect of spreading a fibre bundle on the tensile properties. Spreading fibre bundles can improve the alignment of the filaments and this may be important when considering the assumptions of the Weibull model and accuracy of current test methods.

2.3 Hybrid Composites

Whilst carbon fibre composites have high specific strength and stiffness, they are susceptible to impact damage and can have a lower failure strain than reinforcing fibres such as E-glass or Kevlar®. The low failure strain of carbon composites is undesirable as it can result in sudden catastrophic failure. The most common method reported to

improve this is hybridisation (Zweben, 1977; Bunsell & Harris, 1974; Manders & Bader, 1981; Czél *et al.*, 2012; Czél & Wisnom, 2013; Diao *et al.* 2014).

Hybridisation involves combining two or more reinforcing fibre types in a single matrix. Common combinations include carbon and glass, carbon and Kevlar®, glass and Kevlar®, carbon and polyethylene, and also glass and polyethylene (Harris & Bunsell, 1975; Gustin *et al.*, 2005; Park & Jang, 2000; Peijs *et al.*, 1990; and Datta, Basu & Banerjee, 2003; Czél *et al.*, 2012; Czél & Wisnom, 2013; Diao *et al.*, 2014).

2.3.1 Types of Hybrid Composite

There are many types of hybrid composite, each with different classifications. Fernando & Al-Khodairi ('Fatigue of Hybrid Composites', in Harris, B. (eds) *Fatigue in Composites*. 1st edn. Cambridge, Woodhead Publishing Limited, pp. 190-241) defined a total of seven different types of hybrid composite Figure 2.27 shows schematic illustrations of each of these.

With reference to Figure 2.27, the following section gives a brief description of each class of hybrid. Image (0) is of a normal mono-fibre composite laminate consisting of one fibre type in one matrix. Image (i) represents an inter-ply hybrid. This is where two fibre types are used in the composite but they are separate i.e. only one fibre type is in each layer. The hybrid is formed by stacking the layers of different fibre types according to the desired design and required properties. Image (ii) represents an intimately mixed or intra-filament hybrid. In this hybrid type, both fibre bundles are mixed at the filament level to create a single hybrid bundle, which is then used to create a lamina. Image (iii) shows a type of hybrid composite known as an intra-ply hybrid. In this case, both reinforcing fibre types are present in a single layer, but are not mixed at

the filament level. This is also known as a bundle-by-bundle hybrid (Swolfs, Gorbatiikh & Verpoest, 2014); the fibre bundles alternate within the layer. Images (iv) and (v) show selective layer hybrids. These can involve special interface reinforcement between lamina or inter-leafing of a different matrix system between the layers. The final two images (vi) and (vii) show different types of skin/core hybrids.

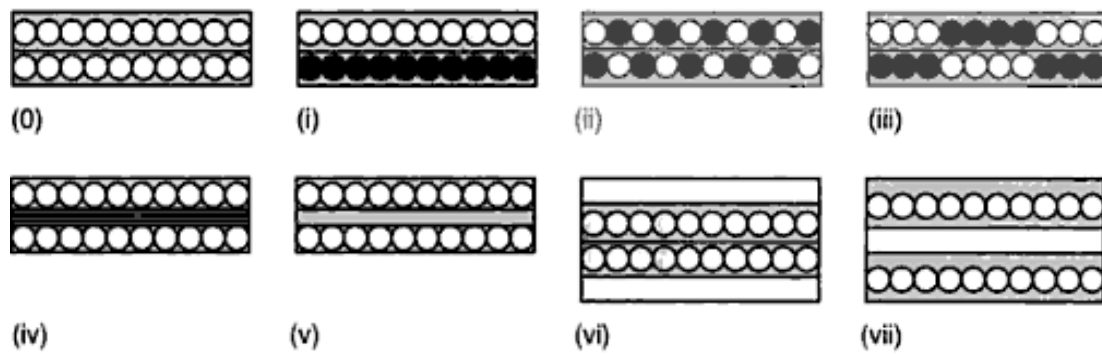


Figure 2.27 Schematic illustrations of different types of hybrid laminates as proposed by Fernando and Al-Khodairi.

In the present literature, the most commonly reported hybrid types are inter- or intra-ply laminates. At the time of writing, the author was aware of only one report where two reinforcing fibre bundles were mixed at the filament level (Diao *et al.* 2014). Hybrid fibre bundles do exist where a reinforcing fibre bundle is intimately mixed with thermoplastic fibres (Peijs *et al.*, 1990; Ye *et al.*, 1995; Thanomsilp & Hogg, 2003); this is known as a commingled fibre bundle.

2.3.2 The ‘Hybrid Effect’

A search of the literature found two definitions of the so called effect observed when hybridising one reinforcing fibre type with another.

The first definition, defines the hybrid effect as an enhancement of the initial failure strain of the lower elongation, or higher modulus, fibre within the hybrid (Manders & Bader, 1981). The second definition of the hybrid effect is based on the rule-of-mixtures

(RoM) approach. The RoM equation, Equation 2.2, is used to work out the properties of a composite containing two reinforcing fibre types; this simple equation however assumes no interaction between the two fibre types.

$$E_{hybrid} = E_{LE}Vf_{LE} + E_{HE}Vf_{HE} \quad \text{Equation 2.2}$$

where E_{hybrid} is the Young's modulus of the hybrid which is the sum of the Young's moduli of the low elongation fibre, E_{LE} , and the high elongation fibre, E_{HE} , as a function of their respective volume fractions (Vf_{LE} and Vf_{HE}).

Presented in Figure 2.28 and Figure 2.29 are graphical representations of the two definitions (failure strain and RoM respectively); sourced from Swolfs, Gorbatikh & Verpoest, 2014.

With reference to Figure 2.28, the load/displacement curves for a mono-fibre LE composite (i), a mono-fibre HE composite (ii) and a hybrid composite of the two (iii) are presented. A hybrid effect is observed if there is a deviation in the failure strain of the hybrid composite when compared to that of the mono-fibre LE composite (iv).

Figure 2.29 presents a graphical representation of the hybrid effect defined using the RoM approach. To determine the presence of a hybrid effect, the predicted values for the property in question, for example tensile failure strain, are plotted (i). The experimentally obtained values for the composite are then plotted on the RoM graph. If the experimental values exceed those that were predicted, there was a positive hybrid effect (ii). Conversely, if the experimental values fall below the predicted values, there was a negative hybrid effect (iii).

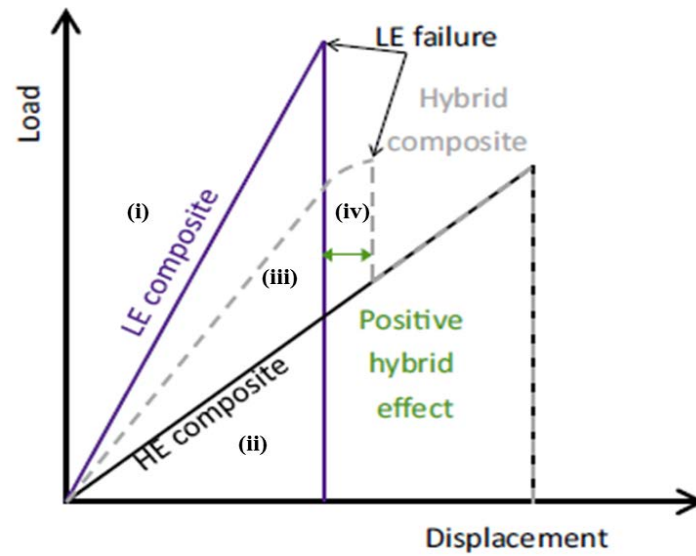


Figure 2.28 A graphical representation of the first definition of the hybrid effect; an improvement of the failure strain of the hybrid composite, compared to the LE composite; Swolfs, Gorbatiikh & Verpoest (2014).

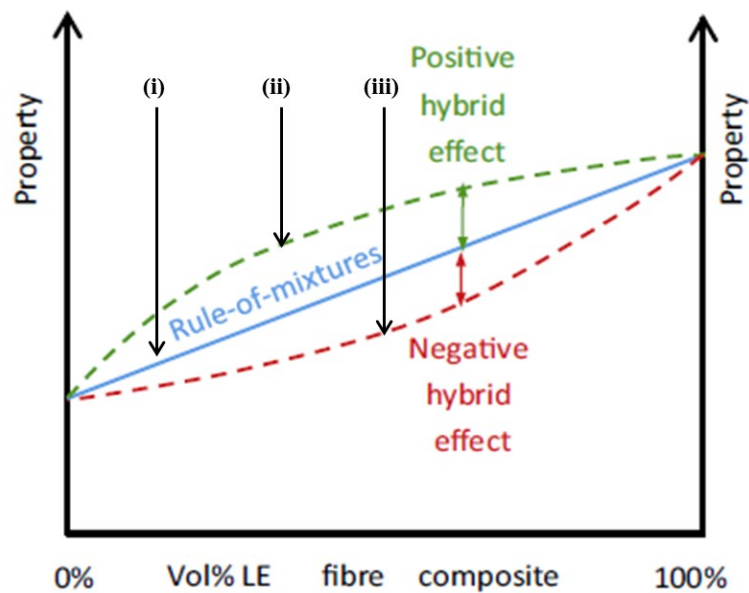


Figure 2.29 A graphical representation of the RoM approach to defining the hybrid effect. Swolfs, Gorbatiikh & Verpoest (2014).

A review by Swolfs, Gorbatiikh & Verpoest (2014) reported that the hybrid effect has been attributed to one, or a combination of, three factors: (i) thermal residual stresses, (ii) failure development, and (iii) dynamic stress concentrations.

- (i) Thermal residual stresses: Bunsell & Harris (1974) proposed that it was possible for the LE filaments in a hybrid composite to be subjected to compression upon cooling from the elevated processing temperatures. This is because the coefficients of thermal (CTE) expansion between the LE and HE filaments (and the matrix) are different. In the current study for example, according to their respective manufacturer's data sheets, the carbon fibre and glass fibres chosen have CTEs of $-0.38 \times 10^{-6}/^{\circ}\text{C}$ and $6 \times 10^{-6}/\text{K}^{-1}$ respectively. An example of this was presented by Czél & Wisnom (2013). They reported that a central carbon layer had a residual compressive strain, post-manufacture, of 5.57×10^{-4} . However, they also reported that this compressive strain was less than 3% of the failure strain of the carbon, and therefore, could not have significantly affected the failure of the hybrid composite.
- (ii) Failure Development: The statistical approach is related to the failure development in a composite with regards to the SCFs experienced by the filaments. The influence of hybridisation can increase the level of strain required for that crack to propagate. This is because the two fibre types generally have different failure strains. Failure will occur when a critical cluster size is reached; hybridisation can retard the formation of clusters as well as increasing the critical cluster size (Swolfs, Gorbatiikh & Verpoest, 2014).

- (iii) Dynamic stress concentrations: Swolfs, Gorbatiikh & Verpoest,(2014) stated in their review that dynamic stress concentrations have been poorly researched. The defining feature of a dynamic stress concentration is a stress wave travelling along the filament length after it fractures creating a stress concentration. In the case of hybrid composites, Swolfs, Gorbatiikh & Verpoest,(2014) reported in their review that two stress waves have been observed when an LE filament breaks. The stress concentrations were subsequently lower as the two waves, one in the LE layers and one in the HE layers were “out-of-phase”.

In the literature, a number of studies have aimed to prove the existence of the hybrid effect through modelling and/or experimental methods (Zweben, 1977; Harlow & Phoenix, 1978; Manders & Bader, 1981; Katri & Koczak, 1995; Czél *et al.*, 2012; Czél & Wisnom, 2013; Swolfs, Gorbatiikh & Verpoest, 2014; Swolfs *et al.* 2015) These studies investigated a range of hybrid types, stacking sequences, reinforcing fibre types and properties. The following sub-sections review these models and experimental studies.

2.3.3 Theory and Modelling of Hybrid Composites

Research into statistical models for the failure of composites was originally focussed on mono-fibre composites; however the emergence of hybrid composites led to more research into the modelling of the failure process in hybrid composites in order to further define the hybrid effect. The following review aims to summarise the main models and highlight the assumptions made. Whilst there is literature concerning the modelling of failure in mono-fibre composites, only the models concerning hybrid composites will be presented here.

Each model is generally defined by three main aspects:

1. The load sharing rule that is applied to the model,
2. The type of hybrid modelled, and
3. The dispersion and relative volume fraction of each fibre type within the modelled composite.

A total of three load sharing rules have been found in the literature search; Zweben & Rosen (1969) presented definitions of the two most common load sharing rules: the equal load sharing rule (ELS) and the local load sharing rule (LLS). The equal load sharing (ELS) assumes that upon a filament failure the load that it was carrying is evenly distributed among the surviving non-failed filaments. By contrast, the local load sharing (LLS) assumes that when a filament fails the load it was carrying is redistributed among its closest surviving neighbours. Surviving filaments would bear increasing proportions of the redistributed load with increasing proximity to a failed filament. A third less common load sharing rule was presented by Swolfs *et al.* (2015): the global load sharing rule (GLS). GLS assumes that when a filament fails the load is redistributed among all of the surviving filaments in the plane of the failed filament.

Presented in Table 2.2 is a summary of the models concerning the hybrid effect including: the author(s)/year, type of model, the hybrid composition, brief conclusions. Following on from this, selected models will be reviewed in more detail.

Table 2.2 A table summarising the literature concerning modelling of hybrid composites.

Author(s) (Year)	Description of Model	Hybrid Composition	Brief Summary of Findings
Zweben (1977)	2D Array	Alternating LE and HE filaments in matrix	Failure strain of LE component in hybrid; should be different compared to mono-fibre LE composite
Harlow & Phoenix (1978)	Chain-of-bundles; ELS and LLS	Four-filament array	Determined combinations of load concentration factors for each of the four filaments
Fukuda & Chou (1982)	Stress concentration factors in fibre breakage model; Monto Carlo simulation of composite strength	“Intermingled” hybrid composite; alternating LE and HE fibres	Found enhanced ultimate failure strain of the hybrid compared to mono-fibre LE composite
Harlow (1983)	Chain-of-bundles; LLS	Unidirectional hybrid composite; alternating LE and HE fibres	The results showed that there was a negative hybrid effect for hybrid breaking strain; a positive effect was observed for hybrid strength
Fukunaga, Chou & Fukuda (1984)	Chain-of-bundles model with shear-lag analysis	Intermingled or intra-ply hybrid sheet	Concluded that the observed hybrid effects were a result of strength scatter. The magnitude of the hybrid effect was determined by the size of the fibre bundle and the state of stress redistribution i.e. load sharing rule
Fariborz, Yang & Harlow (1985)	Modified chain-of-bundles approach with Monte Carlo	Intra-ply hybrid composite; fully dispersed alternating LE	Hybrid effect for strain was observed; it was influenced by

	simulation; LLS	and HE filaments	the degree of dispersion and the volume ratio of the two fibre types
Fukunaga, Chou & Fukuda (1989)	Shear-lag and chain-of-bundles	Four-layer inter-laminate hybrids; varying degrees of dispersion/ V_f	Laminates with uniform distributions of LE and HE fibres were stronger than laminates with clusters of LE fibres
Harlow (1997)	Chain-of-bundles; ELS and LLS	Intra-ply hybrid composites	LLS led to conservative estimates for the cumulative distribution functions. Hybrid effect maximised with two fibre types as uniformly distributed as possible. The model was simple enough for application to variety of hybrid types
Chiang <i>et al.</i> (2005)	3D fibre tow based model; incorporated shear-lag and Monte Carlo	Intimately mixed, randomly dispersed, carbon/epoxy glass epoxy tows	Low V_f of carbon was detrimental to strength (failure initiation); found no synergistic effects of hybridisation on tensile properties
Mishnaevsky Jr & Dai (2014)	Numerical analysis incorporating Monte Carlo simulations	Randomly mixed carbon and glass fibres (randomly mixed in computer program)	Hybrid composites, compared to mono-fibre glass, demonstrated higher stiffness, but lower strength and failure strain. As the volume of glass fibres increased, the failure strain increased.
Jalalvand, Czél & Wisnom	2D FE-analysis	Carbon and glass hybrid	As the thickness of the central

(2014)		laminate; [G/C/G] and [G ₂ /C ₂ /G ₂]	carbon fibre layer increased, there was a corresponding change in failure modes and stress concentrations. Model was successfully applied to a variety of stacking sequences.
Swolfs <i>et al.</i> (2015)	Global load sharing model	Carbon/glass hybrid composites; V_f of two fibre types taken to be 50%	Hybrid effect of up to 15% for failure strain. Weibull modulus of carbon influenced the magnitude of the hybrid effect
Swolfs <i>et al.</i> (2015)	Chain-of-bundles	Hexagonal array of carbon and glass fibres; various degrees of dispersion and hybrid V_f i.e. ratio of carbon to glass	Higher V_f of glass delays failed carbon fibre cluster development. Random dispersion not the most effective to increase magnitude of hybrid effect
Swolfs, Verpoest & Gorbatikh (2016)	Chain-of-bundles	Intimately mixed, randomly dispersed carbon and glass fibres	The Weibull modulus of the carbon fibres influences the hybrid effect

From Table 2.2 it can be observed that the ‘chain-of-bundles’ model, or variations thereof, has been consistently utilised (Harlow & Phoenix, 1978; Harlow, 1981; Fariborz, Yang & Harlow, 1985, Fukunaga, Chou & Fukuda, 1989; Harlow, 1997; Swolfs *et al.*, 2015; Swolfs, Verpoest & Gorbatiikh, 2016)

Presented in Figure 2.30 is an illustration a two-dimensional chain-of-bundles model. With reference to Figure 2.30, the model, for a hybrid composite (i), is based around a single-layer with alternating fibre types, with an axial length, L . The two fibre types are usually considered to be low elongation (ii) and high elongation (iii). Each of the alternating fibres is sub-divided into shorter lengths (iv); this is known as the ineffective length and can be defined as the length over which a failed filament (v) is unable to contribute to the load bearing capacity of the composite.

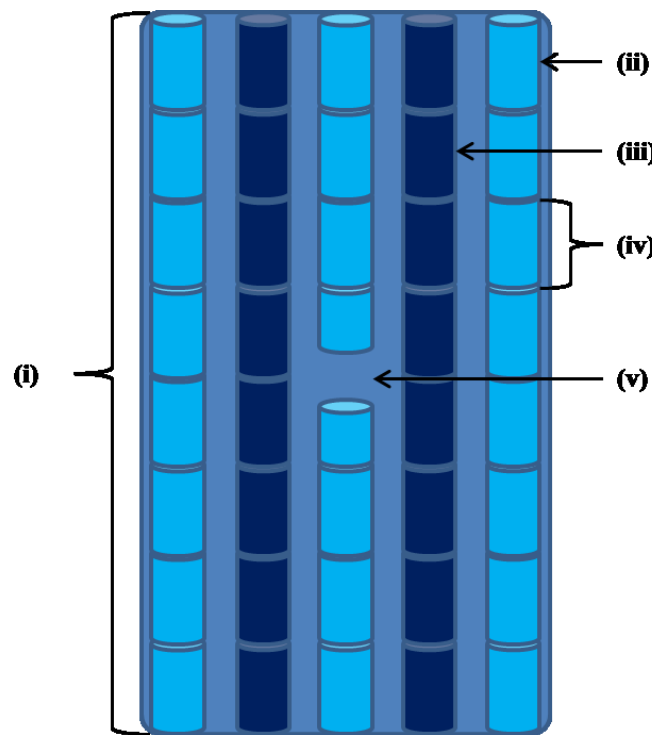


Figure 2.30 An illustration of a 2D chain-of-bundles model, adapted from Zweben (1977).

Zweben (1977) proposed a simple model based on Figure 2.30. The hybrid composite considered was assumed to be a uni-directional composite consisting of a 2D array of alternating high elongation (HE) and low elongation (LE) reinforcing filaments. This hybrid design was that of a highly dispersed intra-filament composite: in other words, the neighbours on either side of a filament were of the other fibre type. Zweben (1977) predicted that the failure strain in the hybrid would be different from that of a mono-fibre composite composed of low-elongation fibres.

Zweben's theory was that HE filaments within the composite would act as crack arrestors and limit crack propagation resulting from a break in an LE filament. With this in mind, it was expected that more LE filaments would break than HE filaments. Zweben (1977) assumed that the filaments supported all the load i.e. the influence of the matrix was negligible.

During loading, LE filaments would break at a given strain, ϵ . When this happened, the two HE filaments that were adjacent to this LE filament would experience a stress concentration factor (SCF). As the applied load and strain was increased, there would be an increase in the number of broken LE filaments within the composite. Eventually, a critical stress concentration factor (SCF) for the HE filaments to break would be reached, resulting in HE filament failure and ultimately resulting in the failure of the composite.

Zweben (1977) suggested that the strain at which the first HE filament breaks could be used as a lower bound for the UTS of the hybrid composite.

The main conclusion of Zweben's work was that, for some hybrid systems, the strain required to propagate filament breaks in a hybrid was increased through the introduction

of the HE fibres. It was suggested that the HE filaments acted as crack arrestors at a micromechanical level. The major issue with this model was that it only really gave a lower bound prediction and was based on a 2D array of alternating filaments.

Fukuda & Chou (1982) and Fukunaga, Chou & Fukuda (1984) used the chain-of-bundles model in conjunction with a Monte Carlo simulation. An advantage of the Monte Carlo approach is the ability to model any type of hybrid composite. In both papers, the influence of hybridisation on the SCFs experienced by surviving filaments in close proximity to failed filaments was modelled.

Fukuda & Chou (1982) determined that in a mono-fibre composite, an average of 5-6 links, in the composite, failed out of 100 before composite failure. By contrast, in a hybrid composite, a larger range of failed links of 5-32 out of 100 was observed. Presented in Figure 2.31 are examples of the failure patterns obtained during the simulations of Fukuda & Chou (1982). With reference to the Figure, (i) represents a mono-fibre composite and (ii) represents a hybrid composite. There are two distinct observations to be made: firstly, there are significantly more failed links in the hybrid composite. Secondly, in the mono-fibre composite, other than the second failure, the subsequent failures are all located, in the horizontal plane, next to the first failed link. By contrast, in the hybrid composite the failure pattern was more random. Thirdly, the LE filaments in the hybrid composite failed multiple times (4-5) before any broken links occurred in the adjacent HE filaments. The LE filaments were therefore able to contribute to the load bearing for a greater length of time.

as the bundle size of LE filaments increased, the ability of the HE filaments to enhance the failure strain was diminished.

Fukunaga, Chou & Fukuda (1984) concluded that the hybrid effect was a result of the strength distribution known to exist in reinforcing fibre bundles. In addition, the magnitude of the hybrid effect was influenced by two factors; the size of the LE fibre bundles and the state of stress redistribution i.e. equal or local load sharing.

Both Zweben (1977) and Fukunaga, Fukuda & Chou (1984) assumed in their models that the filaments could represent impregnated fibre bundles. This is an oversimplification.

The advantages of the models proposed by Fukuda & Chou (1982) and Fukunaga, Fukuda & Chou (1984) were: (i) the calculation of SCFs within the chain of bundles model, a good improvement over the more simple approach of Zweben (1977), and (ii) the ability to modify the models to enable the simulation of failure behaviour in a mono-fibre or hybrid composite. One disadvantage of this model was the lack of the incorporation of strength scatter. There was no consideration of Weibull distribution which could have led to over-estimation of the composite strength.

Fariborz, Yang & Harlow (1985) also looked at proposed a model in which a modified chain-of bundles model was incorporated with Monte Carlo simulation. Using this modified chain-of-bundles model it was reportedly possible to model any unidirectional intra-ply hybrid system consisting of two reinforcing fibre types. As with Fukuda & Chou (1982) the effect of filament dispersion and V_f on the hybrid effect was considered. The hybrid effect was defined here by any apparent change in the failure strain.

The fibres in the model were either high modulus (low elongation, LE) or low modulus (high elongation, HE) and modelled as a parallel structure of n continuous fibres with a length, l . It was assumed that the load was applied axially in the filament direction and the model applied LLS.

In contrast to Fukuda & Chou (1982), a Weibull distribution with cumulative distribution functions was applied by Fariborz, Yang & Harlow (1985). The Monte Carlo simulation was adopted in order to investigate the effects of volume ratio and filament dispersion on the ultimate strain and ultimate strength of the hybrid composite. The simulations conducted were for single fibre bundles assumed to consist of 6000 filaments. For each volume ratio and degree of dispersion, 65 simulations were conducted.

It was found that the mean breaking strain depended heavily on the volume ratio and degree of dispersion of the two reinforcing fibre types. Two hybrid configurations were found to have very similar mean failure strains. The configurations of these model hybrid composites were: (i) 8 HE and 8 LE filaments and (ii) 8 HE and 4 LE filaments. The reason given for the similarity in behaviour was based on the idea of HE filaments acting as crack arrestors in the hybrid. If a cluster of 8LE filaments failed the resulting crack would be so large as to make the crack arresting properties of the HE filaments ineffective. Having a cluster of 8LE filaments resulted in failure behaviour similar to that seen in a mono-fibre composite made of LE reinforcing fibres. Fariborz, Yang & Harlow (1985) concluded that the dispersion of the HE filaments was also an important factor in the failure behaviour of the composite. They suggested that the greatest crack arresting could be achieved when the HE filaments were dispersed to the maximum degree.

Fukuda (1991) reviewed previous work conducted on statistical approaches to modelling failure in hybrid composites. The first issue raised was that of load sharing. In early studies such as Rosen (1964), it was assumed that when a filament failed in a composite, the remaining surviving filaments shared the extra load equally. However it is more likely that stress redistribution takes place more locally as in LLS. For example, an intact filament next to a failed filament will uptake a proportion of the redistributed load, $K_r\sigma$, where σ is the average stress and r is the number of broken filaments; K_r is then a stress concentration factor. During failure the probability that a filament next to a broken neighbour will subsequently break due to the increase in stress is $F(K_r\sigma) - F(\sigma)$, where $F(\sigma)$ is the cumulative distribution function for fibre strength. In the LLS rule the stress concentration factor is $K_r = 1 + r/2$.

A Monte Carlo simulation was again used to estimate the strength of hybrid composites. Fukuda (1991) chose to model a single layer intra-ply hybrid composite. The two fibre types were carbon and glass, denoted as low and high-elongation fibres respectively. They reported similar results to Fukuda and Chou (1982) where the initial failure strain of the carbon fibre in the hybrid was similar to that seen in a carbon mono-fibre composite. However, after the initial failure, a hybrid effect was observed with an increase of 50% in the failure strain.

The Monte Carlo simulation also showed that failure in a hybrid composite was different to that in a mono-fibre composite. In a mono-fibre composite, once failure had begun it generally propagated drastically leading to catastrophic failure. By contrast, multiple fractures were observed in a hybrid composite where LE filaments were breaking in a number of locations along the gauge length.

Harlow (1997) used the chain-of-bundles to explore the lower bound of failure strain in a hybrid composite. This is similar to the suggestion by Zweben (1977) that the HE fibre failure strain can be used as a lower bound for the final failure strain in a hybrid composite. Yet in contrast to Zweben (1977), the chain-of-bundles approach was used to model an intra-ply hybrid composite consisting of LE and HE fibres.

The basic rules of the chain-of-bundles model were still applied, such as the ineffective length. The LLS rule was chosen and the methods for the determination of the stress concentration factors given were the same as those in Fariborz, Yang & Harlow (1985). The LLS rule was reported to be simple enough to allow for any volume ratio and hybrid configuration. Probability distribution functions were also given for the bundle breaking strain as well as the hybrid breaking strain. Previous models, such as Fariborz, Yang & Harlow (1985), pointed towards a critical cluster size for the two fibres. The chance of an HE fibre arresting a crack originating from a broken LE fibre was said to increase if the cluster of LE fibres was smaller. Harlow (1997) extended this and proposed four factors that could influence the critical cluster size. These were the strain in the hybrid, the strain concentration factors in the hybrid, the size of the hybrid and the hybrid configuration, namely the volume ratio of the fibre types and the geometry or degree of dispersion.

Swolfs *et al.* (2015/2016) have developed a series of models in order to determine the influence of different parameters on the magnitude of the hybrid effect.

Swolfs *et al.* (2015) utilised the chain-of-bundles approach to determine the effect of the dispersion on the initial failure strain of carbon fibres in a hybrid composite. Presented in Figure 2.32 is a schematic illustration of their model. With reference to the Figure (i)

and (ii) represent the LE and HE filaments respectively and (iii) highlights a representative segment of a filament defined as the ineffective length.

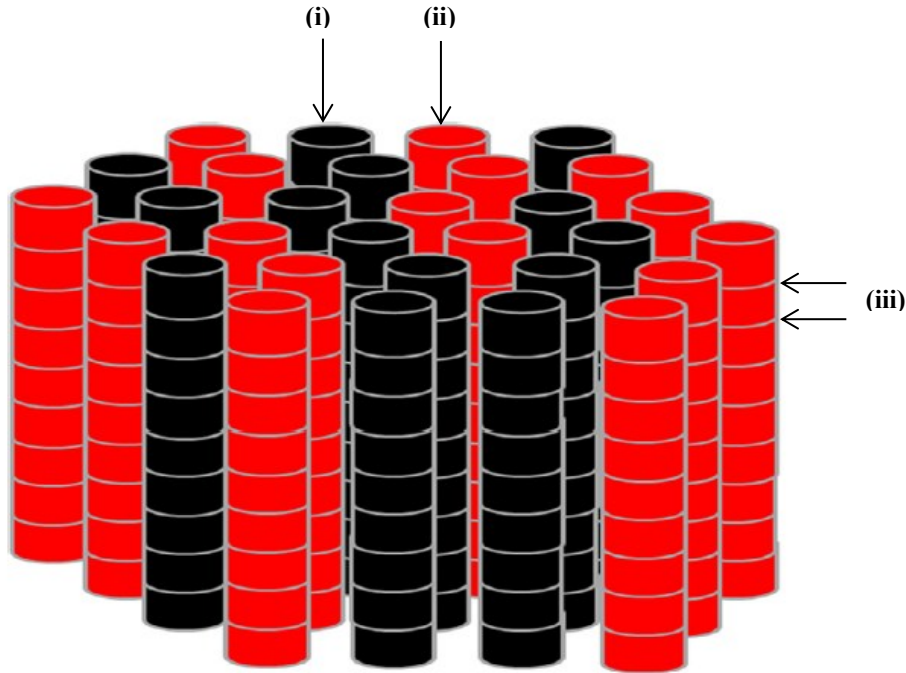


Figure 2.32 A schematic illustration of the chain of bundles model used by Swolfs *et al.* (2015).

By contrast to the previous 2D models discussed earlier (Zweben, 1977; Fukuda & Chou, 1982; Fukunaga, Fukuda & Chou, 1984; Fariborz, Yang & Harlow, 1985), the model presented here used a 3D hexagonal packing of filaments. One assumption with this model is that the filaments have the same diameter. The LLS rule was used and the six closest filaments to a failed filament took up the redistributed load.

Numerical simulations were conducted with a range of glass V_f ranging from 0-100% with the filaments randomly dispersed. As the volume fraction of glass increased there was a corresponding increase in the failure strain. The randomly dispersed hybrid

composite failed when a critical cluster size of broken LE filaments was present. The model showed that the failure strain of carbon fibres could be improved, if they were hybridised with well dispersed glass fibre of a greater volume fraction. On the other hand, the model also predicted a drop in glass fibre failure strain with the addition of 10% carbon filaments. The carbon filaments acted as crack initiators that would not be present in a mono-fibre glass composite.

For mono-fibre composites, the model predicted critical cluster sizes of 22 and 11 for carbon and glass fibres respectively. This was related to the inherent strength distribution in the reinforcing fibre bundles. If there is a large strength distribution, the probability that a failed filament would be directly next to another weaker filament was reduced. The presence of stronger filaments in close proximity to a failed filament increased the strain required to propagate any crack originating from that failed filament. The critical cluster size for the hybrid composite was observed to fall between those of the mono-fibre composites.

Swolfs *et al.* (2015) also modelled the influence of the degree of dispersion on the hybrid composite properties. Presented in Figure 2.33 are examples of the different hybrid types and dispersions modelled. With reference to the Figure, there were two hybrid types, bundle-by-bundle hybrids and layer-by-layer hybrids. The bundle-by-bundle hybrids consisted of layers of alternating fibre bundles. These layers ranged from two layers with two bundles per layer, to sixteen layers with sixteen bundles per layer. With respect to the layer-by-layer hybrids the two fibre types were dispersed as layers of filaments ranging from alternating layers of single filaments to alternating layers of eight filaments.

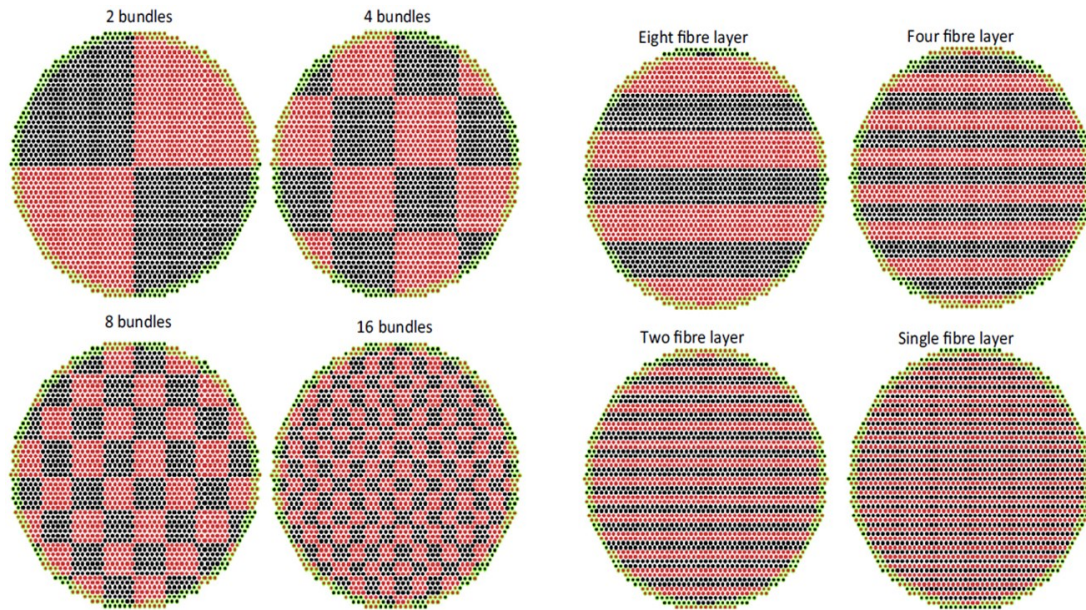


Figure 2.33 Schematic illustrations of the two hybrid types, with various levels of dispersion, modelled by Swolfs *et al.* (2015).

Hybrid effects, defined by enhancement of the failure strain, were observed in the bundle-by-bundle hybrids, ranging from 1.5% in the two bundle hybrid to 7% in the sixteen bundle hybrid. This suggested that increased dispersion resulted in an increase in the hybrid effect and an increase in the critical cluster size.

The effect of dispersion in the bundle-by-bundle hybrids was enhanced in the layer-by-layer hybrids. The largest hybrid effect of 16% was observed in the single-layer hybrid composite. Interestingly this was even higher than the 9% hybrid effect observed for a randomly dispersed hybrid.

In the single-layer hybrid composites modelled by Swolfs *et al.* (2015), when a carbon filament failed its nearest neighbours were two more carbon filaments and four glass filaments. The resultant strain and stress concentration factors would not be great enough to propagate the crack in this situation. The crack was not able to propagate into

the glass layer; it could only traverse through the carbon layer until a critical crack grew which would eventually have propagated into the glass layer.

The authors suggested that the single-layer hybrid was more effective than the randomly dispersed material as there were fewer pathways for the crack to take. As discussed, in a single-layer hybrid the crack could traverse only in the horizontal plane into a neighbouring carbon filament.

Presented schematically in Figure 2.34 are the potential crack propagation paths in a single-layer and randomly dispersed hybrid respectively, proposed by Swolfs *et al.* (2015). Referring to Figure 2.34 each circle represents a single filament of either LE (blue) or HE (white) reinforcing fibres. Case (i) shows that a crack in an LE filament in a single-layer hybrid would only be able to propagate into another LE filament because it would not yet be large enough to propagate into a neighbouring HE filament. However in case (ii), the randomly dispersed hybrid, there would be more potential paths for the crack to take, increasing the chance of a critical cluster occurring and the crack propagating into an HE filament.

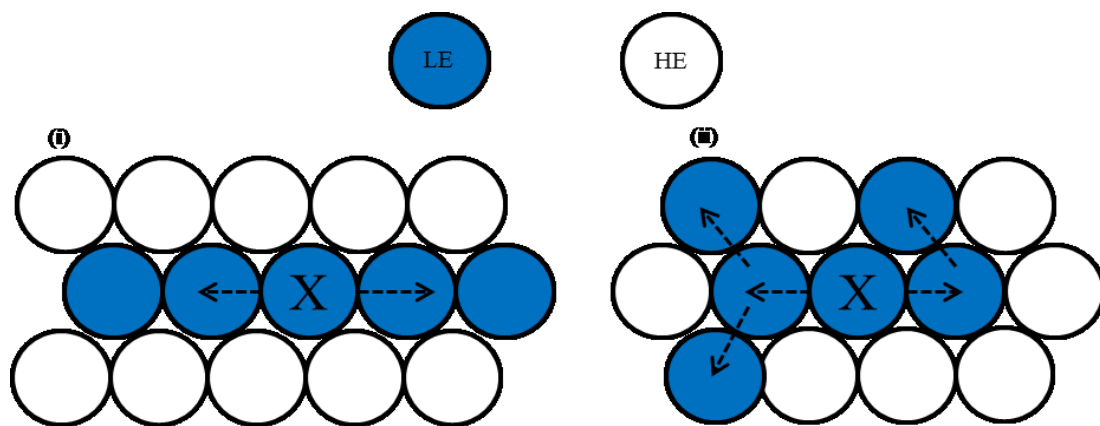


Figure 2.34 A schematic illustration of the potential crack propagation paths in: (i) a single-layer hybrid and (ii) a randomly dispersed hybrid.

Further to this work, Swolfs, Verpoest & Gorbatiikh (2016) analysed the influence of LE fibre strength scatter, the failure strain ratio of the reinforcing fibres and the stiffness of the HE fibre on the size of the hybrid effect. In contrast to the previous work (Swolfs *et al.*, 2015) the effect of filament dispersion was not measured by Swolfs, Verpoest & Gorbatiikh (2016). In addition, only a composite with a random fibre packing was modelled.

Presented in Figure 2.35 is the model used by Swolfs, Verpoest & Gorbatiikh (2016). With reference to the Figure, (i) denotes a LE filament and (ii) denotes a HE filament. This model was based on the chain on bundles model in which the filaments were subdivided into filament elements (iii). Each of the filaments was given a strength value consistent with the Weibull distribution for the respective reinforcing fibre type. One change from the previous study, Swolfs *et al.* (2015), was the introduction of more representative filament diameters.

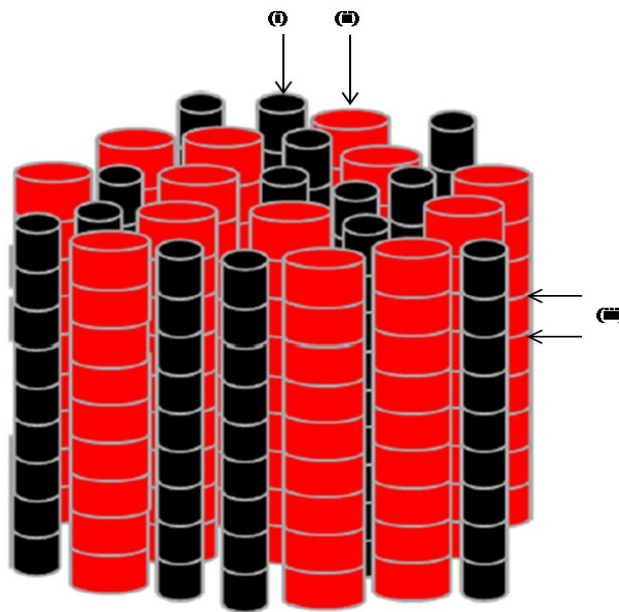


Figure 2.35 Schematic illustration of a section of the model presented by Swolfs, Verpoest & Gorbatiikh (2016).

The hybrid effect was defined here as any increase in the initial failure strain of the LE elements in the model compared to a mono-fibre LE composite.

The hybrid composites showed a delayed critical cluster development when compared to LE mono-fibre composites in all of the simulations. As the fibre strength distribution became smaller, it was observed that the magnitude of the hybrid effect was also predicted to decrease. In addition, the authors stated that a larger hybrid effect was also predicted if the failure strain ratio between the two reinforcing fibre types was larger. Finally, the authors stated that the stiffness of the HE reinforcing fibre had an influence on the stress concentration factors experienced by surviving HE filaments. Higher stress concentration factors were predicted for HE filaments with a lower modulus.

The review of this literature has shown that there are a number of factors that can influence the hybrid effect. A number of papers have been reviewed and many appear to have based their statistical approach on the chain-of-bundles model. Later papers incorporated the Monte Carlo simulation which removed some of the restrictions of the chain-of-bundles. The addition of the Monte Carlo simulation allowed for any hybrid configuration to be modelled. This was important as it is known that the fibre volume ratio and degree of dispersion are important factors within hybrid failure behaviour.

Another important area that has been highlighted during this review is the appropriate selection of a load sharing rule and the influence this has on the stress concentration factors experienced by the reinforcing fibres. It is more likely that surviving filaments in close proximity to a failed filament will experience a greater increase in load and a SCF compared to those further away. The models vary from assuming that only the four closest filaments to the broken filament would experience a load increase (Zweben and

Rosen, 1969) to providing equations to calculate the SCFs experienced by any filament in the composite (Harlow, 1997). The survival probability of the filaments is another important aspect and this was generally managed through the incorporation of a Weibull distribution.

A theme throughout was the effect of dispersion on the size of the hybrid effect. Studies such as Zweben (1977) suggested that the optimum dispersion is alternating filaments of the two reinforcing fibre types. Swolfs *et al.* (2015) predicted that the largest hybrid effect would be realised in hybrids composed of single-layers of the reinforcing filaments. This was predicted to be the most effective configurations and better than randomly dispersed hybrids. Furthermore Swolfs, Verpoest & Gordatikh (2016) suggested that in addition to the dispersion of the two fibre types, the ratio of the failure strains and the strength scatter of the lower elongation fibre type are important factors to consider.

The mechanism of the hybrid effect appears to be in the HE filaments acting as crack arrestors for the LE filaments. This is related directly to the degree of dispersion. In a more dispersed hybrid, the propagation of a critical crack is delayed by two things. Firstly, a larger cluster of failed LE filaments is required before the crack becomes critical and propagates into the HE filaments or layers. Secondly, due to the smaller crack, a greater strain is required in order for the crack to propagate and induce catastrophic failure of the composite.

A smaller hybrid effect will be observed with a larger cluster of LE filaments. Fariborz, Yang & Harlow (1985) suggested an LE cluster of 4 filaments for an optimum hybrid effect. They also observed that having an LE cluster of 8 filaments resulting in failure

similar to that of a mono-fibre LE composite. This is because any crack resulting from a broken cluster of LE filaments would be too large for the HE filament cluster to arrest, even if the cluster of HE filaments was also 8.

2.3.4 Tensile Properties: Hybrid Effect

The following section summarises the scientific literature concerning the hybrid effect and tensile properties of hybrid composites. A review of hybrid composite tensile properties, including other mechanical properties such as flexural, impact and compression can be found in the following articles: Short & Summerscales (1980), Kretsis (1987) and more recently Swolfs, Gorbatiikh & Verpoest (2014).

The first report of an apparent change in the tensile behaviour of carbon fibres, through hybridisation, was by Hayashi (1972). Carbon fibres were hybridised with glass fibres and initial fracture strength and strain of the hybrid composites were reported to be 40% greater than predicted values.

This apparent change in failure strain has also been reported by Zweben (1977) in Kevlar®/Thornel 300 carbon fibre and graphite/glass hybrids. Zweben reported increases in the initial failure strain of the hybrid composites when compared to mono-fibre carbon composites.

Other work in which a higher failure strain was reported for hybrid composites, includes: Aveseton & Sillwood (1972), 204 filament glass fibre bundles hybridised with 10,000 filament carbon fibre bundles; Bunsell & Harris (1974), carbon fibre and E-glass fibre pre-impregnated tapes; Manders & Bader (1981), E-glass hybridised with either high modulus or high strength carbon fibres; Khatri & Koczak (1995), E-glass fibre and

AS4-graphite fibre; and Pandya, Veerraju & Naik (2011), 8H T300 satin weave carbon fabric and plain weave E-glass fabric.

The predominant types of hybrid composite manufactured for these studies were inter-ply and intra-ply. These hybrid configurations, with respect to the models, do not fit the optimum dispersion of alternating filaments (Zweben, 1977; Fukuda & Chou, 1982; Fukunaga, Fukuda & Chou, 1984) or alternating layers of single filaments (Swolfs *et al.* 2015).

Various values for the magnitude of the hybrid effect for tensile properties have been reported. Manders & Bader (1981) reported calculated hybrid effects for works previous to theirs. Furthermore, a review by Kretsis (1982) reported hybrid effects for tensile behaviour of hybrid composites.

Table 2.3 presents a summary of the findings of Manders & Bader (1981) and Kretsis (1982). It can be seen that a wide range of magnitudes for the hybrid effect, positive and negative have been reported in the literature. The difference in magnitude is most commonly reported to be an effect of the composition of the composite with regards to the relative fibre volume fractions and the degree of dispersion; the degree of dispersion can also be thought of in terms of the stacking sequence used.

Table 2.3 A summary of the reported hybrid effects up to 1982; adapted from Manders & Bader (1981) and Kretsis (1982).

Author(s) (Year)	Materials	Magnitude of Hybrid Effect (%)
Hayashi (1972)	Glass and carbon fibres	45 (average)
Bunsell & Harris (1974)	Glass and carbon fibres	42 to 85
Perry & Adams (1975)	Carbon fibre and glass or Kevlar® fibres	12 to 14
Phillips (1976)	Glass and carbon fibres	2 to 20
Aveston & Sillwood (1976)	Glass and carbon fibres	116
Zweben (1977)	Kevlar® and carbon fibres	4
Manders & Bader (1981)	Glass fibres and HM or HS carbon fibres	8.7 to 46
Chamis, Lark & Sinclair (1981)	Carbon fibre/S-glass fibres or carbon fibre/Kevlar® 49 fibre	-66 to 16
Ji (1982)	Carbon fibres and glass or Kevlar® fibres	9
Bhatia (1982)	Carbon HM fibres/S-glass fibres	10

2.3.4.1 Effect of Dispersion and V_f

The most common hybrid configurations reported in the literature are inter-ply and intra-ply hybrids. For example, the hybrids manufactured by Zweben (1977) and

Bunsell & Harris (1974) were inter-ply laminates. Bunsell & Harris (1974) reported no significant difference in the tensile behaviour of four-layer type-I carbon fibre E-glass fibre composites, with a change in the lay-up from [G/C/G] to [C/G/C]. However, the relative dispersion of the two fibre types in this case was constant. In each hybrid two layers of the respective pre-impregnated sheets were used. The volume fraction of each fibre type (0.4 and 0.6 for carbon fibre and E-glass fibre sheets respectively) was constant between the two stacking sequences.

Manders & Bader (1981) reported on the influence of hybrid configuration on the magnitude of the hybrid effect. This was achieved through tensile testing of three hybrid configurations. These were an alternating laminate (inter-ply) hybrid, a divided tow hybrid in which each sample contained one carbon fibre bundle sandwiched between E-glass (also known as an intra-ply hybrid) and a spread tow hybrid, the same as a divided tow hybrid except for the single carbon fibre bundle had been thinly spread prior to manufacture of the composite.

Manders & Bader (1981) reported that the largest hybrid effect, for initial failure strain of each of the configurations considered, was observed when the carbon fibre element was more dispersed in the composite.

Pandya, Veerraju & Naik (2011) studied inter-ply hybrid composites, with two stacking sequences: [G₃/C₂] and [C₂/G₃]. The hybrid effect, based on the rule-of-mixtures, was found to be greater in the [G₃/C₂] hybrid composite. This stacking sequence, with the E-glass layers on the outside, had higher tensile strength and failure strain.

With regards to the effect of V_f , Khatri & Koczak (1995) reported changes in failure strain with different carbon fibre volume fractions. For 16-layer hybrid composites, with

a carbon fibre V_f of 75%, the failure strain was 1.35%. However, at 25% carbon fibre V_f , the failure strain of the carbon fibre increased to 1.41%. In the mono-fibre composite the recorded failure strain of carbon fibre was 1.28%. The measured hybrid effect ranged from 5.04%, at higher carbon content, to 8.05% at lower carbon fibre content.

2.3.4.2 Failure Behaviour of Hybrid Composites

A review of the literature has highlighted that the failure of hybrid composites differs from that observed in mono-fibre composites. During tensile loading mono-fibre carbon and E-glass composites failed in different ways. Carbon composite failure is characterised by sudden catastrophic failure at peak load (Bunsell & Harris, 1974; Manders & Bader, 1981; Pandya, Veerraju & Naik, 2011). By contrast, the failure of E-glass composites is less sudden and characterised by extensive longitudinal splitting (Bunsell & Harris, 1974; Manders & Bader, 1981). The following section presents a review of the observed failure modes of hybrid composites.

Presented in Figure 2.36 and Figure 2.37 are load/strain curves for inter-ply hybrid composites tested by Bunsell & Harris (1974). In Figure 2.36, it can be seen that there was linear loading up to the initial failure strain. There was then a large load drop associated with brittle failure; Bunsell & Harris (1974) stated that this was indicative of the failure of the carbon fibre layer in the hybrid. The load then began to increase as the strain once again increased. The failure in the second part of the curve was more gradual and multiple load drops were observed. In this case, the initial failure strain was the same as that observed in reference mono-fibre carbon fibre composites.

Figure 2.37 presents different failure behaviour observed in an inter-ply hybrid. In this case, the individual layers of carbon fibre and E-glass fibre were bonded together along

their gauge length. The effect of the bond was that all of the layers were loaded equally from the start of the test. In the first specimens, un-bonded (Figure 2.36), the residual strains were measured and it was found that the carbon core was under a compressive strain of 0.029 %; this meant that the carbon fibre was compressed to 10 % of its failure strain. Therefore the initial load was carried by the E-glass fibre layers until the carbon fibre layer was effectively '*straightened*'.

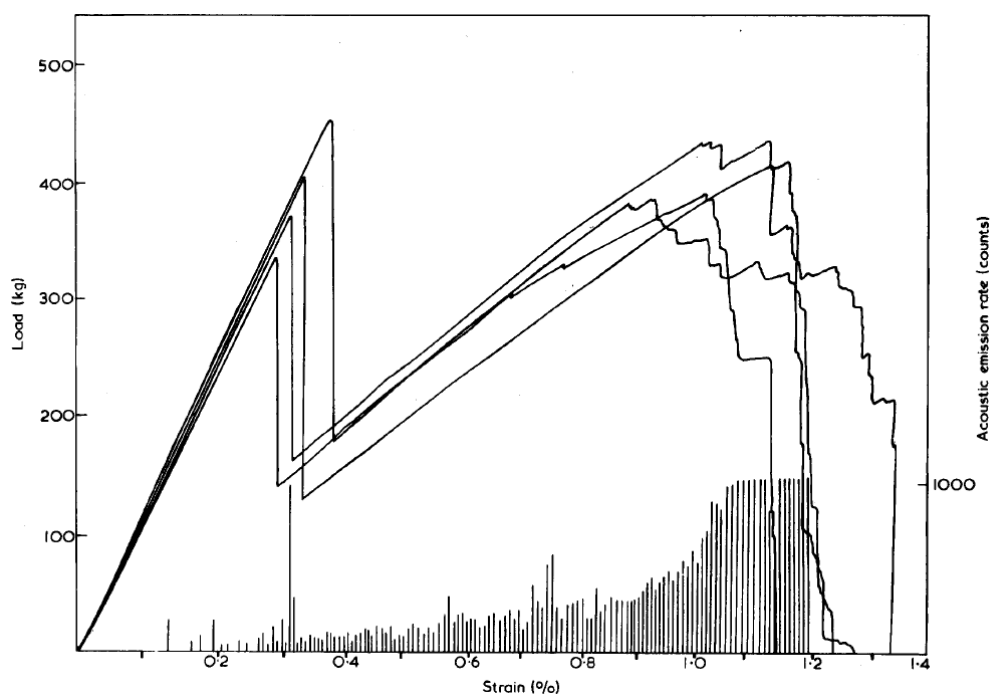


Figure 2.36 The load/strain traces of un-bonded carbon/E-glass hybrid composites presented in Bunsell & Harris (1974). Exhibiting the large load drop upon carbon fibre failure and the load increase as the E-glass takes up the redistributed load until final failure.

In the bonded specimens (Figure 2.37) there was no load drop associated with the failure of the carbon layer. The failure of the bonded hybrid composite was more stable with multiple failures up to peak load. The carbon fibre layer exhibited multiple fractures along its length; confirmed by visual analysis post-testing. The carbon fibre

layers were examined and the cracks were found to have split the layer into individual lengths of approximately 1.5 mm. Whilst the load transfer was improved in the bonded inter-ply hybrid, it was observed that this resulted in a lower final failure strain in the composite.

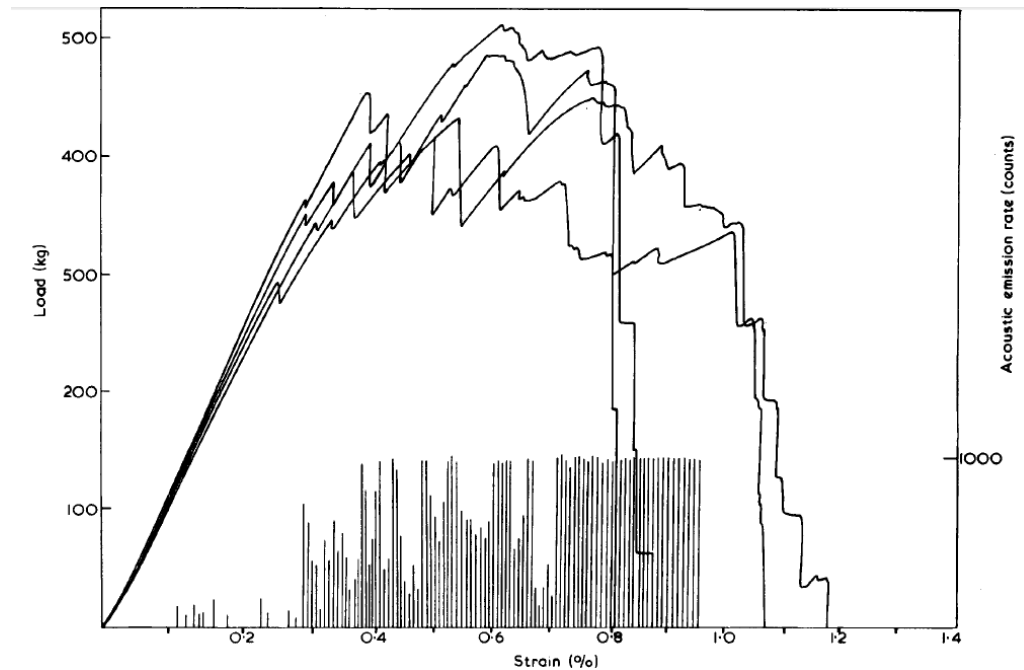


Figure 2.37 The load/strain traces for the bonded carbon/E-glass hybrid composites; presented by Bunsell & Harris (1974). There was no large load drop associated with carbon fibre failure.

Manders & Bader (1981) reported similar failure behaviour for an inter-ply hybrid to the un-bonded hybrid composite reported by Bunsell & Harris (1974). Manders & Bader (1981) observed an initial load drop at first failure, associated with a transverse crack in the central carbon fibre layer. The carbon eventually stopped contributing to load carrying and final failure was governed by the E-glass layers. One important observation of Manders & Bader (1981) was that the crack that initiated in the central carbon fibre layers did not propagate into the E-glass layers.

Manders & Bader (1981) also reported multiple fracture of a carbon fibre layer in a hybrid. In contrast to Bunsell & Harris (1974) the hybrid in which multiple fractures were reported by Manders & Bader (1981) was of the intra-ply configuration. There was a load drop observed as the carbon fibre layer failed however the drop in load was smaller. This was attributed to the low carbon fibre V_f of this hybrid composite.

Even more complex failure was reported by Manders & Bader (1981) for the intra-ply composite in which a spread carbon fibre layer was embedded between two layers of E-glass fibre. The fracture of carbon fibres in the spread tow hybrids occurred in random areas, both in groups and as individual filaments. Even though there was an accumulation of damage, failure did not occur through a single crack propagating across the sample as the failed areas were isolated.

One study by Czél *et al.* (2012) incorporated thin spread carbon plies to the centre of an E-glass composite with a view to changing the failure behaviour to a more pseudo-ductile failure. This is the second reported use of spread carbon fibre bundles after Manders & Bader (1981). In the case the composite was an inter-ply hybrid and the thickness of the carbon layer was greatly reduced via fibre spreading. The central carbon ply therefore was significantly thinner compared to previous studies. Reducing the thickness meant that any cracks initiating in the carbon layer would be smaller than in a thicker laminate; this made it more likely that E-glass filaments would be able to arrest or deflect the crack as seen in previous work (Manders & Bader, 1981).

Figure 2.38 shows a microscope image of the thin carbon layer embedded between two E-glass layers. The lighter coloured circles are the central carbon layer with the darker

grey circles being the E-glass filaments. The black regions are voids, pockets of entrapped air from the manufacturing process.

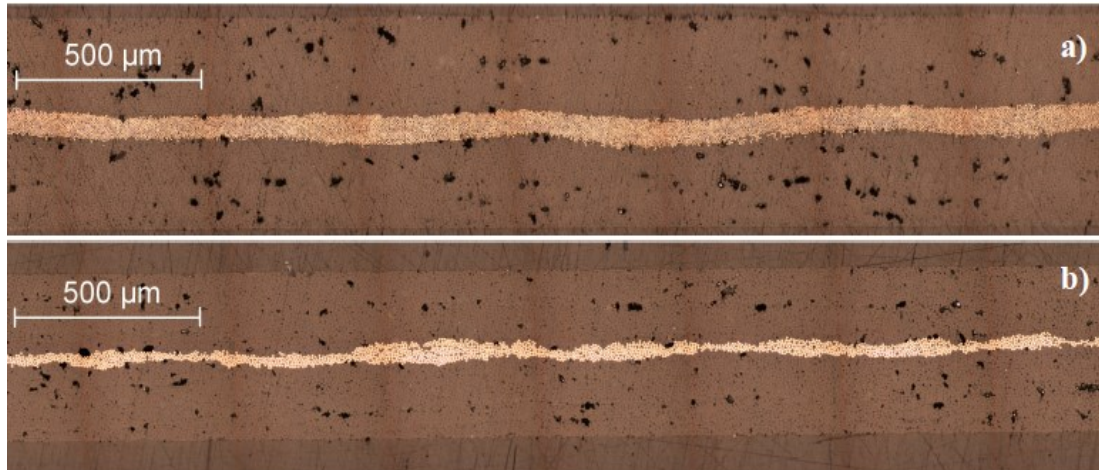


Figure 2.38 Microscope image of the E-glass/carbon hybrid with a thin central layer of carbon fibre, Czél *et al* (2012).

The aim of this study was to reduce the load drop associated with carbon/E-glass hybrid composites (seen in Bunsell & Harris, 1974; Pandya, Veerraju & Naik, 2011) and shift the behaviour to a more stable failure. An example of the conventional hybrid stress-strain curve and the idealised thin-ply hybrid stress-strain curve can be shown in Figure 2.39.

The blue line represents the failure of a conventional carbon/E-glass hybrid. The load increases until the improved carbon fibre failure strain, as a result of the hybrid effect, is reached. The carbon filaments then fail and there is a corresponding load drop as the E-glass filaments recover as the stress is redistributed throughout the composite. The load then gradually increases again up to the E-glass failure strain at which point the composite fails. The idea with thin ply hybrids is to slow down the failure of the carbon

filaments and therefore stop the significant load drop occurring, creating a more stable failure process.

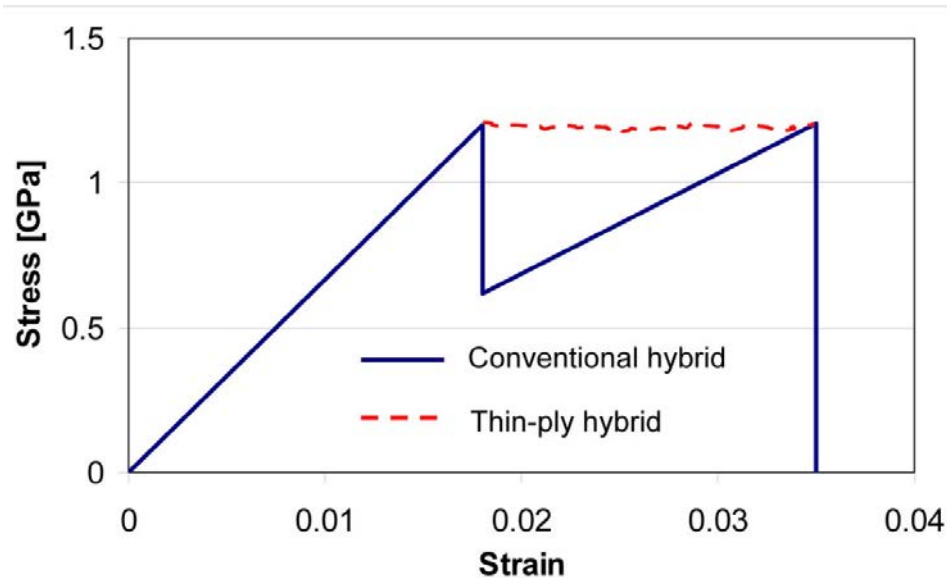


Figure 2.39 An example of the behaviour normally associated with hybrid composites (blue line) and the idealised change that occurs in thin-ply hybrid composites; Czél *et al.* (2012).

The hybrids manufactured in this study were $[G_2/C/G_2]$ with the central carbon layer being either $67.2\ \mu\text{m}$ or $36.5\ \mu\text{m}$ in thickness; the two hybrid types were denoted as the conventional thick hybrid and thin-ply hybrid respectively.

During testing the thick hybrid behaved as has been seen in previous studies. The load increased up to a failure strain, in this case 2.1%, at which point the carbon fibres failed through delamination. The E-glass fibres then carried the load until final failure. Whilst this wasn't pseudo-ductile behaviour it was a more gradual failure than is seen in mono-fibre carbon composites.

Thin-ply hybrids however did exhibit more pseudo-ductile failure behaviour according to the authors. At a strain of 2.3%, higher than that observed in thick hybrids, the carbon

layer began to fail. However instead of delamination along the entire length of the specimen, delamination occurred in localised regions around cracks within the spread carbon layer. Each individual delamination slowly developed until eventually linking up with its nearest neighbouring delamination. Eventually the composite failed at 3% strain.

In a further study, Czél & Wisnom (2013) demonstrated and characterised the pseudo-ductile behaviour of thin-ply carbon/E-glass hybrid composites. They proposed that if the carbon fibre layer was too thick, catastrophic failure could occur as the crack initiating in the carbon fibre layer becomes too large and the E-glass fibre layers fail to constrain it; presented schematically in Figure 2.40.



Figure 2.40 A schematic illustration of the catastrophic crack propagation caused by crack initiation in a thick carbon ply.

Figure 2.41 presents a schematic illustration of failure in a central carbon ply of lower volume fraction. In this case, the failure occurs first in the central carbon fibre layer. The crack that forms eventually results in delamination at the carbon/E-glass interface along the length of the composite as the E-glass layer deflects the crack. This is when a large load drop is observed on the stress-strain curve.

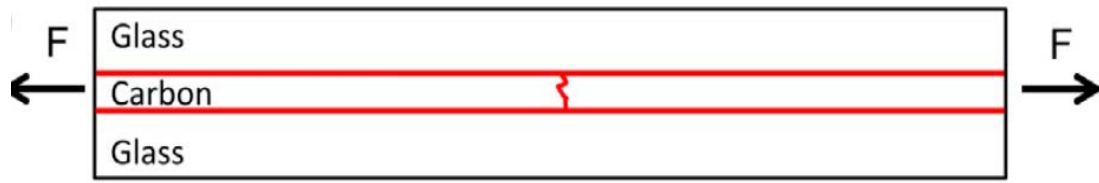


Figure 2.41 Schematic illustration of crack initiation in a central carbon ply resulting in delamination between the carbon and E-glass layers. This is the cause of the observed load drop in hybrid composite load traces.

For pseudo-ductile behaviour to occur the carbon layer in the centre must be considerably thinner than in conventional hybrids. The failure in this case is shown schematically in Figure 2.42 (Czél & Wisnom, 2013). Instead of one crack leading to total delamination, the carbon layer cracks in multiple locations and smaller delaminations occur. These delaminations are suppressed by the presence of the E-glass layers and the load is transferred back into the carbon layer. This was reported by Manders & Bader (1981).

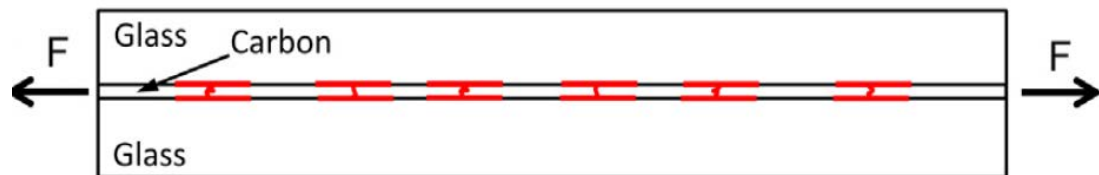


Figure 2.42 A schematic illustration of the multiple failures in thin-ply carbon that would result in pseudo-ductile behaviour in the thin-ply hybrids.

Czél & Wisnom (2013), used a thinner 25 μm central carbon fibre ply than was used in Czél *et al.* (2012). Four stacking sequences were considered; $[G_2/C_1/G_2]$, $[G_2/C_2/G_2]$, $[G_2/C_3/G_2]$ and $[G_2/C_4/G_2]$. The thermal residual strain was measured in the central layer of the $[G_2/C_1/G_2]$ hybrid and was calculated to be less than 3% of the carbon fibre failure strain.

Tensile tests showed that pseudo-ductile behaviour was only achieved in the thin-ply carbon hybrid composites containing one or two layers of spread carbon. The four layer thin-ply carbon hybrid showed conventional hybrid behaviour with a large load drop at carbon failure. However, the three layer thin-ply carbon hybrid showed intermediate behaviour with a much smaller load drop.

Analysis of one and two thin-ply carbon hybrid composite samples from interrupted tests confirmed the failure modes. In both cases the carbon filaments exhibited multiple carbon cracks along the sample length eventually leading to localised delamination. As the load increased each delamination became larger before finally joining with others causing failure of the composite.

The results of this study would suggest that thinner plies of carbon fibres surround by E-glass result in the best hybrid effect where the carbon fibre failure strain is enhanced and the failure mode is pseudo-ductile. However, no comparison with mono-fibre composites is made, which makes it difficult to quantify the degree to which the hybrid effect was present. It would also seem that there is a critical ply thickness for carbon fibre layers when considering the shift in failure mode. Plies thicker than $\sim 65 \mu\text{m}$ would appear to result in conventional hybrid composite failure with those lower than $60 \mu\text{m}$ exhibiting more pseudo-ductile behaviour as the central spread carbon ply becomes thinner.

The literature review regarding the properties of hybrid composites has discovered the following:

- (i) A positive hybrid effect for the tensile properties of hybrid composites, of carbon fibre and glass fibre, has been observed.

- a. True for both definitions
 - i. Enhancement of initial failure strain of LE component
 - ii. Deviation from rule-of-mixtures predicted properties
- (ii) The magnitude of the hybrid effect is influenced by
 - a. The stacking sequence of the hybrid
 - b. The relative volume fractions of the two fibre types in the hybrid
 - c. The degree of dispersion of the two fibre types
- (iii) The failure mode of hybrid composites is different compared to mono-fibre composites and there are two predominant examples:
 - a. Linear loading to initial failure, characterised by sudden load drop associated with carbon fibre failure, followed by re-loading and hybrid composite failure being governed by the glass fibre content
 - b. Pseudo-ductility: linear loading to initial failure, no load drop associated with carbon fibre failure, more stable multiple failures up to, and following failure stress.

2.4 Re-statement of Aims and Their Context

The aims were stated in the Introduction section of the thesis. In this section they are re-stated and their context with respect to the literature review is discussed.

- (i) To modify a fibre spreading rig to enable the spreading of E-glass and carbon fibre bundles to their optimum state.
- (ii) To determine the effect of fibre spreading on the tensile properties and Weibull survival probabilities of the two fibre types.
- (iii) To determine the effect of fibre spreading on the properties of mono-fibre composites compared to as-received composites.

- (iv) To determine a baseline for the effect of hybridisation on the properties of as-received mono-fibre composites compared to as-received hybrid composites.
- (v) To determine the effect of using spread fibre bundles in the production of hybrid composites.

With respect to the first aim (i), the literature review found that fibre spreading is predominantly referred to in the patent literature. There are only a handful of experimental studies that go into detail on the technique of fibre spreading and quantify the results. The purpose of the first aim was to modify an existing fibre spreading rig to enable the spreading of two reinforcing fibre types to their optimum state. Following the review of the literature the current author believed that previous work had not achieved the optimum state of spreading.

Once a technique for optimised fibre spreading was achieved it was necessary to quantify the effect the spreading had on the properties of the dry fibre bundles themselves, and any composites manufactured using spread fibre bundles. Therefore the second and third aims were presented. It was determined during the literature search that no information has been provided on the influence of spreading on the properties of dry fibre bundles.

Finally the fourth and fifth aims are related to hybridisation. Firstly a baseline for the influence of hybridisation on the mechanical properties of composites manufactured using as-received fibre bundles needed to be determined. The properties of hybrid composites manufactured using as-received fibre bundles were compared to mono-fibre composites manufactured using the same as-received fibre bundles.

Ultimately the aim of the current study was to determine the effect of hybridisation when using spread fibre bundles to manufacture composites. The literature review highlighted that, at the time of writing, there was only one report of spread fibre bundles being used to manufacture a hybrid composite. The method used by Diao *et al.* (2014) produced a hybrid composite with a random dispersion. The final aim of the current study was to produce a uniformly dispersed hybrid composite using spread fibre bundles and determine the effect on the mechanical properties.

3. Design and Experiments

3.1 Materials

3.1.1 Resin Systems

The following resin systems were used for specified applications:

(i) *Epoxy-amine resin system for the production of composites:* This was a commercially available epoxy-amine resin system, LY3505-XB3403, Huntsman Advanced Materials (UK) and was used in the manufacture of all the composites manufactured in this study. The stoichiometric ratio recommended by the manufacturer for the epoxy-amine resin system was 100:35 by weight percent respectively. The required masses of the epoxy resin and amine hardener were weighed on an analytical balance, Ohaus Analytical Plus (model AP110S), and mixed manually for 5 minutes. The mixed resin system was then degassed in a vacuum chamber at -0.026 MPa for 30 minutes. The impregnation of the various preforms was carried out immediately after degassing.

(ii) *Norland optical adhesive for the production of fibre bundle tensile test specimens:* NOA63 was a liquid photopolymer sourced from ThorLabs, UK. The optimum curing wavelength was 350 nm to 380 nm and this was achieved using a UV light source operating at between 280 - 450 nm, with a peak wavelength of 365 nm.

(iii) *Scotchweld 9323-2 resin for bonding of end-tabs to fibre bundle and composite tensile test specimens:* This was a commercially available structural aerospace two-part resin system sourced from 3M. It was used to bond end-tabs to fibre bundle and composite tensile test specimens. The recommended stoichiometric ratio, by weight, was 100:27; the required masses of the two-parts were weighed on an Ohaus. Analytical

Plus (model AP110S) balance. Once weighed the resin system was mixed for 3 minutes before being applied to the specimen side of the end-tabs.

(iv) *Loctite Power Flex Gel*: This was commercially available super glue (Ehtyl-2-cyanoacrylate). It was used during the manufacture of composites to secure the desired spread fibre architecture prior to impregnation.

3.1.2 Fibres:

This section outlines the details of all of the fibres that were used in this study.

(i) *Carbon FT300B-6K*: The 6k carbon fibres were provided by Toray Carbon Fibre Europe. These were used as part of the preliminary fibre spreading experiments. These were re-coded as fibre type-IC fibres.

(ii) *Carbon T700-SC-12K-60E*: These were 12k carbon fibres with a 0.2 % sizing and they were supplied by Toray Carbon Fibre Europe. The fibres were used for the experiments involving fibre spreading, fibre bundle tensile tests and composite manufacture. They were re-coded as fibre type-IIC fibres.

(iii) *E-glass Hybon® 2026*: The 2400 TEX E-glass Hybon® 2026 fibres were provided by PPG Industries UK Ltd. These fibres were used in the preliminary fibre spreading experiments and fibre bundle tensile tests. These were re-coded as fibre type-I fibres.

(iv) *E-glass Owens-Corning Advantex® R25H*: The 2400 TEX E-glass Owens-Corning Advantex® R25H fibres were supplied by Halyard Precision Composites (UK). These fibres were used in the fibre spreading experiments, fibre bundle tensile tests and composite manufacture. These were re-coded as fibre type-II fibres.

The relevant properties of the above-mentioned fibres are presented in Table 3.1.

Table 3.1 Details and properties of the fibre types used in the current study.

Commercial Code	Study Code	Fibre Type	TEX (g/1000m)	Average Filament Diameter (μm)	Size Content (%)	Tensile Strength (MPa)	Elongation to break (%)	Manufacturer
FT300B-6K	Type-IC	Carbon	396	7	0.7	3530	1.5	Toray Carbon Fibre Europe
T700-SC-12K-60E	Type-IIC	Carbon	800	6	0.2	4900	2.1	Toray Carbon Fibre Europe
Hybon® 2026	Type-I	E-glass	2400	17	0.7	2790	3.2	PPG Industries (UK) Ltd
Advantex® R25H	Type-II	E-glass	2400	24	0.5	2750	3.0	Owens-Corning

3.2 Fibre Spreading

3.2.1 E-glass Fibre Spreading Rig

A custom-built in-house fibre spreading rig (Irfan *et al.* 2012) underwent a series of modifications in order to optimise the degree of fibre spreading that could be achieved.

The criteria for the idealised spread state of a fibre bundle were defined as follows:

- (i) maximum spread width;
- (ii) minimum segmentation in the bundle; and
- (iii) no visually observable filament damage.

The modified spreading rig for spreading E-glass fibre is presented in Figure 3.1(a-c). A full description is presented throughout this next section.

With reference to Figure 3.1 the spreading rig consisted of three major parts; the pay-out system (Figure 3.1a), the fibre spreading rig (Figure 3.1b) and the post-tension system and haul-off winder (Figure 3.1c).

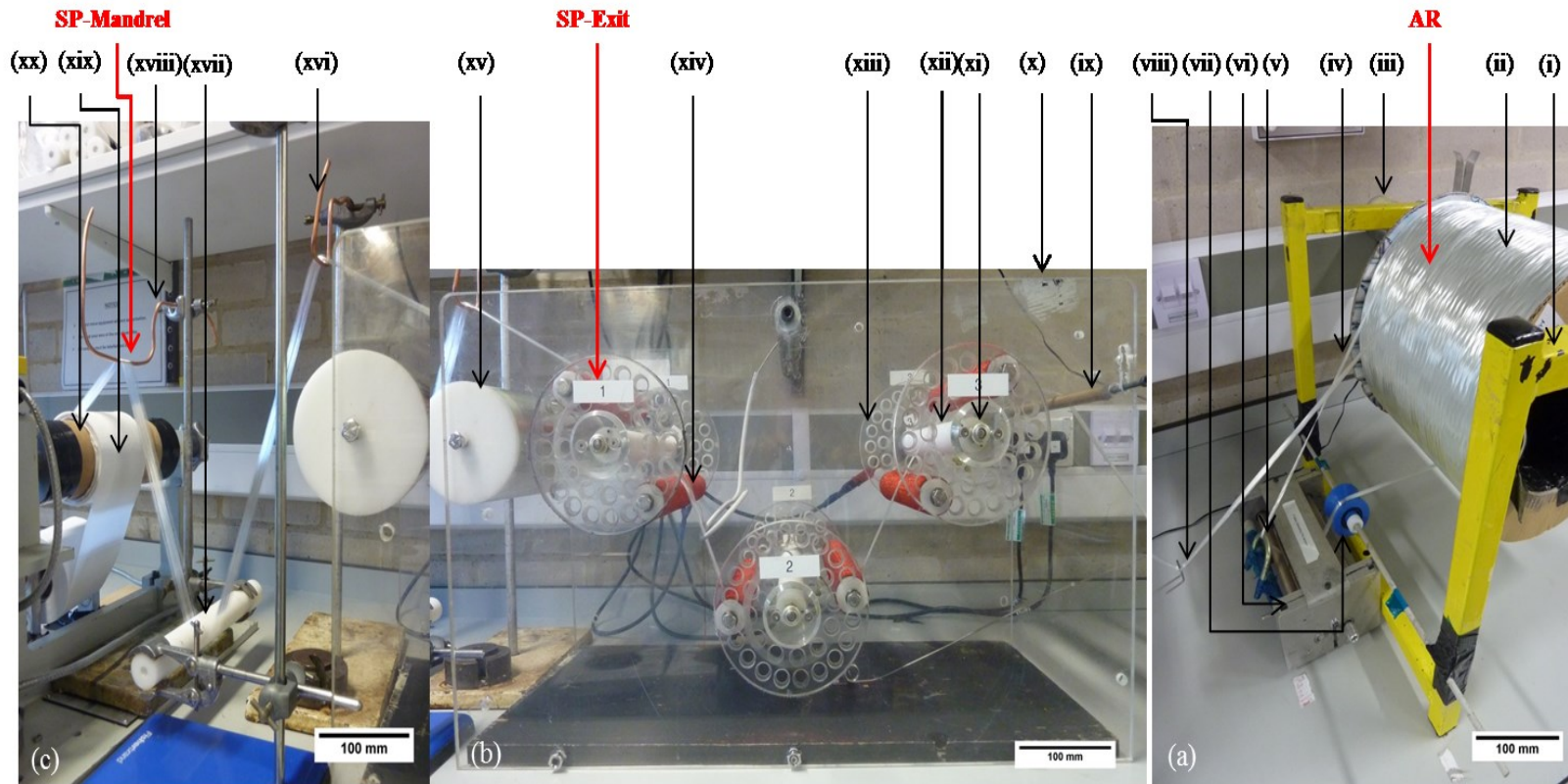


Figure 3.1 (a) the pay-out system, (b) the fibre spreading rig, (c) the post-tension system and haul-off winder.

The pay-out system, presented in Figure 3.2, consisted of a frame (i) on which a fibre creel (ii) could be mounted horizontally. The pay-out rate was controlled by an individual 12-Volt DC direct-drive motor and gearbox (iii). The motor was sourced from an off the shelf cordless drill and connected to one of the individual channels on a pair of dual-channel power supply units (PSU) TTI CPX200 Dual 35V 10A PSU. Mounting the creel in this manner allowed the fibre bundle (iv) to be outside pulled from the creel; this method is preferable to centre-pulling which can result in random twisting in the fibre bundle (Murray, 2013). The fibre bundle then traversed through a D-eye ring (v) at the entrance of a pre-tension rig (vi), a full description of which is given with reference to Figure 3.3. At the exit of the pre-tension rig the fibre bundle traversed around a concave freely rotating roller (vii) before wrapping back around the creel and traversing downwards and through a guide spring (viii). The pre-tension system, convex roller and the fibre bundle traversing back around the creel ensured a straight trajectory when the fibre bundle entered the spreading rig (Figure 3.1b).

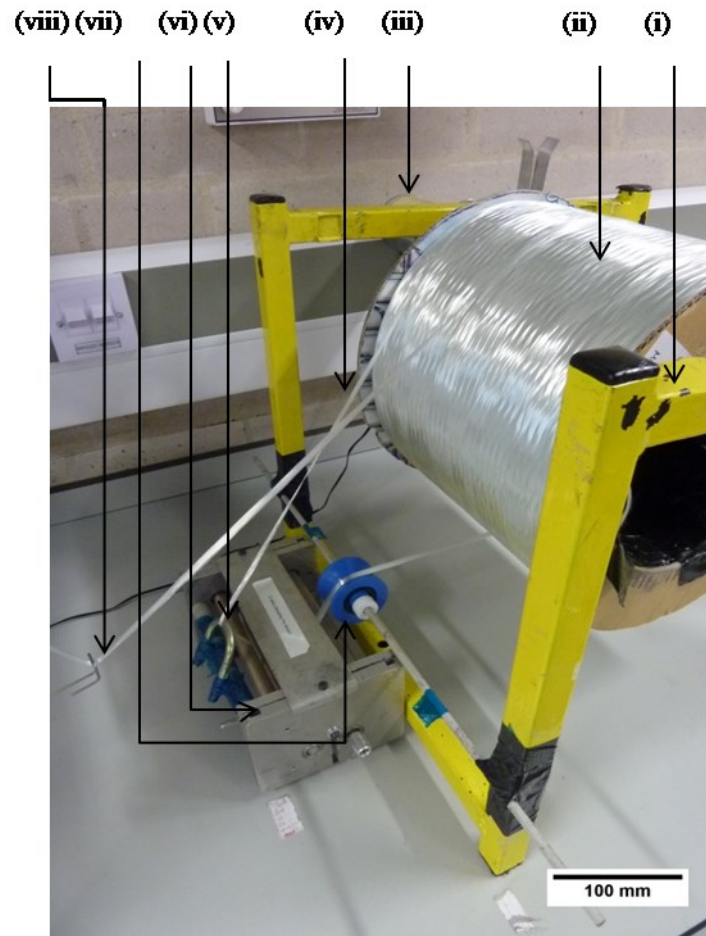


Figure 3.2 The pay-out system used for E-glass fibre spreading experiments.

In the pre-tension system, item (vi) in Figure 3.2, the fibre bundle then traversed across a guide pin (with a diameter and length of 15 mm and 160 mm respectively) before traversing through five PTFE-covered aluminium rollers, presented in Figure 3.3, (diameter and length of 12.75 mm and 180 mm respectively), following a serpentine trajectory. Upon exiting the pre-tension system the fibre bundle passed back around the fibre creel and was then fed into the fibre spreading rig.

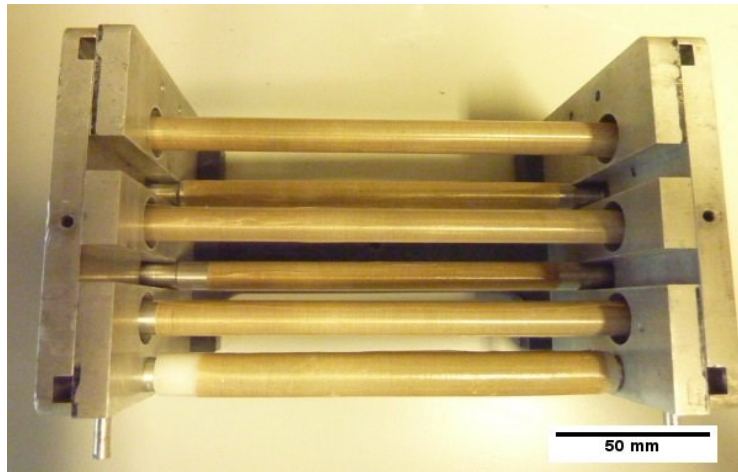


Figure 3.3 The inside view of the pre-tension system used in the modified spreading rig. The fibre bundle is traversed through the rig in a serpentine fashion. The rollers are covered in PTFE to reduce friction and the risk of damage. The fibre bundle would traverse from bottom to top in the above image.

A photograph of the fibre spreading rig is presented in Figure 3.4. At the entrance of the rig the fibre bundle traversed across a PTFE-coated guide bar (ix), with a length of 320 mm and a diameter of 12.75 mm. The fibre spreading rig itself consisted of a Perspex chassis (x) containing three pairs of carrier-hubs (xi). Each carrier-hub consisted of an acetyl drive shaft (xii), with a diameter and length of 30 mm and 300 mm respectively, the opposing ends of which were located in Perspex bearing housings (xiii); discs with a diameter of 150 mm. On each of the Perspex bearing housings, a series of recesses were machined around the circumference to enable ball bearings, 16 mm outer diameter, to be mounted. The ball bearings served to secure a micro-fibre fabric covered acetyl rod (xiv) (Direct Plastics, UK) with a diameter of 30 mm and a length of 300 mm, between a pair of the bearing housings. The roller carrier-hubs were designed to accommodate single or multiple acetyl rods around the circumference. These acetyl rods were designed to be used as pins or freely rotating rollers. The fibre bundle traversed through

the spreading rig across the roller carrier-hubs in a serpentine fashion. Each carrier-hub was powered by individual 12-Volt DC direct-drive motor and gearbox; as with the pay-out motor these were connected to individual channels on a PSU. This allowed independent control of the revolutions per minute (rpm) of the three carrier-hubs. The rotation rates of the individual roller carrier-hubs was set to 100 rpm which was measured using a digital photo tachometer (Model RM1501, RS Calibration, UK).

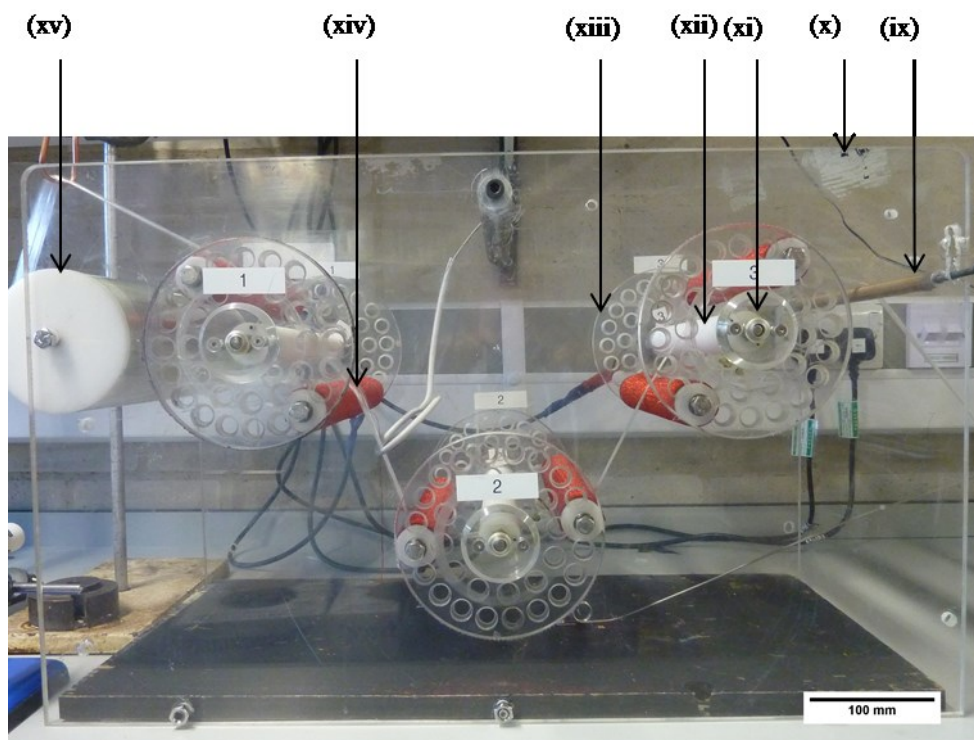


Figure 3.4 The fibre spreading rig used to spread E-glass fibre bundles.

With reference to Figure 3.4, an acetyl roller (xv) with a diameter and length of 115 mm and 320 mm was secured at the end of the Perspex chassis; its role being the preservation of the degree of spreading achieved.

The major modification was with the acetyl rollers located on the roller carrier-hubs. Adhered directly to the surface of the roller was a micro-fibre tufted velvet-type fabric. As can be seen in Figure 3.5 the fabric covered the entire circumference (i) and length (ii) of the roller and the nap was directed to follow the direction of traverse of the fibre bundle; (iii) is a magnified view of the micro-fibre fabric. Each of the motorised carrier hubs housed identical rollers with the nap of the micro-fibre fabric always facing the direction of the fibre traverse.

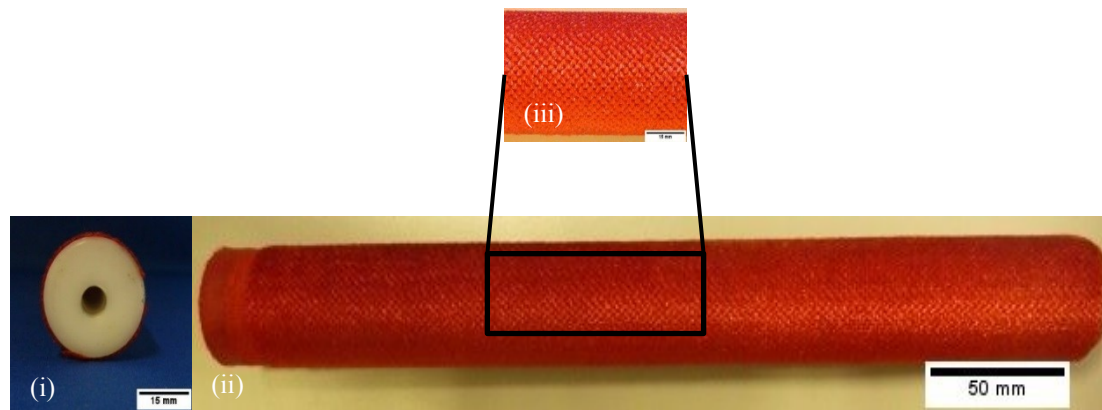


Figure 3.5 The micro-fibre fabric covered roller; (i) the end on transverse view showing the fabric wrapping around the entire circumference of the roller, (ii) longitudinal view of the fabric covered roller, (iii) a closer view of the fabric on the surface of the roller.

Presented in Figure 3.6 is the post-tension system through which the fibre-bundle traversed after exiting the fibre spreading rig. With reference to the numbered items in Figure 3.6 the fibre bundle first traversed across a width control bar (xvi), positioned at a height greater than that of the rig, which began to reduce the width and segmentation in the spread fibre bundle. It then traversed downwards in a vertical fashion to a horizontally positioned acetyl rod (xvii). This increased the tension in the fibre bundle slightly; again reducing the segmentation. Finally, the fibre bundle traversed upwards in a vertical fashion to a copper guide bar (xviii). The spread fibre bundle was then co-

wound with a release film (xix) onto a rotating mandrel (xx) controlled by the haul-off unit (Pultrex, UK Ltd) at a speed of 1 mm/minute.



Figure 3.6 The post-tension system and haul-off winder.

3.2.1.1 Micro-fibre Fabric

Figure 3.7 present images of the front (a) and back (b) surfaces respectively of the micro-fibre fabric used. Figure 3.7a presents the front surface of the micro-fibre fabric; it can be seen that there is a series of bundles of filaments. From the image analysis of the back surface (Figure 3.7b) it was determined that the micro-fibre fabric was a type

of tufted velvet. Analysis of the micro-fibre fabric determined that in 1 cm² of fabric there were on average ~29 bundles of micro-fibre filaments.

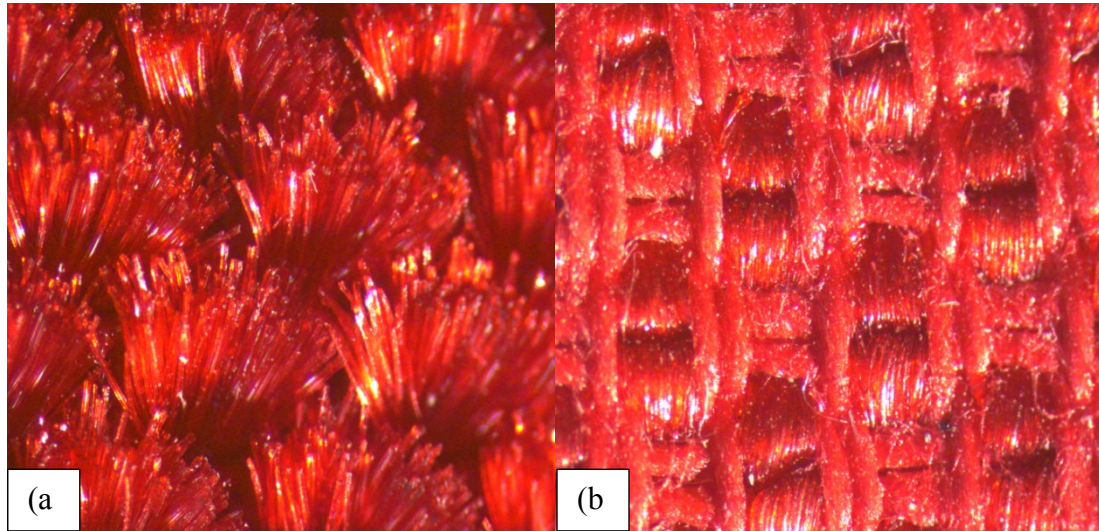


Figure 3.7 (a) the front or top face of the micro-fibre fabric, (b) the reverse or bottom face of the micro-fibre fabric.

Figure 3.8 and Figure 3.9 present SEM micrographs of the fabric surface. Figure 3.8 again shows the repeating series of bundles of filaments. From Figure 3.9 it can be seen that the filaments are triangular. This could enable the micro-fibre filaments to pass in between E-glass filaments in a bundle during spreading. As the micro-fibre filaments came into contact with the E-glass filaments they gradually separated them resulting in an increase in the width of the fibre bundle.

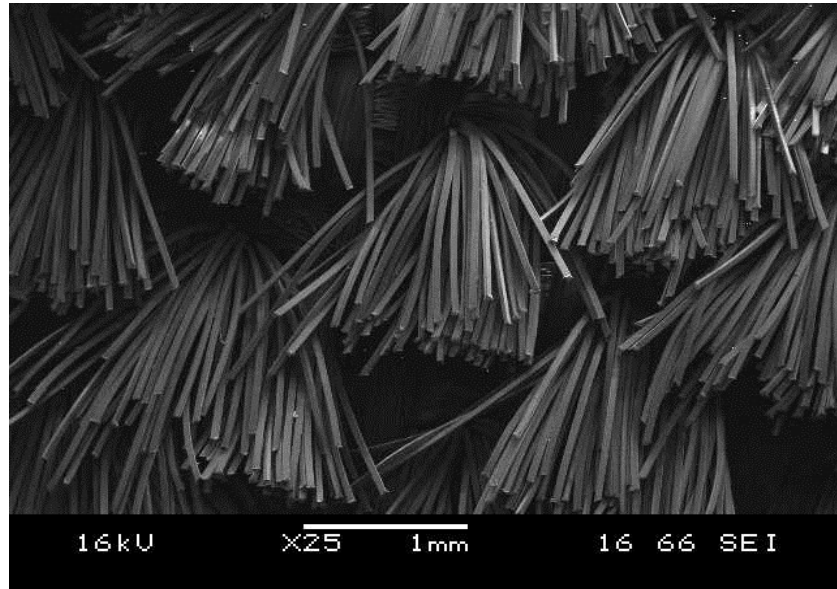


Figure 3.8 An SEM micrograph showing the tufted micro-fibre fabric bundles.

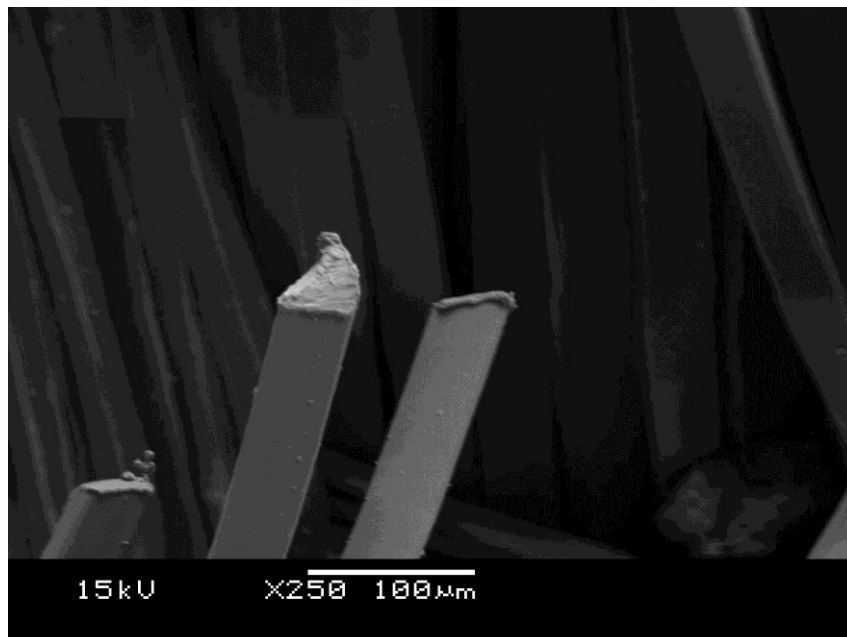


Figure 3.9 A close-up SEM micrograph of two of the individual filaments that make up bundles of the micro-fibre fabric.

3.2.2 Post-Processing: E-glass

A post-processing method was used to improve the fibre architecture of the spread fibre bundle with reference to manufacturing composite laminates. An 8 stage post-processing method involving ‘brushing’ using two micro-fibre fabrics and manual manipulation was developed and will be described in detail.

Sections of aluminium sheet were cut to make plates (300 mm x 120 mm x 1.5 mm). These plates were coated on one side with PTFE adhesive backed glass fibre sheet (Elder Engineering Ltd). The pre-spread E-glass was unspooled in lengths of 300 mm from the mandrel. One end of the E-glass fibre was secured to aluminium sheet using adhesive tape; care was taken to ensure all filaments within the bundle were secure. The opposing end of the E-glass fibre bundle length was then left free. This completed stage 1. An example of the spread fibre architecture is presented in Figure 3.10.

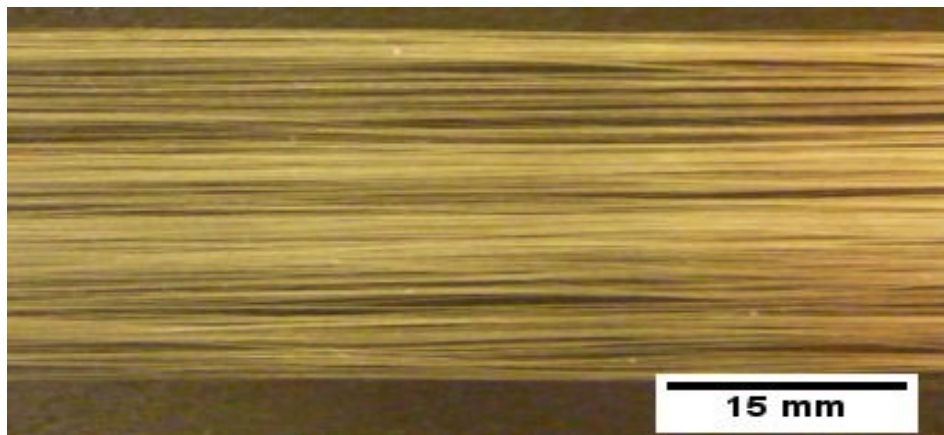


Figure 3.10 A section of E-glass fibre spread using the rig, no post-processing has occurred.

Stage 2, was manual '*brushing*' of the fibre bundle using a micro-fibre fabric covered roller as seen in Figure 3.5. Starting at the loose end the fibre was gently 'brushed' in small lengths working back towards the secured end until the full length was 'brushed'. Figure 3.11 shows an example of a fibre bundle after stage 2 of post-processing.

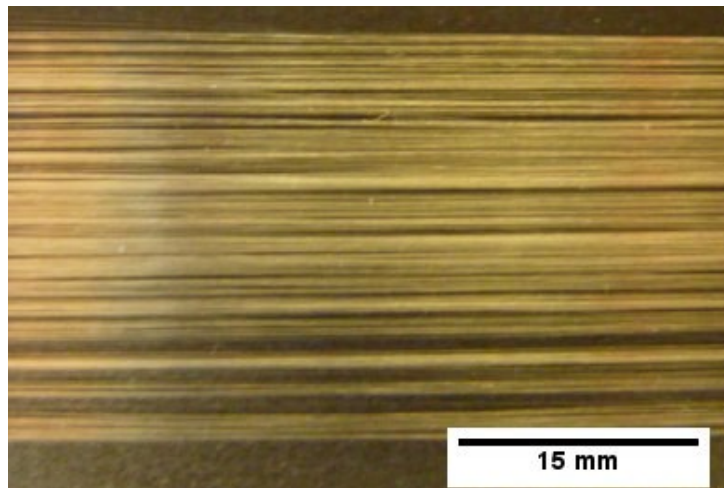


Figure 3.11 Stage 2 of the post-processing method; the E-glass fibre bundle has been gently brushed using a micro-fibre fabric covered roller.

Stage 3 was the first of 3 manual manipulation stages. The free end of the 'brushed' fibre bundle was gently manually manipulated using a flat edged wooden spatula. There were a number of purposes for this manual manipulation:

- (i) increasing the width of the fibre bundle end;
- (ii) reducing the segmentation between the individual filaments; and
- (iii) reducing the thickness of the fibre bundle to as near a mono-layer of filaments as possible.

Figure 3.12 shows a fibre bundle after stage 3 post-processing.



Figure 3.12 The manually manipulated wide end of a spread E-glass fibre bundle. This is after stage 3 of post-processing.

After the manual manipulation one end of the fibre bundle was much wider than the rest of the bundle. The first step of stage 4 was to secure the wider end of the fibre bundle using adhesive tape. The adhesive tape at the opposing end was then removed releasing the filaments. Following the release of the thinner end of the fibre bundle the micro-fibre fabric was used again to ‘brush’ the filaments. The ‘brushing’ that was started at the free end was moved gradually back to the opposite end of the fibre bundle. This resulted in the fibre bundle width becoming uniform along its length with reference to the wider manually manipulated end an example picture of this stage is presented in Figure 3.13.



Figure 3.13 An E-glass fibre bundle after 'brushing' with micro-fibre fabric during stage 4 of post-processing.

The fibre bundle was then re-brushed during stage 5. This re-brushing was done with a finer micro-fibre fabric than in the previous stages. The fibre bundle was 'brushed' along its length starting at the free end gradually working backwards. The free end of the fibre bundle was then manually manipulated for stage 6 as described in stage 3; results presented in Figure 3.14. The filaments of the spread fibre bundle were gently coaxed into a wider position. The segmentation was also reduced at the manually manipulated end. The result can be seen in Figure 3.14. The manually manipulated end was then taped again making sure all the filaments were secured so that none would slip during further processing.

The opposing end of the fibre bundle was then released. During stage 7 the fibre bundle was 'brushed' using the micro-fibre fabric to ensure uniform width along the length of the fibre bundle, before being 'brushed' again with the finer micro-fibre fabric. The fibre bundle at the end of stage 7 can be seen in Figure 3.15.

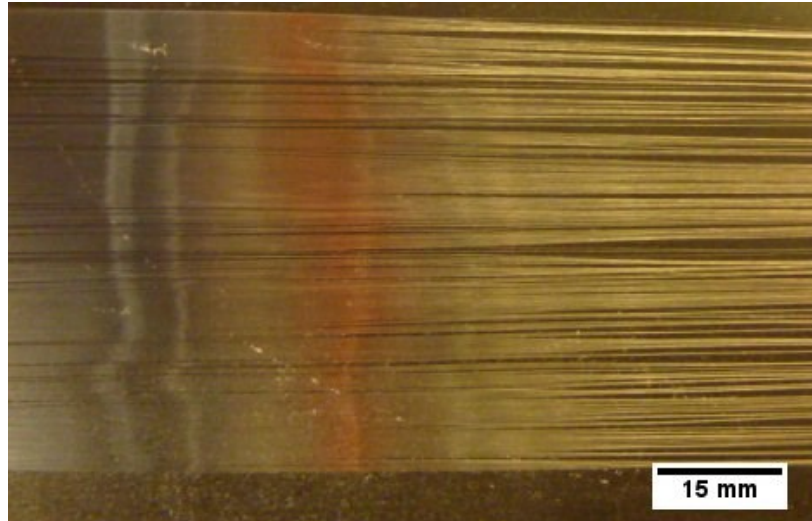


Figure 3.14 The manually manipulated end of an E-glass fibre bundle; this is after stage 6.

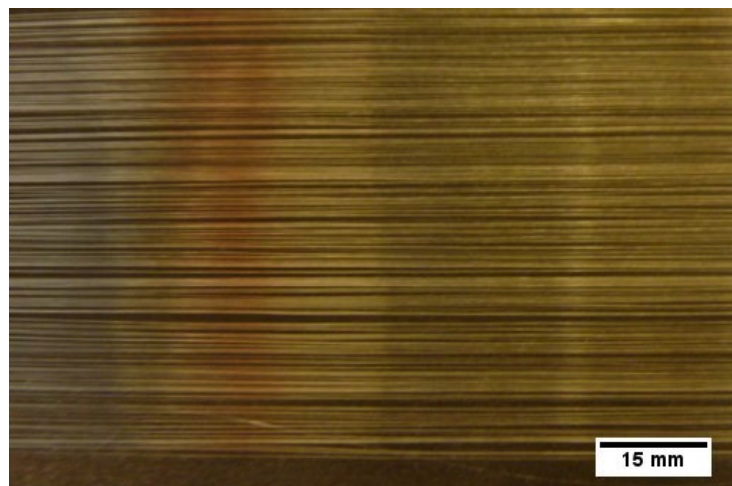


Figure 3.15 The spread E-glass fibre bundle after stage 7 and 'brushing' with the two micro-fibre fabrics.

During the final stage, stage 8, the flat wooden spatula was used along the length of the fibre bundle to remove any remaining areas of segmentation and create the final fibre bundle architecture which can be seen in Figure 3.16.

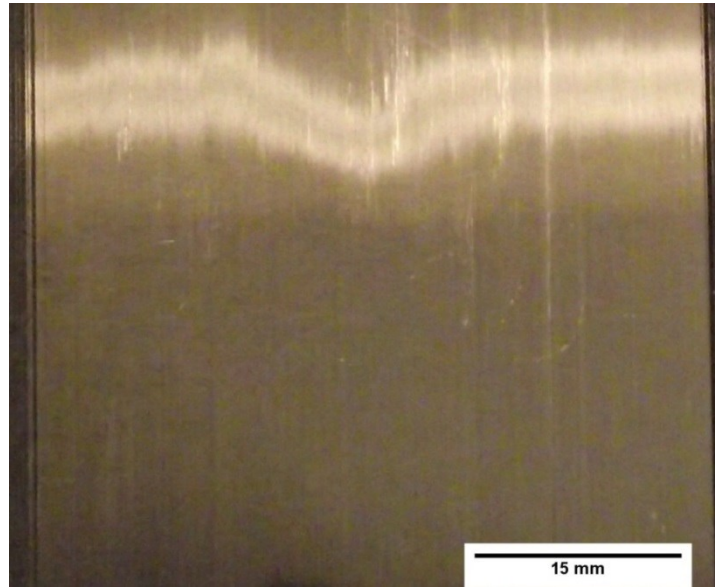


Figure 3.16 The final architecture of the post-processed E-glass fibre bundle.

3.2.3 Carbon Fibre Spreading Rig

The modified spreading rig for carbon fibre is presented in Figure 3.17(a-c). Figure 3.17a is the pay-out system, Figure 3.17b is the spreading rig and Figure 3.17c is the vacuum aperture and mandrel. Each section will be described in detail.

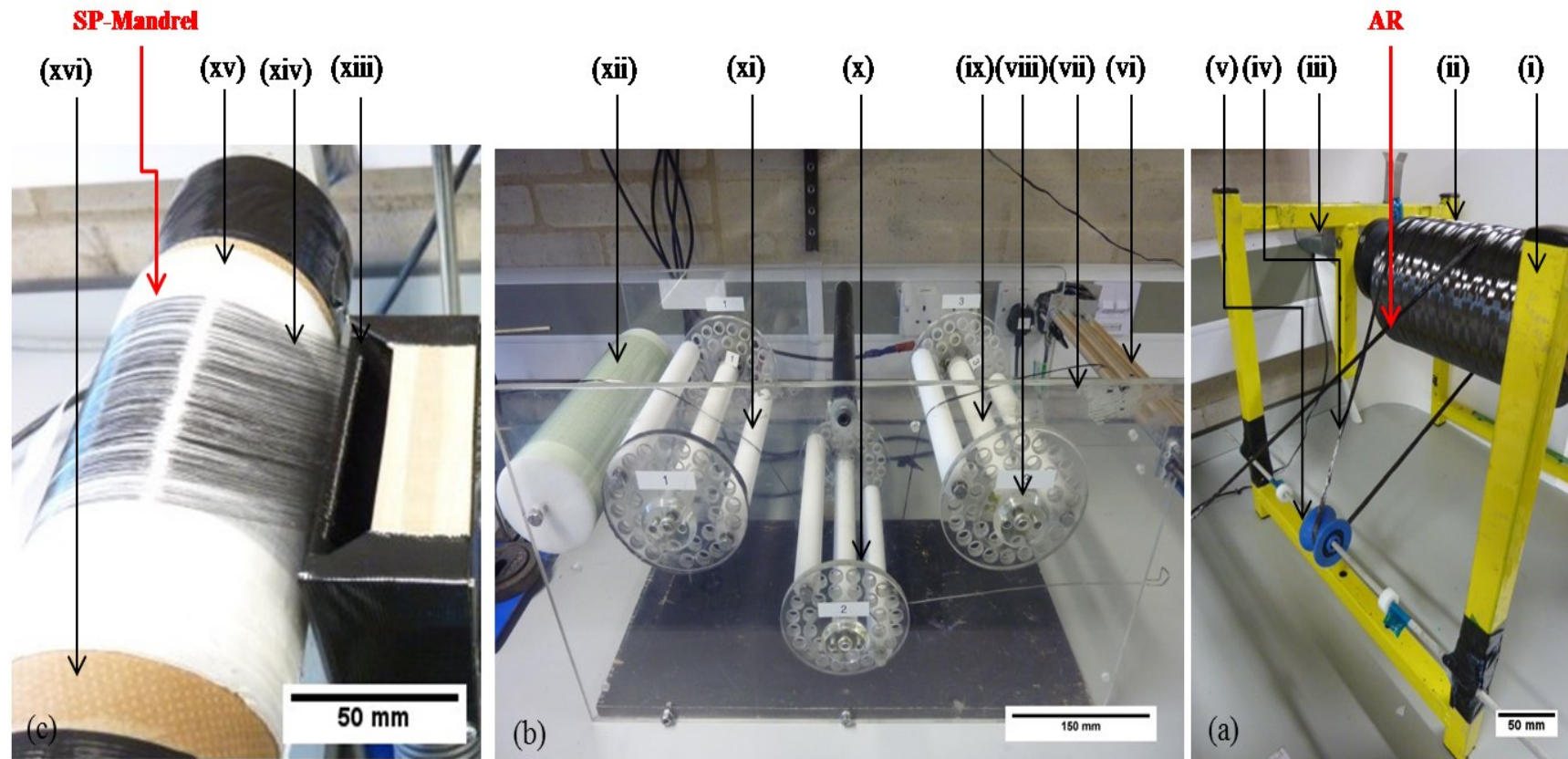


Figure 3.17 The modified fibre spreading rig used to spread a carbon fibre bundle.

In Figure 3.18, the pay-out system used for spreading carbon fibre consisted of a frame (i) on which a creel of carbon fibre (ii) was mounted horizontally. The rate of fibre bundle pay-out was controlled by a 12-Volt DC direct-drive motor and gearbox (iii). This was controlled by one of the PSUs mentioned previously. The fibre bundle (iv) traversed from the creel downward in a vertical fashion to a freely rotating and traversing concave roller (v). The fibre bundle then wrapped back around the creel from the convex roller which ensured a straight trajectory as the fibre bundle traversed toward the spreading rig.

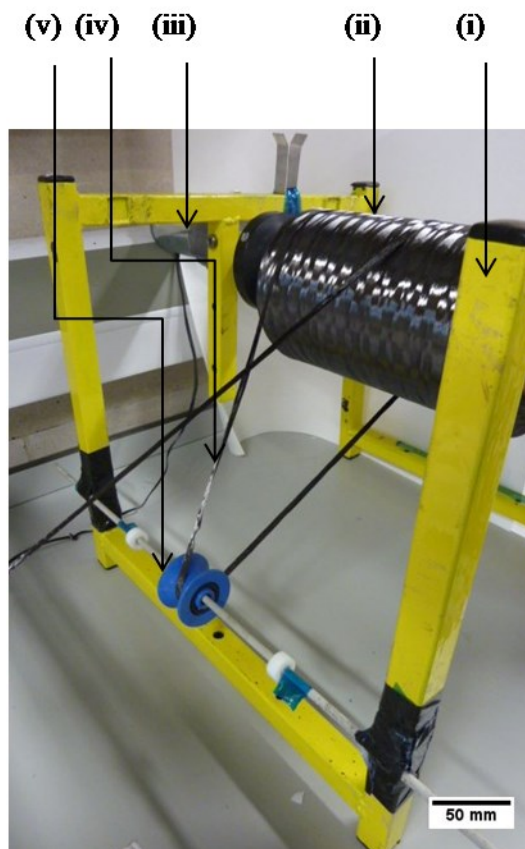


Figure 3.18 The pay-out system used for spreading carbon fibre.

The carbon fibre spreading rig is presented in Figure 3.19. The fibre bundle traversed from the pay-out rig and entered the spreading rig through, numbered item vi, a series of PTFE-coated pins (diameter and length of 12.75 mm and 320 mm respectively). The fibre bundle traversed through these pins in a serpentine manner. The fibre bundle then traversed into the spreading rig which consisted of a Perspex chassis (vii) in which there were three roller carrier hubs (viii). Each of these carrier-hubs consisted of a central acetyl drive-shaft (ix; diameter and length of 30 mm and 300 mm respectively) at each end of which was positioned a Perspex bearing housing (x). These bearing housings had a series of recesses (diameter of 16.5 mm) into which ball-bearings could be placed in order to mount an acetyl rod (xi). These acetyl rods were allowed to freely rotate and acted as rollers. During spreading the first two roller carrier-hubs were stationary whilst the final roller carrier-hub rotated, powered by an individual motor and gearbox linked to a PSU, as discussed previously. At the end of the fibre spreading rig was a larger diameter (115 mm) acetyl roller; this enabled any spreading to be maintained before entering the vacuum aperture.

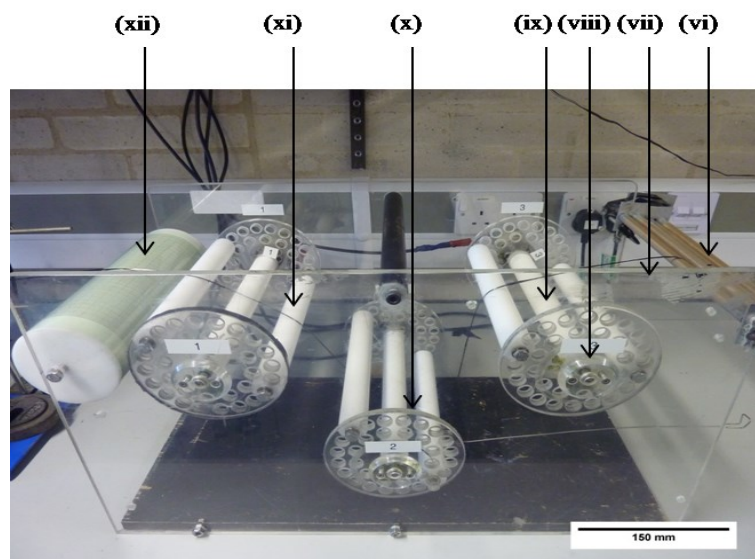


Figure 3.19 The spreading rig used for carbon fibre bundles.

Figure 3.20 presents the vacuum aperture and haul-off mandrel used for spreading carbon fibre bundles. The fibre bundle exited the spreading rig (Figure 3.19) and traversed into a vacuum aperture (xiii), this is where the fibre bundle was spread to its ideal state. Attached to the base of the aperture was a variable power vacuum cleaner (Sebo D2 Airbelt). The spread fibre bundle can be seen labelled as item (xiv). In order to separate the spread fibre bundle layers and enable subsequent post-processing a release film (xv) was co-wound onto the haul-off mandrel (xvi).

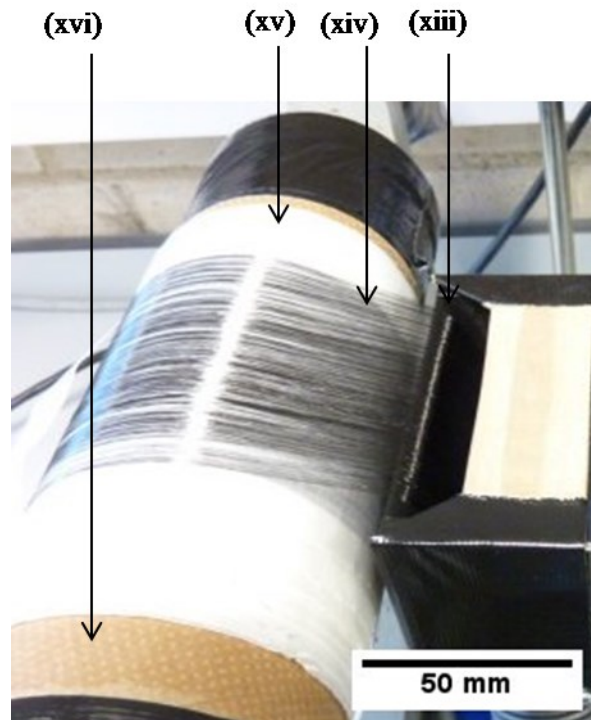


Figure 3.20 The vacuum aperture, spread fibre bundle and the haul-off mandrel.

The major modification of the rig for carbon fibre spreading was the addition of a vacuum and aperture system. Two different designs were trialled and were denoted as prototype-I and prototype-II. A schematic illustration and a photograph of prototype-I

are presented in Figure 3.21 and Figure 3.22 respectively. The labelled items in Figure 3.21 and Figure 3.22, are as follows; (i) is the vacuum port to which the vacuum was attached. In prototype-I the vacuum was attached on the right hand side. Prototype-I consisted of a bevelled entry (ii) a shallow vacuum aperture (iii) and a bevelled exit (iv). The edges of the prototype were bevelled and coated in PTFE fabric in order to prevent damage to the carbon fibre through friction.

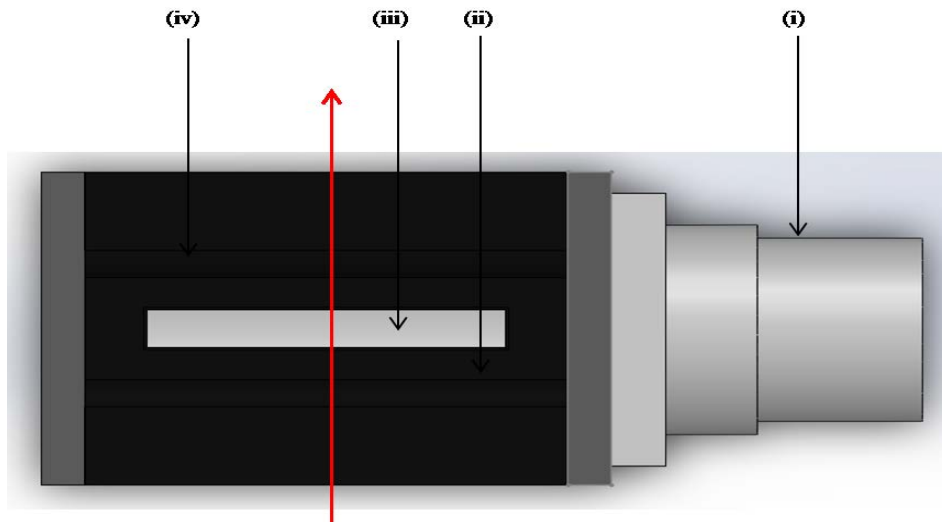


Figure 3.21 Schematic illustration of prototype-I; (i) vacuum connection port, (ii) bevelled entrance, (iii) vacuum aperture, (iv) bevelled exit. The red line denotes the direction of fibre bundle traverse.

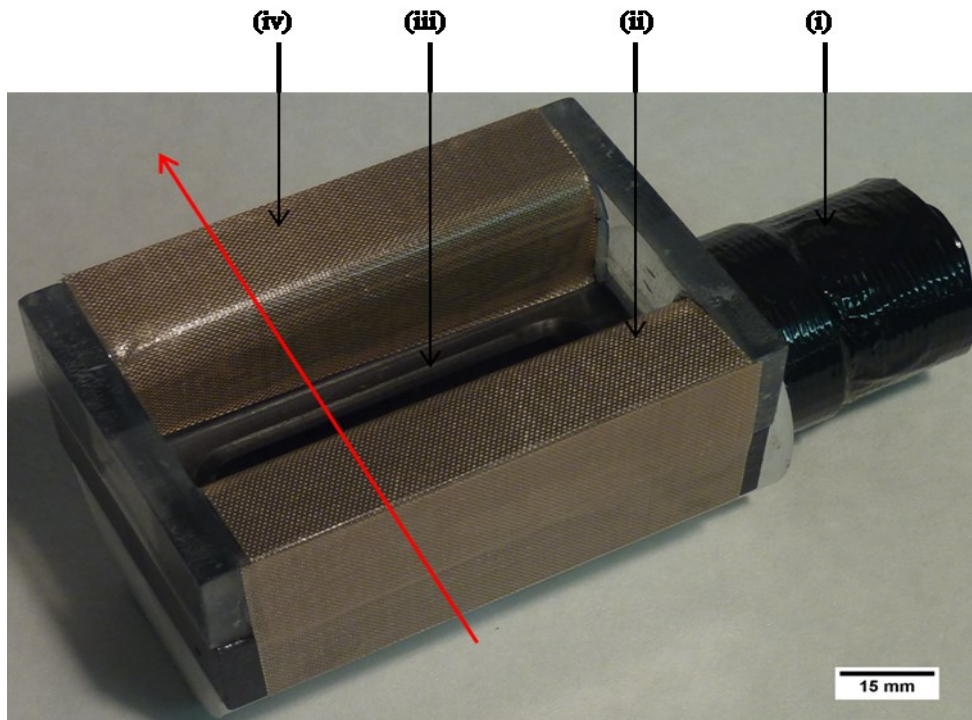


Figure 3.22 Photograph of prototype-I; (i) vacuum connection port, (ii) bevelled entrance, (iii) vacuum aperture, (iv) bevelled exit. The red line denotes the direction of fibre bundle traverse.

Presented in Figure 3.23 is a picture of prototype-II, the second design trialled to spread carbon fibre. With reference to the Figure 3.23a, prototype-II (i) had a curved front (ii) which enabled positioning of the prototype close to the mandrel. The fibre bundle traversed through the aperture (iii). The air-flow was restricted through the use of an aperture cap (iv); this was a PTFE-covered aluminium plate with the same as the profile as the prototype aperture with a section removed from the exit. Figure 3.23b shows the vacuum port (vi) to which the variable power vacuum was attached. The inside of the aperture, presented in Figure 3.23c, housed a light travelling bar (v). This bar was in constant contact with the fibre bundle and helped maintain the spreading achieved in the aperture.

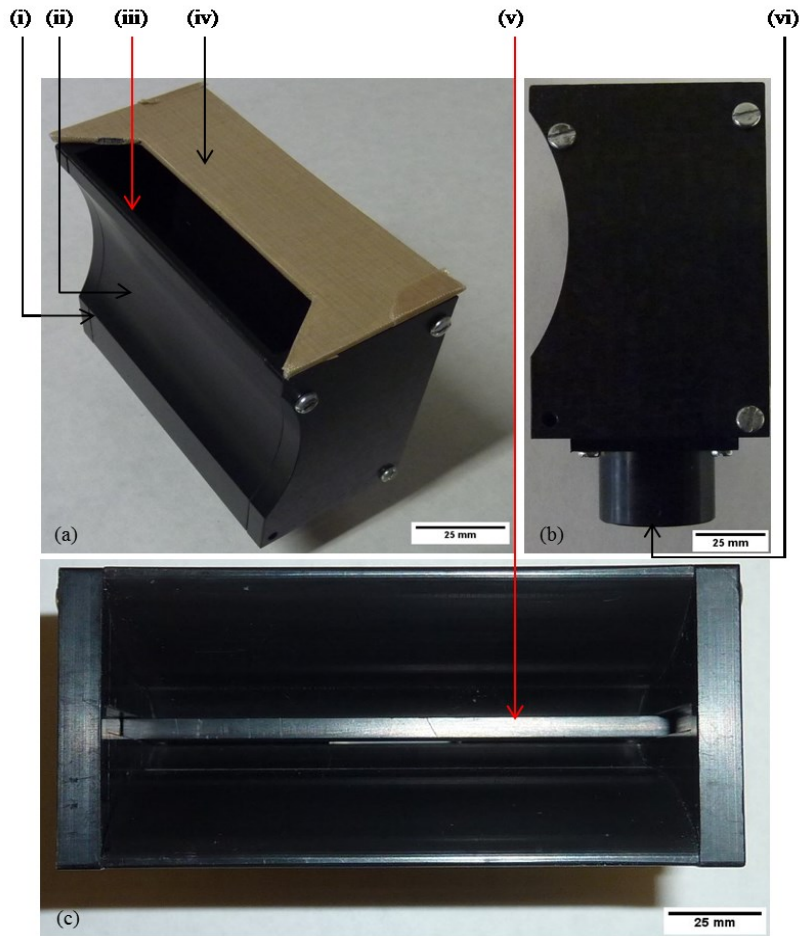


Figure 3.23 Prototype-II vacuum aperture system used for spreading carbon fibre bundles (a) experimental set-up with aperture cap, (b) side view, (c) the internal view with the aperture cap removed.

3.2.3.1 Differential Pressure Measurements: In order to define the mechanism of spreading, a number of experiments were conducted to determine the air-flow profile of prototype-II. A Fluke 922 air-flow meter (Figure 3.24) was used to measure the air-flow profiles; with reference to Figure 3.24 the numbered items are as follows (i) port through which the meter recorded the ambient pressure, the screen (ii) which displayed the pressure measurement and the input port (iii) which measured the pressure in the aperture of the prototype.

Pressure profiles were taken during four different conditions; (a) open aperture with no obstruction, (b) solid substrate placed across aperture in the direction of fibre travel, (c) tensioned bundle placed across aperture in the direction of fibre bundle traverse, and (d) spread bundle placed across the aperture in the direction of fibre bundle traverse. A total of ten differential pressure measurements were taken from seven locations across the width of the prototype apertures. The reference port on the Fluke 922 air-flow meter was left open to the atmosphere and determined the reference baseline pressure of 0 Pa. A pilot tube was connected, via a rubber hose, to the input of the Fluke air-flow meter in order to measure the differential pressure within the prototype aperture. Using this method meant that all of the differential pressure measurements came out as negative values.



Figure 3.24 Fluke 922 air-flow meter (image sourced from www.fluke.com) used to measure differential pressure across the aperture of prototype-II.

3.3 Fibre Bundle Tensile Testing

Fibre bundle tensile tests were conducted on the carbon and E-glass fibre bundles. For E-glass testing fibre type-I was tested in the as-received state and fibre type-II fibre was tested in the as-received and spread state. The type-IIC carbon fibres were tested in the as-received and spread state.

3.3.1 Preparation of Tensile Test Bundle Samples

With reference to Figure 3.25 the as-received E-glass creel, 400 mm lengths were taken from the centre portion of the bore of the creel (i), as illustrated schematically, the red section (ii) indicates the position within the bore where the samples were obtained.

In the case of the spread fibre bundle, 400 mm sections were taken directly from the mandrel without any post-processing. Fibre bundles spread for tensile testing were spread to the ideal state in order to fit within the end-tabs, i.e. they were not post-processed.

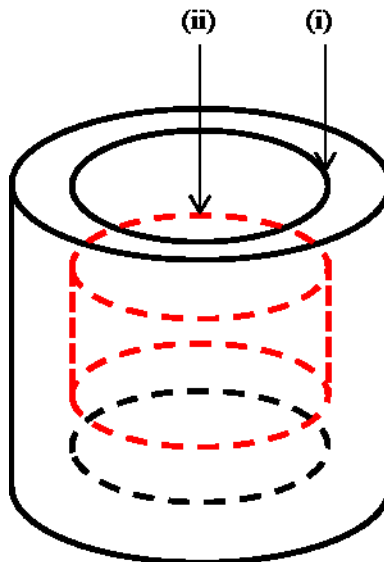


Figure 3.25 Schematic illustration of the as-received creel highlighting the area from which tensile samples were obtained.

With reference to carbon fibre lengths of 400 mm were unspooled from an as-received creel and checked for damage prior to mounting. For spread fibre bundle samples lengths of 400 mm were unspooled from the mandrel after spreading and post-processed to reduce the width to 24 mm.

A custom-built end-tab jig, as shown in Figure 3.26, was used to bond aluminium end-tabs to the test specimens. Thirty samples were prepared for each condition and fibre type. The custom-made jig ensured that the spatial orientation of the fibre bundle and end-tabs was maintained during curing of the adhesive. Aluminium end-tabs measuring 60 mm x 25 mm x 1.5 mm were cut from a sheet (dimensions of 1000 mm x 1000 mm) and the leading edge of each was abraded using a 240 grit abrasive disc to remove any burrs that could potentially damage the test specimens. End-tabs were then degreased in an acetone ultrasonic bath for ten minutes before being dried in an air-circulating oven at 60 °C for 30 minutes. Once the end-tabs were fully dried each one was individually primed on one side with a thin-layer of Scotchweld two-part structural adhesive (9323-2 3M UK). Primed end-tabs were then placed in the air-circulating oven to cure at 65 °C for 120 minutes. Priming was done to further reduce the risk of the bonding face of the end-tabs causing undue damage to the fibre bundles.

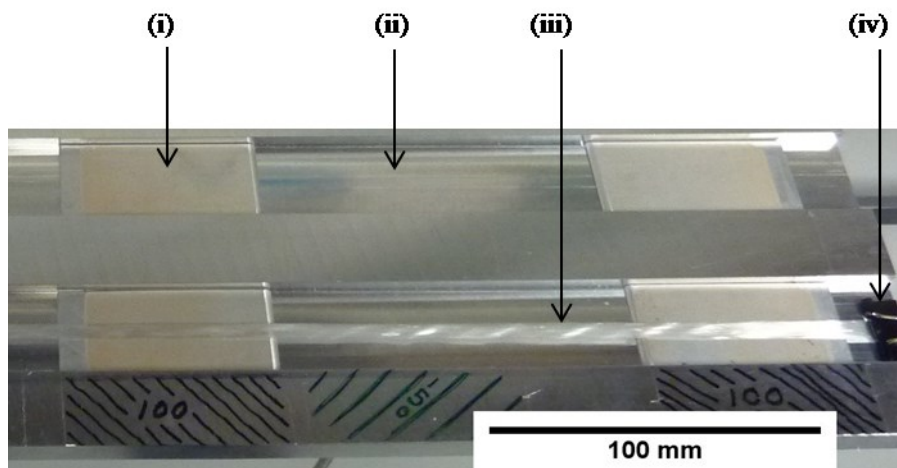


Figure 3.26 The end-tab jig used for the preparation of fibre bundle tensile test specimens.

The preparation of tensile test specimens will be described with reference to Figure 3.26. The primed end-tabs (i) were placed into a groove (ii) in a custom-made jig (measuring 500 x 500 mm) before a single as-received or spread fibre bundle (iii) was placed on top and secured at each end to the jig using clips (iv). After the fibre bundle had been secured, the structural adhesive was applied to the end-tab and the fibre bundle and a second end-tab was placed on top of the fibre bundle. A layer of Melinex™ was then added over the jig before a top plate was positioned over the entire area. A total of five 2 kg weights were spaced evenly onto the top-plate.

3.3.2 Tensile Testing

Dry fibre bundles were tensile tested on an Instron 5566 tensile testing machine. A loading rate of 0.2 mm/min was used; a slow rate was used to enable recording of acoustic emission (AE) data. All tests were carried out at room temperature (20 ± 2 °C) and the gauge lengths used for the as-received and spread fibre bundles were 50 and 100 mm.

3.3.3 Acoustic Emission Monitoring

Acoustic emission data were recorded during tensile tests through two wideband piezo-electric transducers (WD, Physical Acoustics (UK). Figure [] presents a schematic illustration of the AE sensor. With reference to the Figure [] (i) is the sample to which the AE transducer has been attached. The face of the sensor that is coupled to the sample is known as the wear plate, this is in place to protect the piezoelectric ceramic element or crystal (iv). Attached to either side of the crystal are electrodes (iii), one of which is electrically grounded, the other is attached to a signal lead. Behind the crystal is a backing material (v) that minimises the degree of reflection the crystal experiences as well as dampening the signal around the resonance frequency. Finally to ensure a

good acoustic path between the sample and the AE sensor a coupling agent is used (vi). The AE signal is obtained through the piezoelectric effect exhibited by the crystal within the sensor. Dynamic surface motion of the sample results in dynamic strain of the piezoelectric crystal through propagation. The frequency response of wideband sensors used in the current study was relatively flat meaning only signals that had a frequency in the range of 20-900 kHz were collected. Any signals collected that had a frequency below 100 kHz could be characterised as noise or persisting echoes from previous events. In addition to the wideband frequency response of the sensors used in the current study they were also differential. By using differential sensors it was possible to reduce the amount of noise being recorded by the data acquisition system.

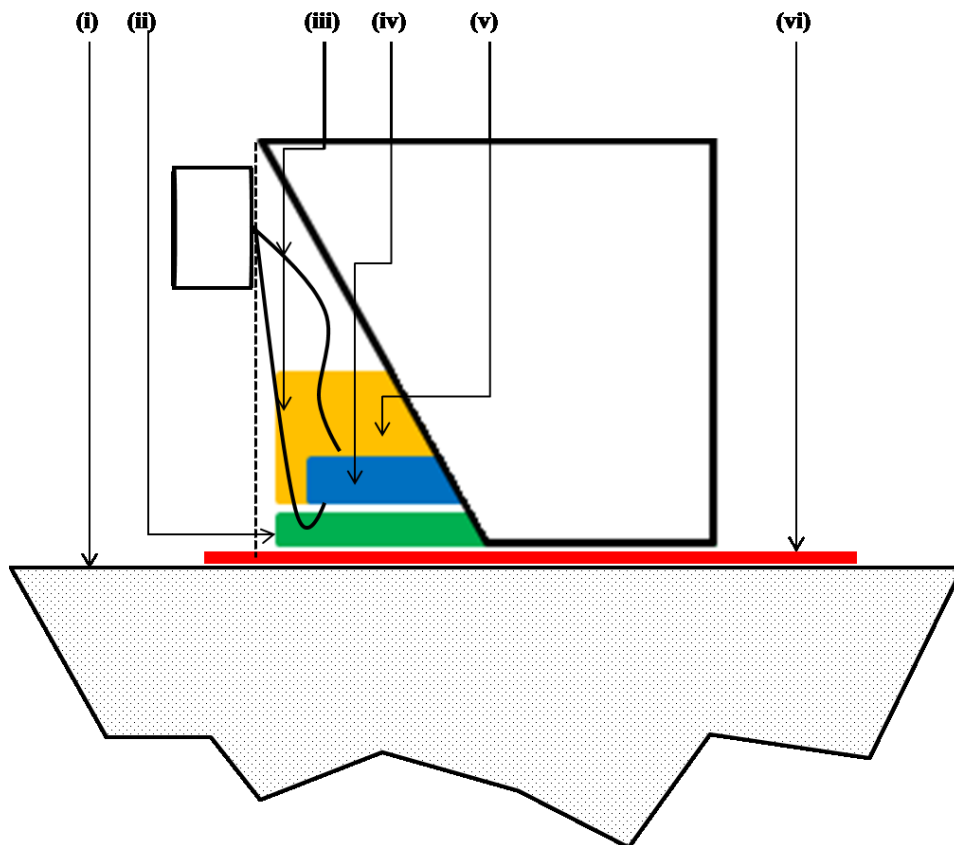


Figure 3.27 Schematic illustration of an AE transducer attached to the surface of a specimen; (i) sampling surface, (ii) protective face plate, (iii) electrodes, (iv) piezoelectric crystal, (v) backing material and (vi) coupling medium.

The experimental set-up is presented in Figure 3.28. With reference to the figure, the transducers (i) were secured to the end-tabs (ii) during testing using clips (iii). Paraffin wax was used as a coupling medium between the end-tab and the transducer. A general purpose low-noise industry standard pre-amplifier with plug in filter provisions, (20/40/60 dB switchable gain, single-ended or differential output), amplified the signals from the piezo-electric transducers by 40 db. For the transducers used the operating frequency range was 100-900 kHz. In order to acquire the load and displacement data, two parametric channels from the data acquisition systems were connected to the Instron directly. A threshold of 35 dB was used for the acquisition of acoustic emission data. The settings for data acquisition are summarised in Table 3.2. In order to measure the efficiency of the coupling between the transducers and the surface of the aluminium end-tabs and evaluate wave speed, the pencil break test was conducted on each end-tab to simulate and acoustic emission event.

Table 3.2 Settings used for acoustic emission data acquisition.

Setting	Threshold (μ s) *(ms)
Peak definition time	50
Hit definition time	100
Hit lock-out time	100
Front-end filter (signal duration)	250
Maximum hit duration	20*

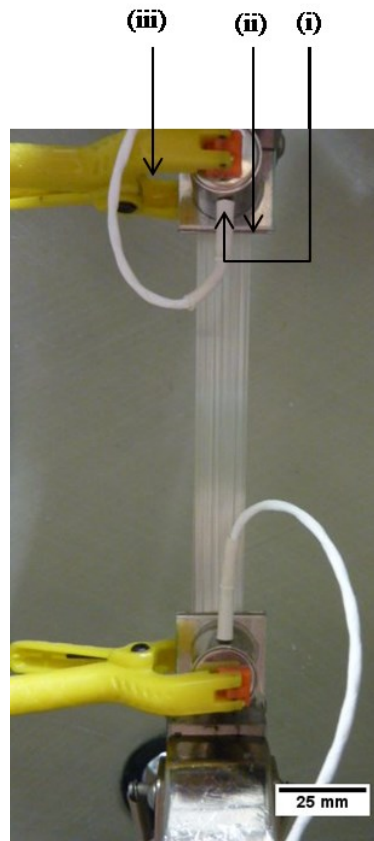


Figure 3.28 The experimental set-up for tensile testing fibre bundles.

3.4 Manufacture of Composites

Composites were manufactured using as-received and spread carbon and E-glass fibre bundles. A summary of the lay-up sequences used is presented in Table 3.3. Both mono-fibre and hybrid composites were manufactured, as-received and spread, using the epoxy-amine resin system (LY3505/XB3403). All samples were manufactured using manual impregnation and wet lay-up.

3.4.1 Manufacture of spread E-glass composites

Spread E-glass fibre bundles were post-processed using the method previously described in Section 3.2.3. Once the post-processing was complete both ends of the fibre bundle were secured using Loctite superglue. This was to maintain the desired

spatial architecture and minimise the loss of filament orientation during impregnation and room-temperature curing.

Table 3.3 Matrix presenting the composites manufactured in this study for testing.

Fibre Type	Mono-fibre or Hybrid (Stacking Sequence)	Number of Layers
E-glass Type-II	Mono-fibre	1
Carbon Type-IIC	Mono-fibre	1
E-glass Type-II	Mono-fibre	3
Carbon Type-IIC	Mono-fibre	3
E-glass Type-II/Carbon Type-IIC	Hybrid	3
E-glass Type-II/Carbon Type-IIC	Hybrid	3
E-glass Type-II	Mono-fibre	6
Carbon Type-IIC	Mono-fibre	6
E-glass Type-II/Carbon Type-IIC	Hybrid	6
E-glass Type-II/Carbon Type-IIC	Hybrid	6

Once the ends of the spread E-glass were secured, a sheet of MelinexTM polyester film measuring 260 mm x 110 mm was carefully slid underneath the sample. A release agent (Würtz PAT-607/PCM) was applied to the MelinexTM sheet prior to use.

Impregnation of the fibre bundles was achieved manually. The resin and hardener were weighed using the previously specified stoichiometric ratio and mixed manually. The mixed resin system was degassed in a vacuum desiccator at -0.026 MPa for 30 minutes. Drops of the mixed resin system were dispensed from a disposable plastic pipette onto the surface of the spread E-glass as shown in Figure 3.29. Twelve rows and three columns of small drops of resin system were introduced to the surface and allowed to impregnate in the longitudinal (x), transverse (y) and through-thickness (z) directions.

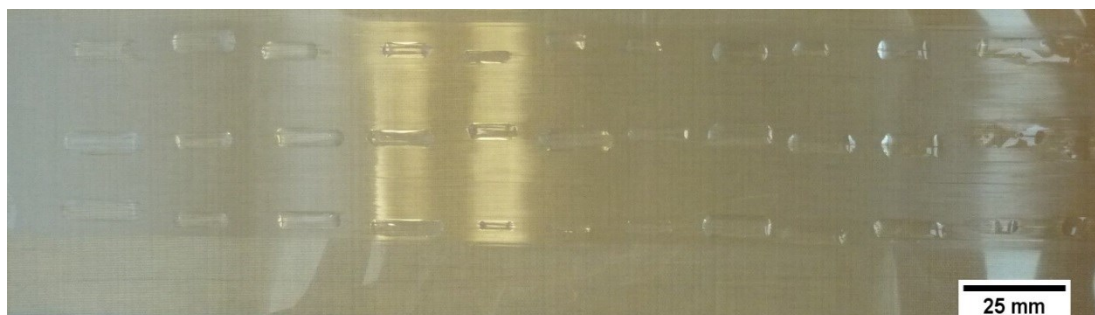


Figure 3.29 Spread E-glass specimen two to three minutes after initial impregnation.

After two to three minutes the resin droplets had spread mainly in the longitudinal direction and in the through-thickness direction. An example of this can be seen in Figure 3.29. The resin was then gently manually manipulated further into the fibre bundle to ensure the entire sample was wetted out as demonstrated in Figure 3.30.



Figure 3.30 A single-layer sample after manual.

For single-layer samples the next stage was to add additional resin in a strip perpendicular to the fibre direction towards one end of the sample and a second sheet of MelinexTM was placed on top. The resin was then spread in the longitudinal direction through the spread fibre layer from one end to the other; this process was repeated from alternate ends twice. This action had a number of purposes the first of which was ensuring that the sample was completely impregnated. Secondly by forcing the resin

through the sample it aided the removal of any small bubbles that may have formed during the impregnation process. Finally any excess resin was removed.

For the case of three and six-layer samples the process was the same, however, once the manual manipulation of the resin had been completed, another un-impregnated spread E-glass fibre bundle was added directly to the top surface of the previously impregnated layer. This was then left for one minute for the resin system to soak into the bottom of the dry sample before the impregnation process was repeated. This cycle was repeated until the desired number of layers had been stacked. Finally, as with the single-layer samples, a small amount of resin (1.5 cc) was added before a MelinexTM sheet was placed on top and the excess was manually spread out through the sample.

3.4.2 Manufacture of mono-fibre spread carbon composites

A separate process had to be utilised for the mono-fibre carbon and hybrid composite manufacture due to the delicate nature of the carbon and the inherent fibre waviness (highlighted by the red boxes in Figure 3.31).

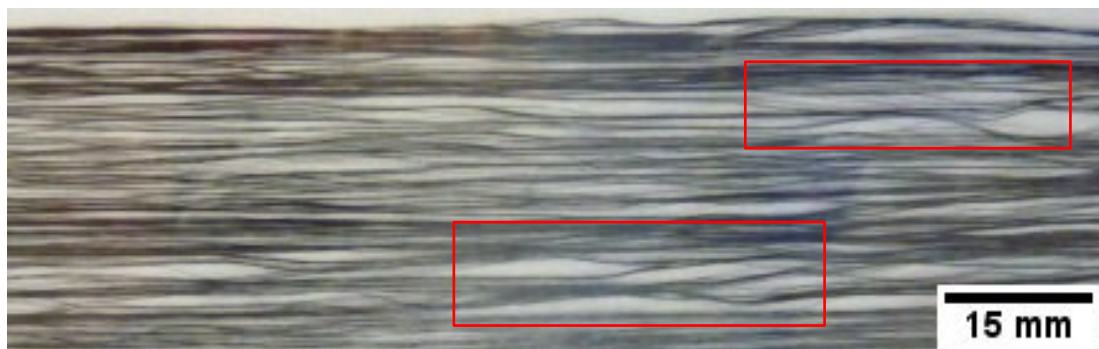


Figure 3.31 A dry spread carbon fibre bundle, the red boxes highlight areas in which the inherent fibre waviness is visible.

For the carbon fibre composites a thin resin layer was created. This was achieved by adding a strip of resin (1.5 cc) to a sheet of MelinexTM to which release agent had been applied; presented in Figure 3.32. Another MelinexTM sheet was placed on top before

the resin was spread evenly along the sheet to form a thin layer of resin. The two sheets were then separated. The spread carbon fibre bundle was unspooled in a length of 350 mm. A PTFE-covered aluminium plate (dimensions of 105 x 30 x 1.5 mm) was placed down on top of the carbon before a 450 g weight was added. This helped to maintain the desired spatial architecture of the filaments. A strip of adhesive tape was used to secure the secured end of the carbon fibre bundle to prevent the filaments slipping or moving during the subsequent stages of processing.



Figure 3.32 A released sheet of MelinexTM with a strip of resin system ready to be spread between two MelinexTM sheets to create a thin resin film for carbon composite manufacture.

A layer of MelinexTM was placed resin side down on to the surface of the spread carbon fibre and allowed to wet the filaments for two minutes. The spread carbon sample was then cut from the mandrel and turned over, MelinexTM side down, which allowed the co-wound release film to be removed. This left the carbon fibre bundle and the wet MelinexTM sheet. The carbon was left to impregnate for a short time before a strip of resin, similar to that used in the E-glass processing, was placed perpendicular to the

fibre direction before another MelinexTM sheet was placed on top. As with the E-glass fibre, this resin was then manipulated along the length of the carbon fibre sample to ensure thorough wetting.

3.4.3 Manufacture of multi-layer mono-fibre spread carbon and spread hybrid composites

During the production of multi-layer mono-fibre and hybrid composites, additional steps were necessary. Here the spread carbon strip was left to impregnate for two minutes before being placed face down onto the next strip of dry unspooled carbon fibre which was in turn secured with adhesive tape at one end prior to being cut. The release film was removed and resin was added to the surface in a method similar to that used in the E-glass process (described in Section 3.4.1). This was left to impregnate before carefully manually manipulating the resin into the bundle. This process was repeated until the desired number of layers were stacked.

With reference to the hybrid composites, the outer layers influenced the method of impregnation. In the case of the hybrids with the E-glass on the outside the method outlined in Section 3.4.1 was used i.e. a MelinexTM sheet was placed underneath prior to impregnation. Once the sample was impregnated it was placed face down on the spread carbon strip and then the carbon impregnation process (outlined in Section 3.4.2) was used to complete the stacking sequence. If carbon was on the outside the method outlined in Section 3.4.2 was used throughout.

3.4.4 Mechanical Properties

3.4.4.1 Composite Tensile Testing: In order to determine the tensile properties of each of the manufactured composites tensile tests were performed according to BS-EN-ISO 527-5:2009.

Tensile test specimens had a gauge length of 150 mm and were 15 mm in width. The width and thicknesses of each individual sample was measured at three positions using a set of digital Vernier callipers and a digital micrometer respectively (RS Components). The specimens were manufactured using the method described in Section 3.3.1. The only difference was in the end-tabs. For composite tensile testing sand-blasted end-tabs were used (dimensions of 50 x 25 x 1.5 mm).

Acoustic emission data were recorded using the procedures described in Section 3.3.3. In addition to the measurement of the load and displacement data the acoustic emission allowed for the determination of fibre breaks. This was important for the hybrid samples as it was necessary to distinguish between the carbon and E-glass fibre breaks during loading. Finally strain gauges were attached to the centre of all of the spread composite samples. The strain gauges chosen were FLA-5-11 longitudinal gauges (Tokyo Sokki Kenkyujo Co. Ltd) with a gauge length of 5 mm, a gauge resistance of 120 ± 0.3 and a gauge factor of 2.13.

3.4.5 Physical Properties

3.4.5.1 Fibre Volume Fraction and Void Content:

Optical Microscopy: Samples for optical microscopy were prepared according to standard metallographic methods for potting and polishing. To analyse the samples a Zeiss Axioskop-2 microscope was used to obtain images. ImageJ image analysis software was used to determine fibre volume fraction. Figure 3.33 presents the stages used to determine fibre volume fraction in a hybrid sample. Selected images were cropped to show the sample area (i) and using the software adjusted to pick up the individual filaments, in the case of hybrids this was done in two stages, stage (ii) for carbon fibre and stage (iii) for E-glass fibre. The percentage area was then calculated using the software and recorded. A total of 40 images for each composite type were analysed and an average used to determine fibre volume fraction.

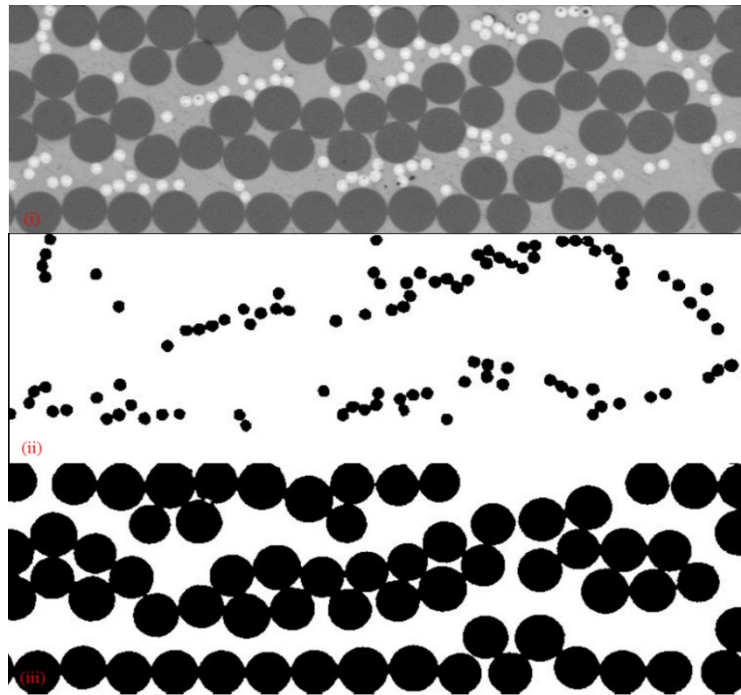


Figure 3.33 Images presenting the method used to determine fibre volume fraction; (i) original sample area, (ii) carbon fibre area, (iii) E-glass fibre area.

4 Results and Discussion

4.1 As-received Fibre Bundles

4.1.1 2400 Tex Type-II E-glass Fibre Bundles

The as-received type-II E-glass fibres were characterised, to determine the fibre bundle architecture using optical microscopy and scanning electron microscopy (SEM). The manufacturer's data sheet stated that the type-II E-glass fibre bundle consists of approximately 2400 filaments with an average diameter of 24 μm (Advantex® glass data sheet, www.3B-fibreglass.com) The tensile strength and Young's modulus were reported to be 2700-2800 MPa and 81-83 GPa respectively. The manufacturer's data did not report a value for failure strain. Hence, it was calculated to be 3.33-3.37% (assuming elastic behaviour). In addition the binder content for this fibre type was reported to be 0.5%.

Figure 4.1 presents representative cross-sections of the as-received type-II E-glass fibre bundle (Ma, 2016). Figure 4.1 highlights the fact that there is variability in the fibre bundle architecture. For example, it can be seen that (a) has a greater width than (c), and the centre portion of (b) is thicker than (d).

Figure 4.2 presents a magnified view of the as-received type-II E-glass fibre bundle (modified and taken from Ma, 2016) and it can be seen that there is inherent variability in the filament diameters.

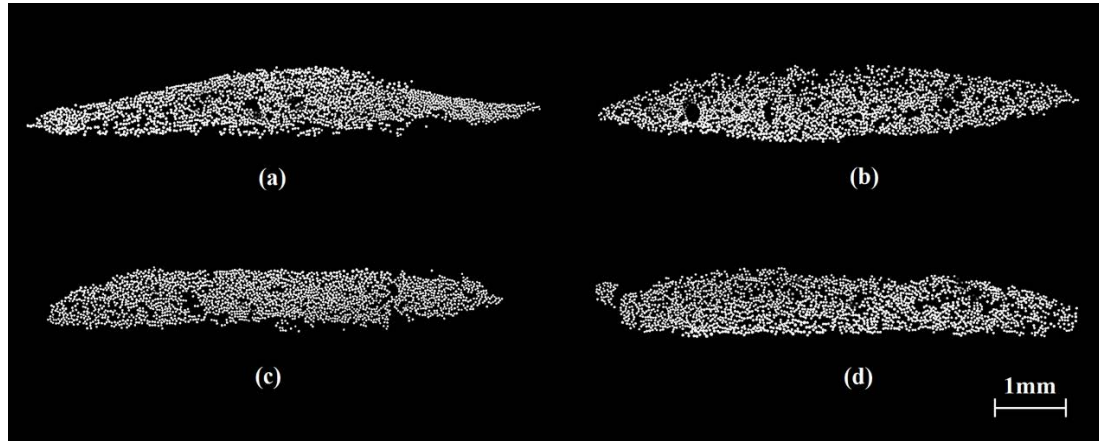


Figure 4.1 A micrograph representing typical cross-sections of the as-received type-II E-glass fibre bundle architecture. Ma, 2016.

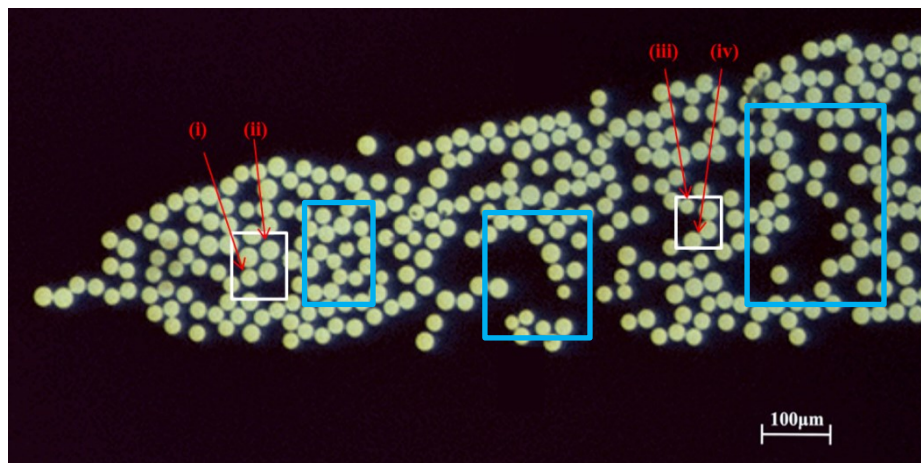


Figure 4.2 A magnified view of a representative cross-section of an as-received type-II E-glass fibre bundle highlighting the variable filament diameter and the spatial architecture of the filaments. Regions (i), (ii), (iii) and (iv) show the variability in filament diameter. The blue boxes highlight the variability in the spatial filament architecture. Modified from Ma (2016).

Figure 4.3 presents representative photographs of the surface topology and other features observed in the type-II E-glass fibre bundles. Figure 4.3(i) presents features observed on type-II E-glass fibre bundles as a consequence of the manufacturing process. The undulations were observed to be present along the fibre bundle length and

are evidence of the traversing winding pattern used during the manufacturing process. From Figure 4.3(i), it was also observed that these undulations were not always uniform. This may be of significance during tensile loading as not all the filaments would be loaded simultaneously. Figure 4.3(ii) presents further evidence of the variable width of the as-received fibre bundle. Figure 4.3(iii) provides evidence of meandering filaments; this could also be a result of the winding pattern as seen in Figure 4.3(i) or the manner in which the filaments were gathered in preparation for the winding operation onto the mandrel. The meandering fibres were observed predominantly in close proximity to or in the undulations.

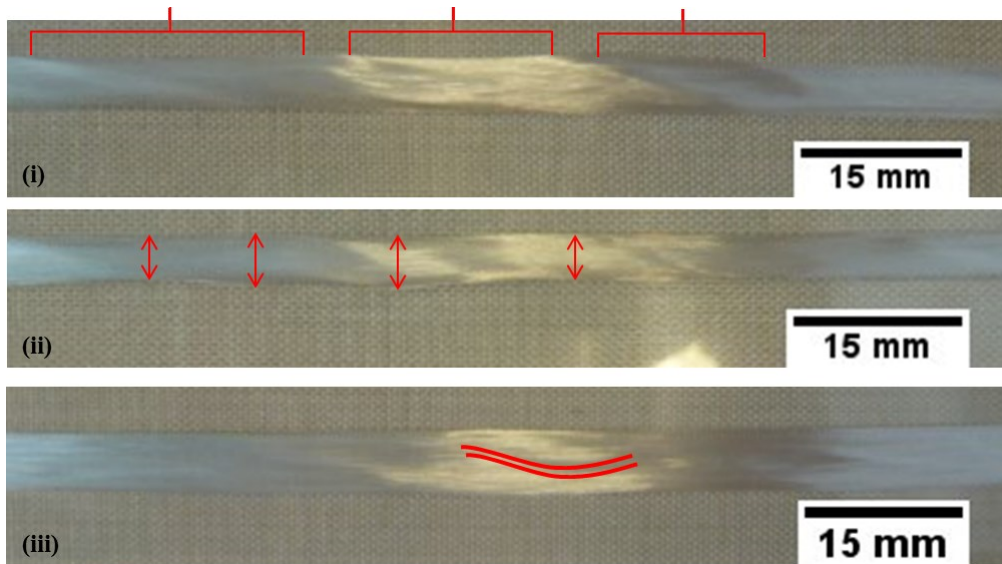


Figure 4.3 Photographs highlighting the surface topology and variability of the features observed in type-II E-glass fibre bundles; (i) undulation caused by the winding pattern during manufacture, (ii) variable fibre bundle width and (iii) meandering filaments.

SEM micrographs representing typical surface features present on a section of type-II E-glass fibre bundle are shown in Figure 4.4(i) and (ii). The red lines superimposed on Figure 4.4(i) and (ii) indicate the relative orientations of some of the E-glass filaments, in the plane of the paper. The superimposed yellow dotted lines indicate filaments that are meandering, into the plane of the paper. The superimposed blue circles highlight the

presence of irregular shaped particles on the surface of the filaments. Accepting the fact that no detailed inspection or analysis was carried out, subsequent to inspecting a large number of micrographs, Irfan (2013) and Wait (2015), it is probable that these particles represent debris or components of the binder content. The superimposed green arrows represent potential clusters of filaments and the orange arrow indicates a plane where, presumably, the binder had fractured. This could have occurred during the preparation of the SEM sample or at the fibre bundle production stage.

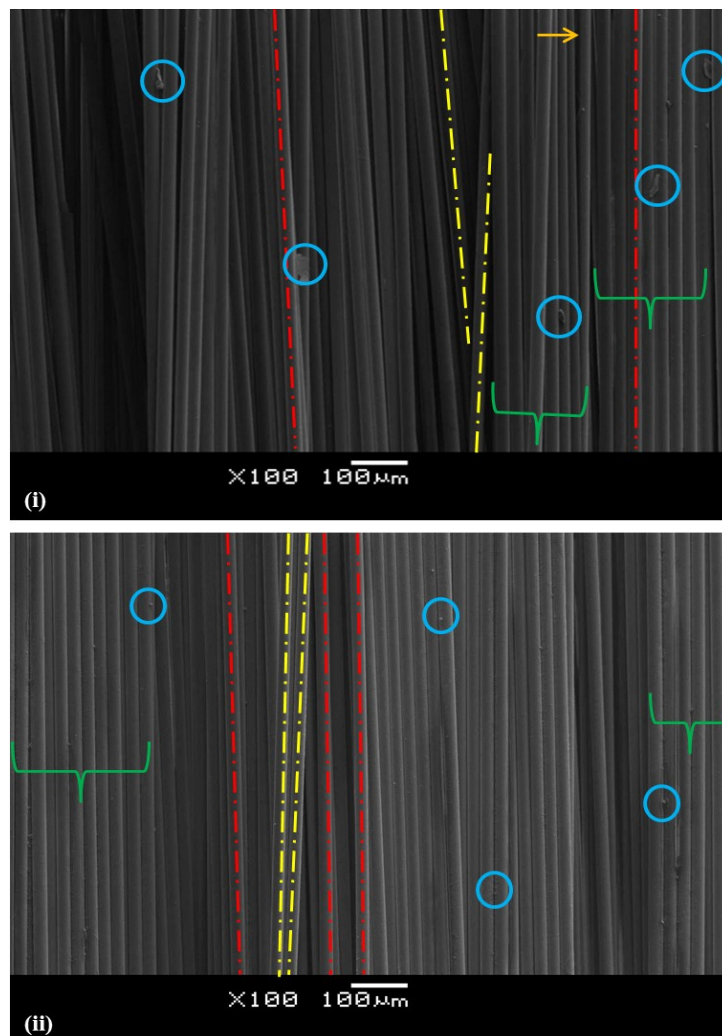


Figure 4.4 Micrographs representing surface views of a section of an as-received type-II E-glass fibre bundle obtained at 100 times magnification; see text for details.

Higher magnification micrographs of as-received type-II E-glass fibres are shown in Figure 4.5(i) and (ii). As before, the red dotted lines indicate the orientation of select filaments, and the yellow line represents a meandering filament (into the plane of the paper). The orange arrows indicate gaps between filaments or segmentation in the fibre bundle. There are a number of notable features on the surface on the filaments in both Figure 4.5(i) and (ii). These features have been attributed to components of the binder (Wait, 2015). The composition and/or origin of these particles were not investigated in the current study. However, these particles may represent components of the binder that had phase separated or precipitated as the solvent (water) was evaporated during the drying operation. These features, with regards to the binder distribution and particulate form, observed in Figure 4.5(i) and (ii) may have an influence on the tensile behaviour and the acoustic emissions that are generated during tensile testing. This will be discussed later in Section 4.4 with specific reference to apparent inter-fibre friction that has been reported to occur during testing of dry or as-received E-glass fibre bundles (Hill & Okoroafor, 1995; R'Mili, Moevus & Godin, 2008).

Referring to Figure 4.5(ii), it is speculated that the longitudinal cords (indicated by the green arrows) represent regions of high residual binder that had accumulated and eventually dried in between the interstitial spaces of the filaments.

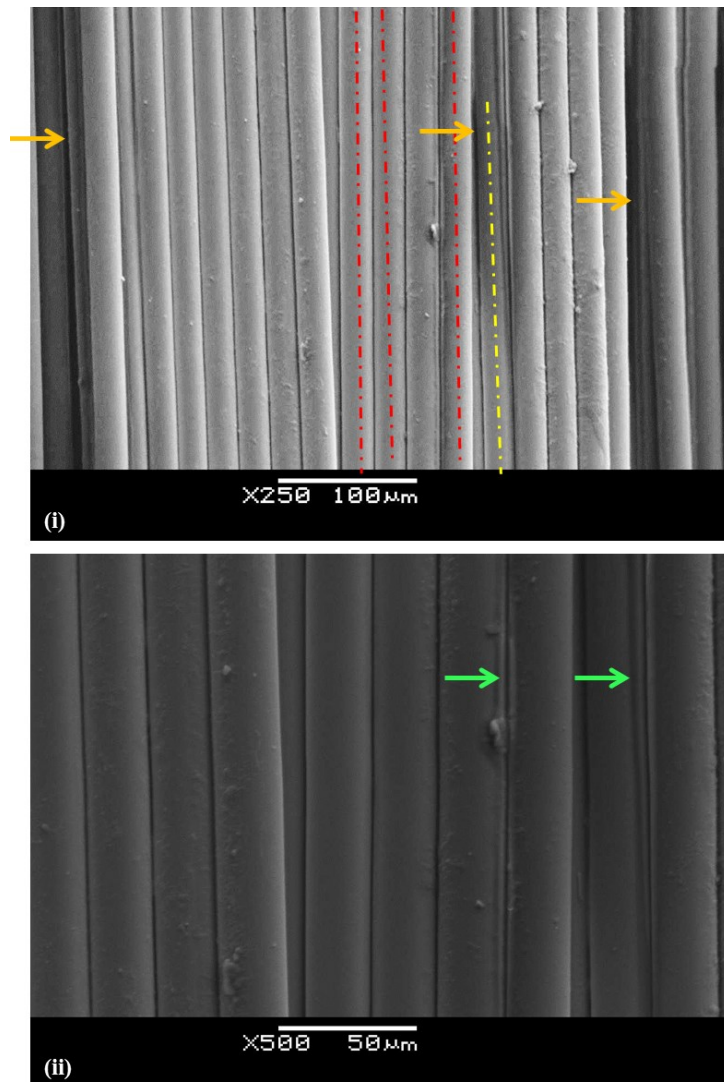


Figure 4.5 SEM micrographs showing; (i) examples of the relative orientations of selected filaments within and into the plane of the paper (red and yellow dotted lines respectively) and gaps within the bundles (orange arrows); and (ii) magnified view of Figure 4.5(i) showing a feature that is best described as “cords” of coating on adjacent pairs of fibres.

Figure 4.6 presents an illustration to show the various conditions under which the observed cord may have formed during the application and subsequent drying of the binder. With reference to Figure 4.6, item-i represents the idealised coating of the binder on an E-glass filament. Considering neighbouring filaments ii and iii, representing the situation where a finite gap exists between them, the resulting profile of the post-dried aqueous binder is illustrated. Depending on the magnitude of the gap between filaments ii and iii, the profile of the aqueous binder (pre-drying) at the top is likely to be concave. On the other hand, the accumulation of liquid between filaments ii and iii, at the bottom, is likely to be convex due to gravity (g). However, as the liquid evaporates, the surface tension is likely to result in a concave profile. The scenario between filament iii and iv represents the case where the gap between the filaments is significantly smaller than the gap between filaments ii and iii. Hence, in this instance, the profile of the liquid on the top and bottom regions is likely to be concave as indicated. The situation where a large gap exists, is represented by filaments iv and v. In this case, depending on the diameter and the position of the filaments below it (not shown), the likely outcome is the accumulation of liquid at the bottom region of filament v, as indicated.

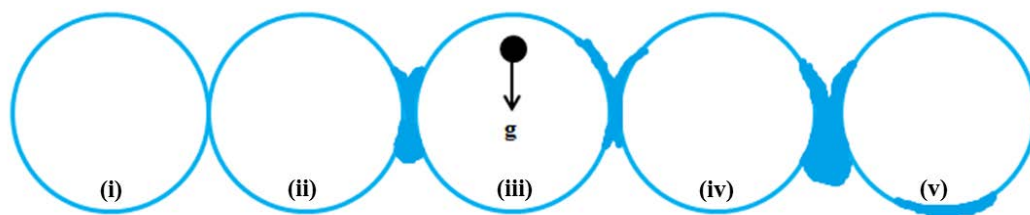


Figure 4.6 A schematic illustration to explain the formation of the “cord” like feature observed in Figure 4.5(iv); see text for details.

The average binder content for type-II E-glass fibre investigated by Wait (2015), using loss-on-ignition (ASTM D4963/D4963M), at specified position within the creel (see Figure 4.7). The binder was reported to be between 0.3% and 0.4% as shown in Figure 4.8. However, sections within the creel were found to contain up to 0.8% of binder. These are referred to as 'high' binder regions in Figure 4.8.

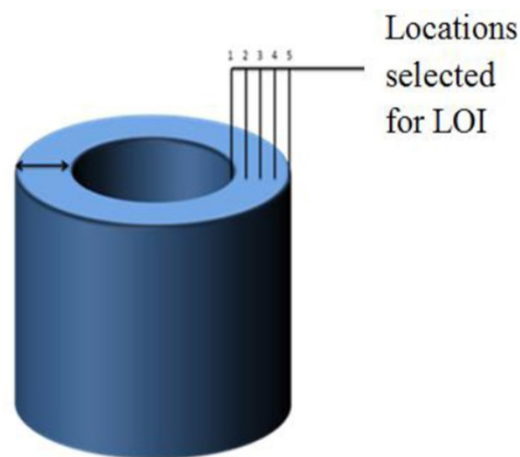


Figure 4.7 Positions in the creel from which samples were selected for loss-on-ignition characterisation of type-II E-glass fibre bundles (Wait, 2015).

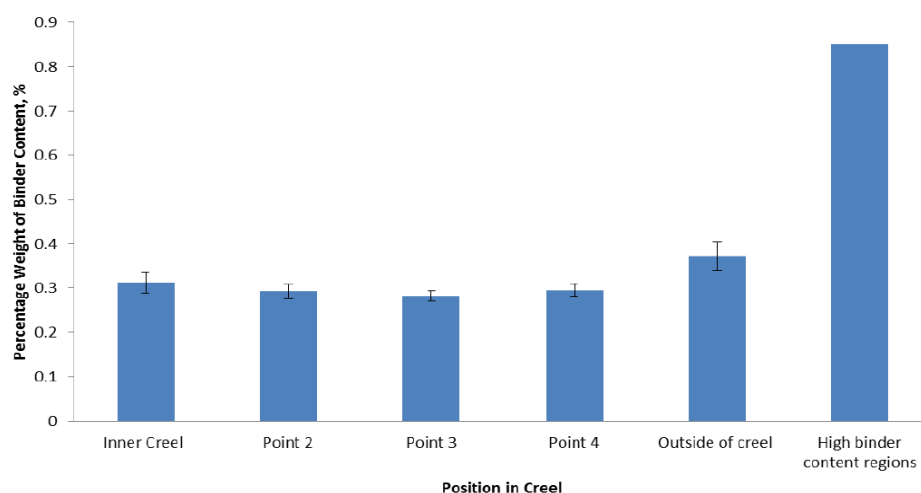


Figure 4.8 The average weight percentage of binder on type-II E-glass fibre bundles, with varying position in the fibre creel and selected 'high binder' regions. Reported by Wait, 2015.

The fibre architecture and the binder will have an influence on the ease of which the bundle can be spread. Moreover, it is also likely to have an influence on the tensile properties including the acoustic emission characteristics.

4.1.2 12K Type-II Carbon Fibre Bundles

With regards to the 12K type-II carbon fibres, the manufacturer's data sheet stated that there were approximately 12000 filaments with an average diameter of 7 μm (Toray Technical data sheet No. CFA-005). The tensile strength, failure strain and Young's modulus were reported to be 4510-4900 MPa, 1.9-2.1% and 221-240 GPa respectively. The binder content was stated to be 0.3%. These fibres as-supplied, were designated as "un-twisted" (private communication, Toray Carbon Fibre). However, Figure 4.9 shows a region (highlighted by the yellow box) where the fibres are twisted. Within the boxed area the presence off-axis and twisted filaments are indicated by the red and yellow lines respectively.

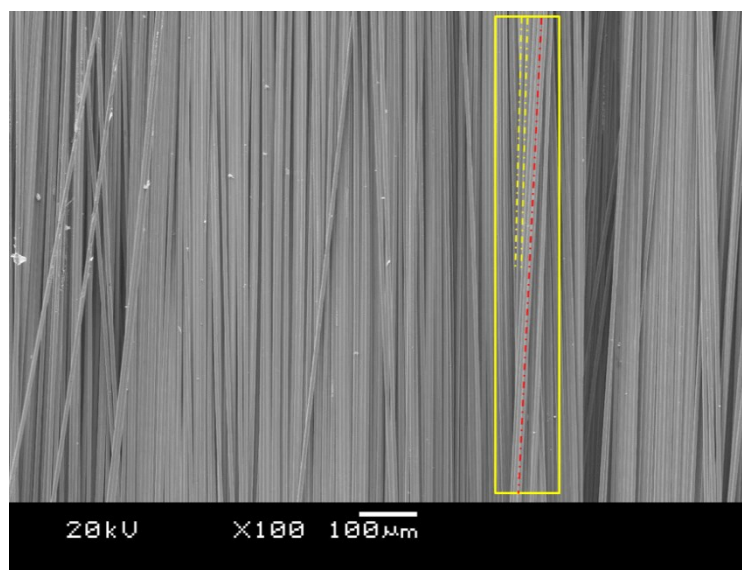


Figure 4.9 An SEM micrograph highlighting twisting (dashed yellow lines) and off-axis (dashed red line) filaments.

Figure 4.10 (i and ii) illustrates typical SEM micrographs for as-received type-II carbon fibre bundles. With reference to Figure 4.10(i), it was observed that there were a significant number of meandering filaments that seemed to weave their way into and out of the plane of the paper as a function of the length of the bundle. However, these fibres were supplied as “un-twisted”. The two regions highlighted in the blue circles, centre and top left, in Figure 4.10(ii) resemble possible debris or contamination incurred in the laboratory. The two regions indicated by the ellipses in blue, on the right in Figure 4.10(ii), resemble fracture of the binder.

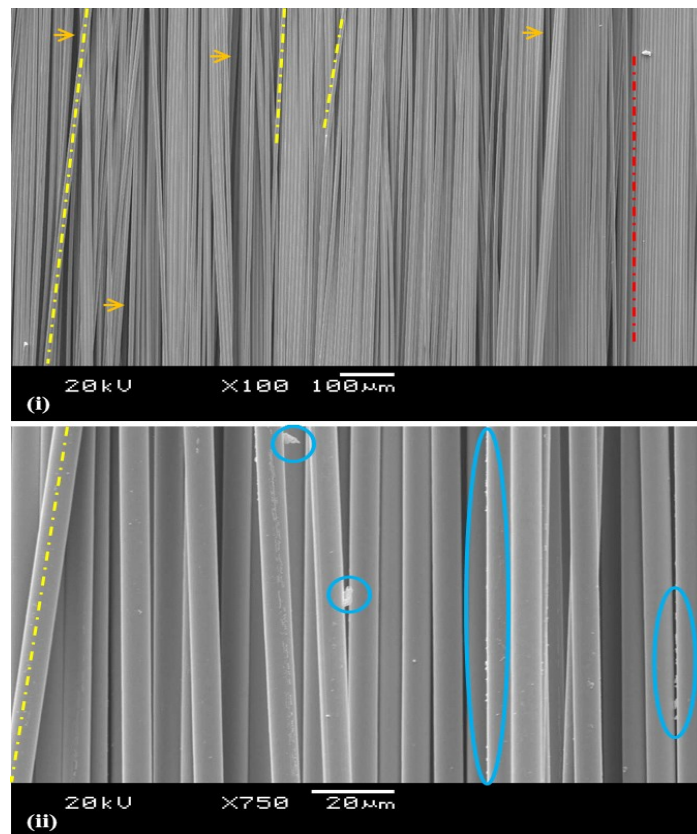


Figure 4.10 Micrographs illustrating the relative orientations of the filaments in type-II carbon fibre bundles: (i) low magnification image showing the presence of gaps (yellow arrows) and off axis fibres (dotted red lines) and fibres meandering into the plane of the paper (dotted yellow lines); and (ii) the regions highlighted in blue indicate the presence of debris; see text for details.

Twisting was not a significant observation with the type-II E-glass fibres. However, this was not the case with type-IIC carbon fibre bundles where a number of intrinsic twists and a greater number of meandering filaments were observed. The consequences of the twisted filaments were found to be an issue in achieving a uniform degree of spreading where the filament distribution across the width was homogenous. It also caused subsequent problems during impregnation and these issues were discussed in the Experimental Methods Section.

4.2 Fibre Spreading

4.2.1 E-glass Fibre Spreading

A significant volume of development work was undertaken in the first phase of the research to investigate various processing parameters involving glass fibres from two suppliers. These experiments were used to define the processing parameters for spreading single bundles of type-II E-glass fibre.

In the current report, the widths of the fibre bundle were measured at specified points along the rig (see Figure 3.1 in the Experimental Methods Section. However, it has been reproduced schematically in each Figure to enable ease of comparison). The measurement points (MP) are referred to as “MP: AR” (as-received), “MP: SP-Exit” (measured at the exit of the rig) and “MP: SP-Mandrel” (measured at the last point in the post-tension system as the fibre bundle traversed towards the mandrel).

It is emphasised that during each experimental series, ten individual measurements were taken to determine the average as-received bundle width. This was necessary because it was found that the width of the bundle was a function of its relative position from within the creel.

Figure 4.11 represents all of the as-received measurements of the width taken during the course of this study. As can be seen the width of the as-received fibre bundles were between 3.25-6.79 mm.

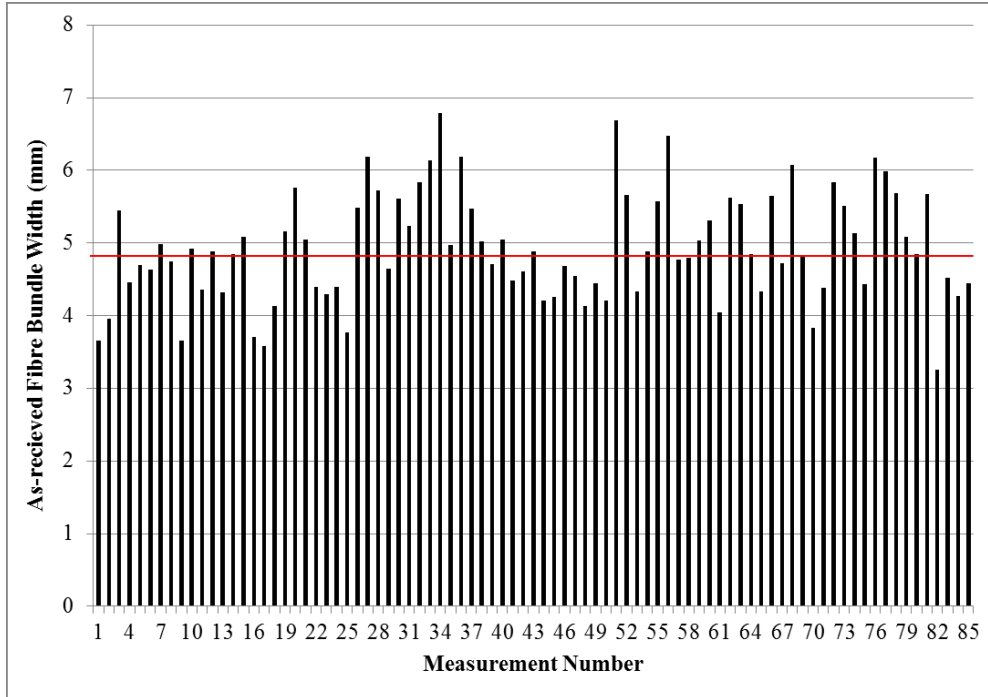


Figure 4.11 The measurements for the width of the as-received type-II E-glass fibre bundles used for the fibre spreading experiments.

Two sets of experiments were conducted for E-glass fibre spreading: (a) A set where the fibre bundle was spread to its maximum achievable width in the rig, before being reduced to a state with minimum segmentation. This was achieved using the width control bar in the post-tension system. (b) A set where the fibre bundle was spread to a state with minimum segmentation prior to entering the post-tension system.

Figure 4.12 presents the results of these experiments. The average width of the as-received fibre bundle measured prior to experiments (a) and (b) were 4.58 mm and 4.42 mm respectively. The average spread fibre bundle widths measured at SP-Exit for

experiments (a) and (b) were 80.19 mm (1652% increase) and 19.84 mm (349% increase) respectively. At the SP-Mandrel measurement point, the average spread fibre bundle width decreased in experiment (a) from 80.19 mm to 27.71 mm but, in contrast, an increase was observed in experiment (b) from 19.84 mm to 25.26 mm. These values were greater than any values reported in the literature (Irfan *et al.*, 2013; Murray, 2013; Murray *et al.* 2013; Diao *et al.*, 2014)

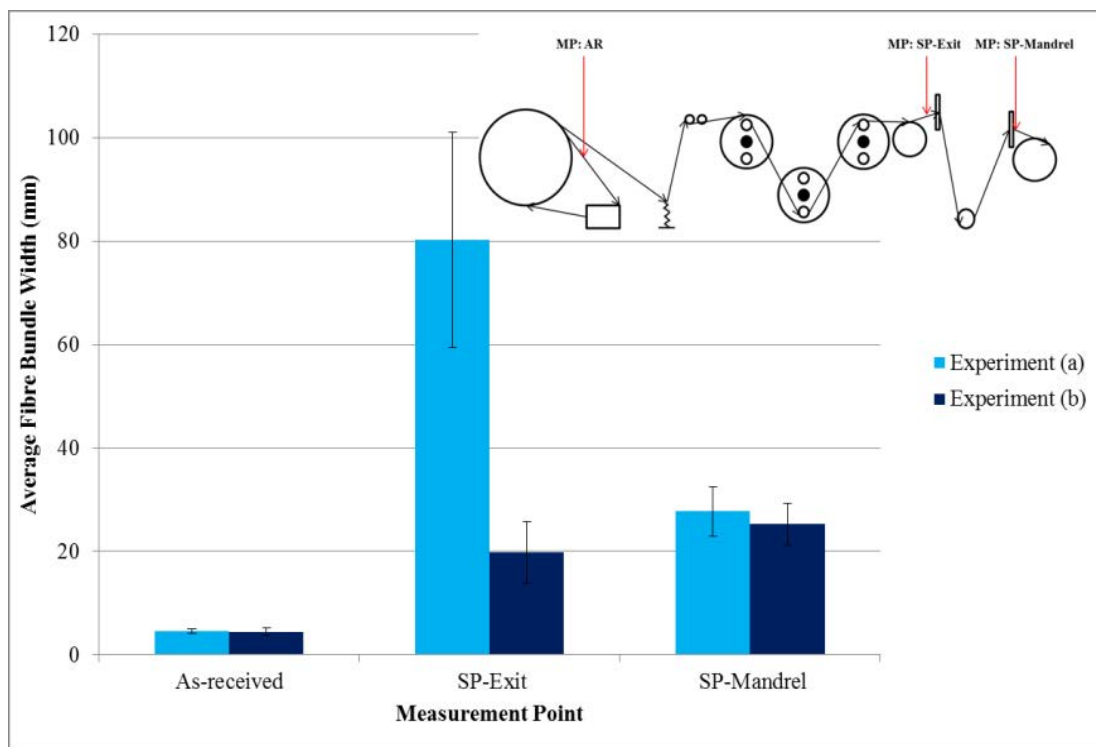


Figure 4.12 The average as-received and spread type-II E-glass fibre bundle widths measured during experiments (a) and (b).

The observed decrease in the spread fibre bundle width, in experiment (a), was a result of the significant coalescence of the filaments at the width control bar. This coalescence or gathering of the filaments, continued as the fibre bundle traversed to the mandrel. The net effect was a significant reduction in the segmentation. In the case of experiment (b), a near-parallel array of filaments was presented at the width control bar and this

trajectory continued through to the mandrel with a small increase in the spread width as it traversed two subsequent bars.

Figure 4.13 shows a photograph of a fibre bundle spread in experiment (a), at SP-Exit. The image shows that there was a large degree of segmentation in the fibre bundle. In the majority of cases it was observed that the edges of the fibre bundle were spread more than the centre. This is because once a divergence was induced this trajectory was exacerbated as it traversed towards the width control bar (Figure 3.6, Experimental Methods Section). With reference to filament damage, in some instances the odd fractured filament section or two was observed on the rollers in the third roller carrier-hub. It is emphasised that this occurrence was rare.

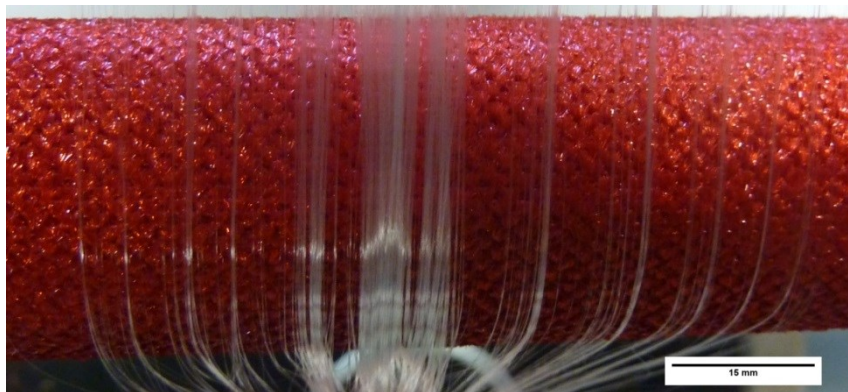


Figure 4.13 An example of fibre spreading achieved in experiment (a), at SP-Exit, where an average spread fibre bundle width of 80.19 mm of could be observed.

Figure 4.14 presents an example of the spread fibre bundle at the end of the post-tension system, at MP: SP-Mandrel. It can also be seen that the spreading is much more uniform compared to that observed in Figure 4.13. Figure 4.14 therefore presents a spread fibre bundle that met the criteria for an ideal spread fibre bundle.

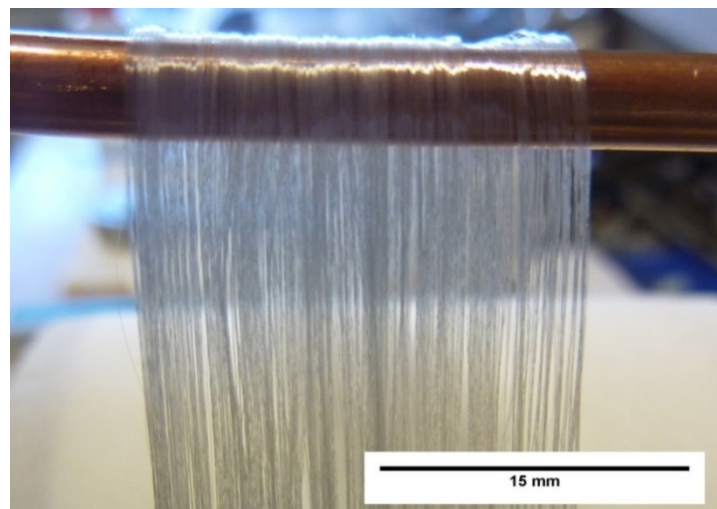


Figure 4.14 An example of the average spread fibre bundle width at the exit of the post-tension system.

4.2.1.2 Post-processing Spread E-glass Fibres

After the type-II E-glass fibre bundle was spread in the rig, specified lengths were subjected to a post-process operation to improve further the spreading, and to rectify manually, any minor segmentation. This process was described previously in Section 3.2.2.

Figure 4.15 presents a summary of the relative widths of the as-received, spread (measure point SP-Mandrel) in the fibre spreading rig, and the final width of the post-processed type-II E-glass fibre bundle. With reference to Figure 4.15, the average as-received, MP: SP-Post-tension and post-processed fibre bundle widths were 4.58 mm,

27.71 mm and 48.35 mm respectively. The error bars demonstrate clearly that post-processing was capable of generating bundle widths that were consistent.

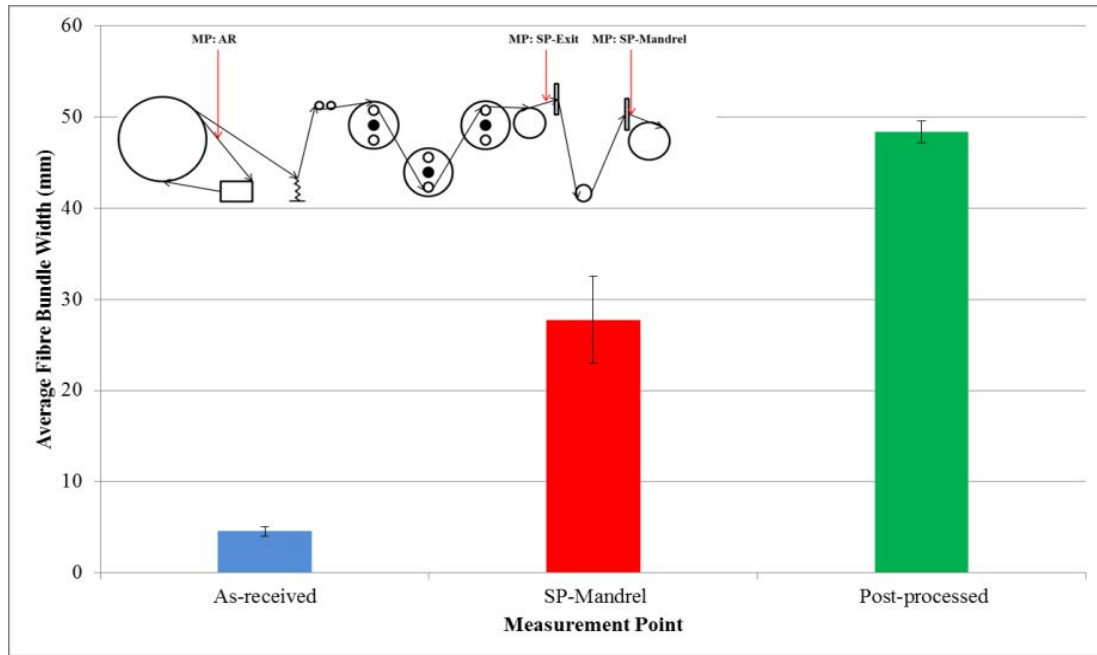


Figure 4.15 A graph showing the average fibre bundle width measured at MP: AR, MP: SP-Exit and MP: SP-Mandrel.

Figure 4.16(i) presents an example of the as-received fibre bundle. Figure 4.16(ii) shows a representative image of a spread fibre bundle after automated spreading using the rig. Figure 4.16(iii-v) represent spread fibre bundles after post-processing (iii).

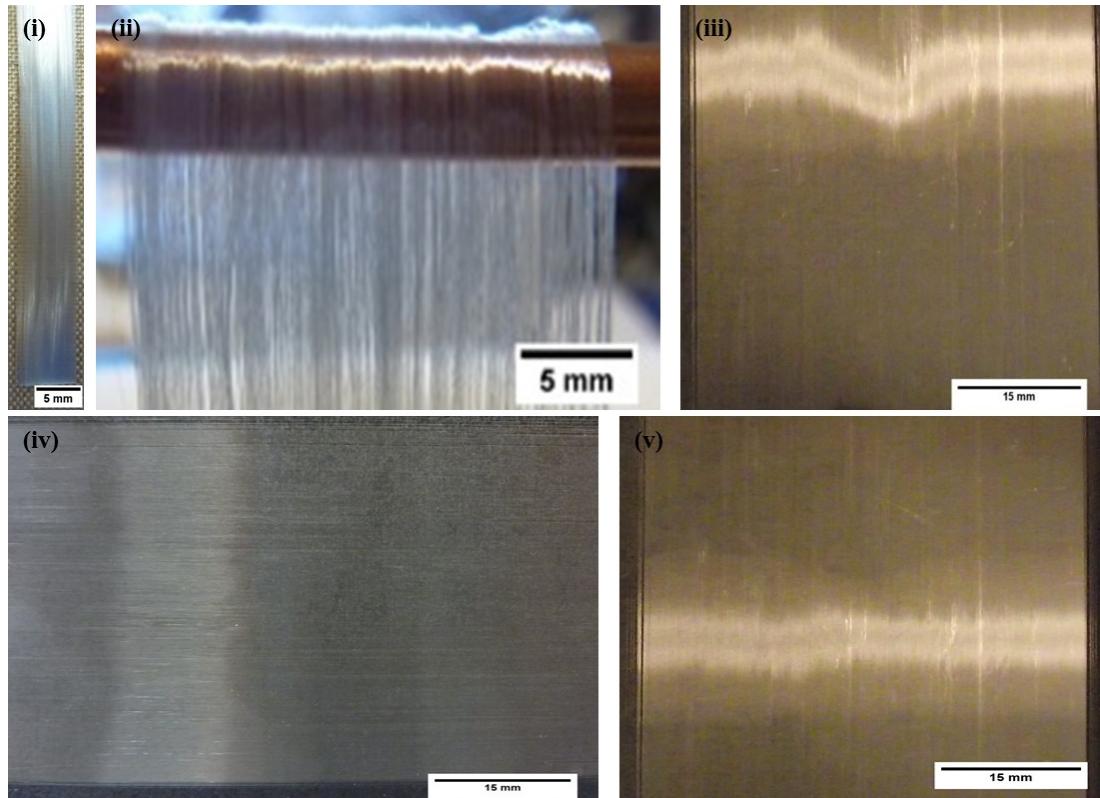


Figure 4.16 Representative photographs of type-II E-glass fibre bundles (i) as-received, (ii) after automated spreading and (iii-v) after post-processing.

A representative cross-section of a post-processed spread E-glass fibre bundle is presented in Figure 4.17. This demonstrates clearly that it was possible to produce mono-filament or single-layer E-glass composites, using the technique developed in this study. This has obvious implications to hybridisation, as it provides a mean of producing intimately mixed hybrid fibre composites.

It was observed that when impregnating the post-processed spread E-glass fibre bundles, there was a significant reduction in the through-thickness impregnation time.

The degree and extent of spreading achieved in this project surpasses that reported in the literature.

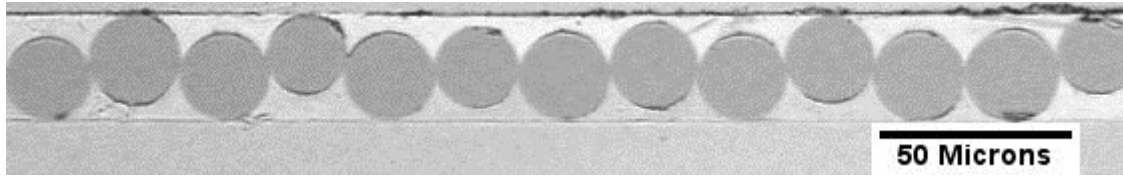


Figure 4.17 A micrograph presenting a typical cross-section of a post-processed type-II E-glass fibre bundle.

4.2.2 Spreading Carbon Fibre Bundles

Similar process parameters were used for spreading type-IC and type-IIC carbon fibre bundles. However, in this instance the micro-fibre fabric was not used as it led to significant damage to the carbon filaments. The experimental set-up, for spreading carbon fibre bundles was presented in the Experimental Method chapter.

In addition to the fibre spreading rig, a vacuum spreading device was positioned downstream from the exit roller but in close proximity to the mandrel on the haul-off unit. The vacuum spreading device was powered by a variable speed vacuum cleaner. The designs of the vacuum spreading devices, prototype-I and prototype-II, were described in the Experimental Method chapter. As with the E-glass experiments, ten individual measurements were taken during each experimental series, to determine the average as-received fibre bundle width.

Figure 4.18 and Figure 4.19 represent the as-received fibre bundle widths for type-IC and type-IIC fibre bundles respectively. The as-received widths were between 2.33-3.25 mm and 5.23-9.81 mm for type-IC and type-IIC carbon fibre bundles respectively.

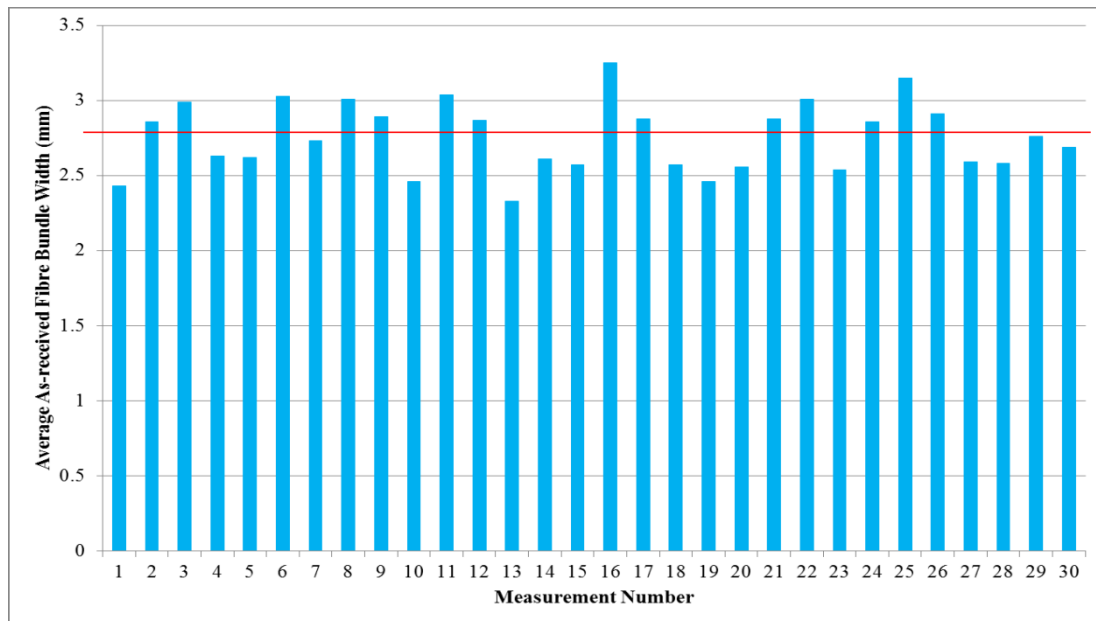


Figure 4.18 The measured widths for the as-received type-IC carbon fibre bundles used for the fibre spreading experiments with prototype-I; the red line indicates the average width.

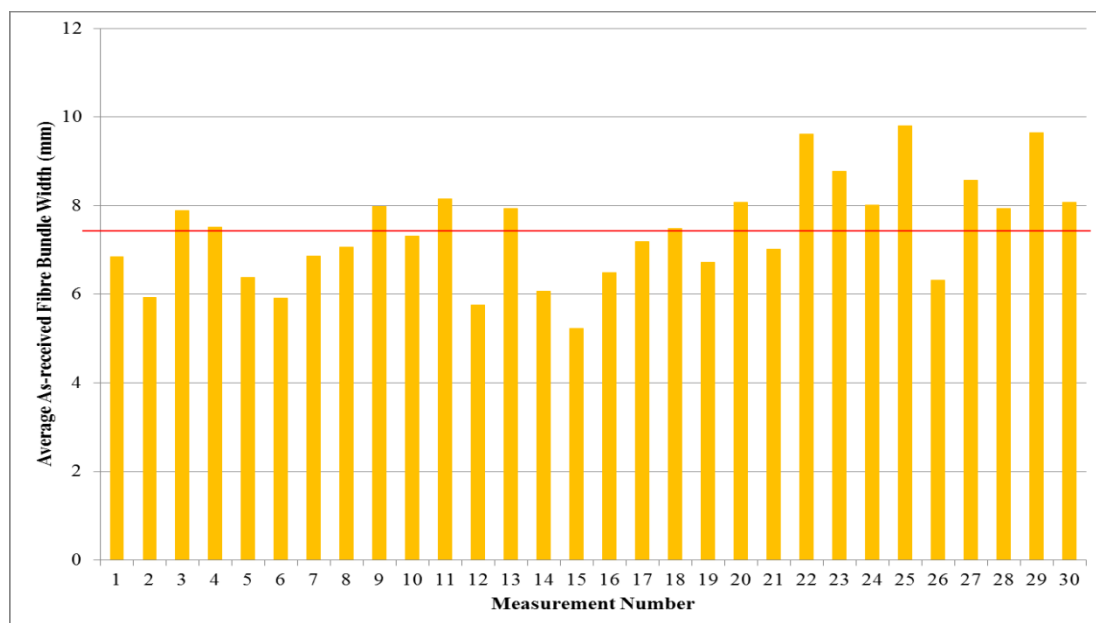


Figure 4.19 The measured widths for the as-received type-IIC carbon fibre bundles used for the fibre spreading experiments with prototype-II; the red line represents the average width.

The results from the type-I and type-II carbon fibre spreading experiments are presented in Figure 4.20, where it can be seen that significant fibre spreading was achieved. Furthermore, a greater average spread fibre bundle width was achieved when spreading type-IIC fibre using prototype-II.

The average as-received fibre bundle widths were 2.76 mm and 6.97 mm for the type-IC and type-IIC carbon fibre bundles respectively. The average spread fibre bundle widths achieved for the type-IC and type-IIC were 23.09 mm and 84.15 mm respectively.

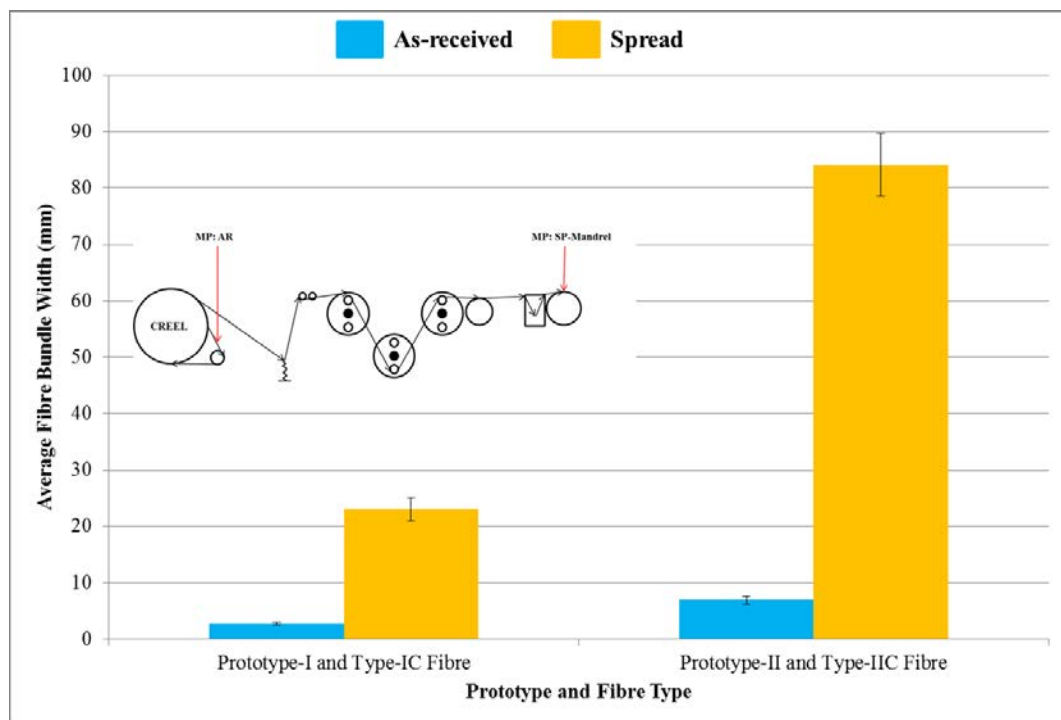


Figure 4.20 Results of fibre spreading experiments using type-IC and type-IIC carbon fibre bundles with prototype-I and prototype-II respectively.

With respect to the spreading carbon fibre bundles reported in the literature, Sihn *et al.* (2007), El-Dessouky & Lawrence (2013) and Diao *et al.* (2014) have reported spread bundle widths of 20 mm, 25 mm and 18-22 mm respectively; the respective reported as-received measurements were 6 mm, 5 mm and 5-7 mm. These values correspond to

percentage spreading of 233%, 400% and 233% respectively. El-Dessouky & Lawrence (2013) and Diao *et al.* (2014) used the same type of carbon fibres (T700SC-12K-60E) as used in the current study. The average maximum fibre spreading reported for type-IIC carbon fibre in the literature was 400%, whereas the average maximum ideal state of spreading in this study was 1121%.

Figure 4.21, Figure 4.22, Figure 4.23 present photographic evidence of the degree of spreading reported by Sihni *et al.* (2007), El-Dessouky & Lawrence (2013) and Diao *et al.* (2014) respectively. In each Figure, the photographic evidence presented is compared to a representative image of the degree of spreading achieved in the current study. With reference to Figure 4.21, Figure 4.22 and Figure 4.23, there was a significant difference between carbon fibre spreading reported in the literature, and, that achieved in this study.

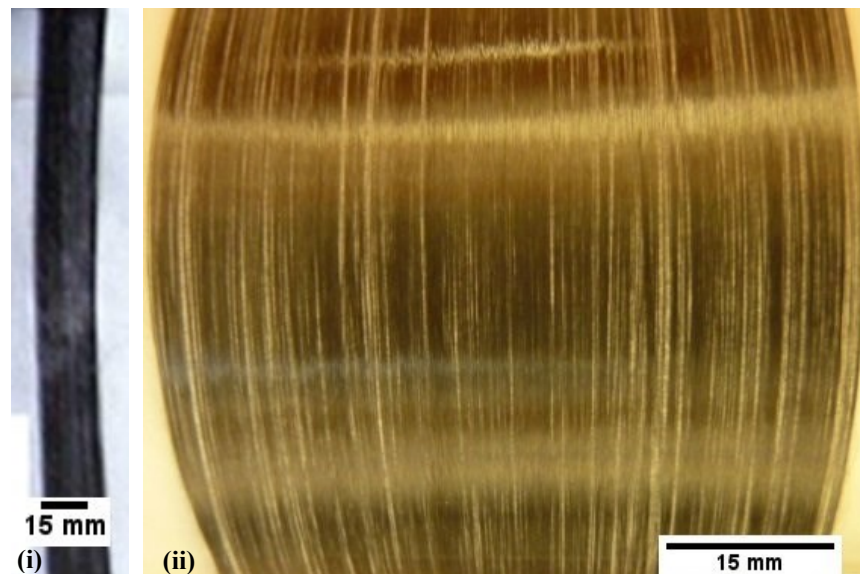


Figure 4.21 Photographs showing a comparison of the degree of spreading achieved by: (i) Sihni *et al.* (2007); and (ii) the current author.

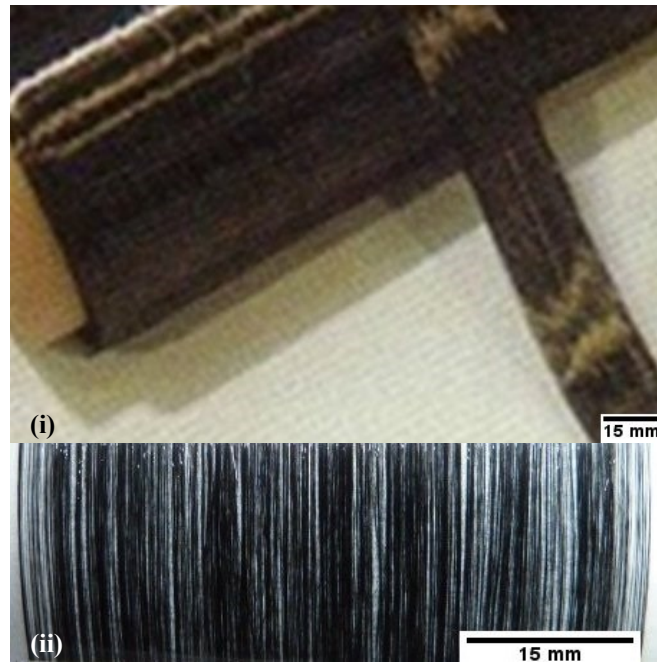


Figure 4.22 Photographs showing a comparison of the degree of spreading achieved by: (i) El-Dessouky & Lawrence (2013) and (ii) the current author.

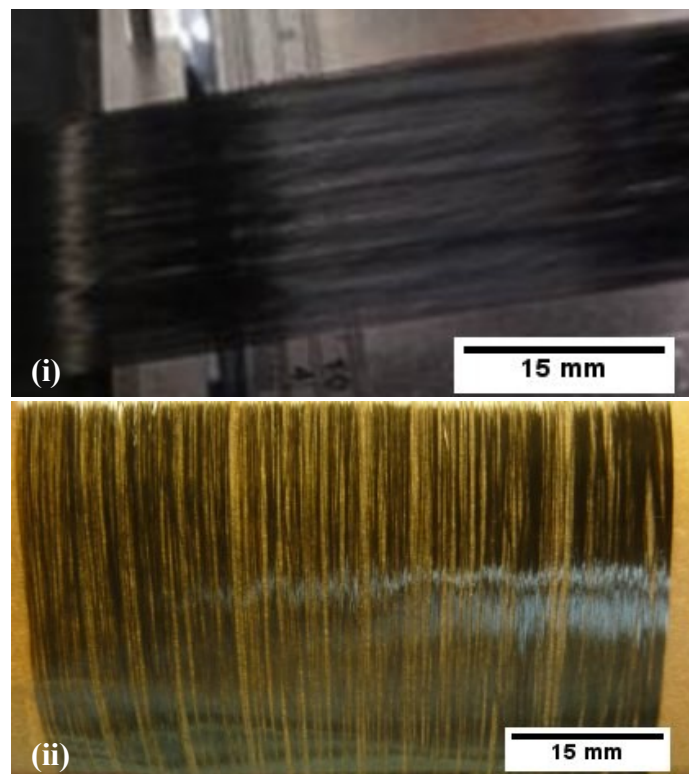


Figure 4.23 Photographs showing a comparison of the degree of spreading achieved by: (i) Diao *et al.* (2014) and (ii) the current author.

On inspecting Figure 4.21(ii), Figure 4.22(ii) and Figure 4.23(ii), it is clear that the negative aspect of spreading the bundles to the extents shown in these micrographs has resulted in segmentation and an uneven distribution in the fibre volume fraction. Obviously the extent of spreading can be selected as required for specified applications.

Sihn *et al.* (2007) stated that, for a 24K carbon fibre bundle, the number of filaments in the through-thickness direction reduced from 24 filaments to 6 filaments after spreading. Figure 4.24 presents a micrograph of an as-received type-IIC 12K carbon fibre composite from the current study where line-(i) represents an example of a filament count in the through-thickness direction. The average value for the number of filaments in the through-thickness direction in the as-received state, obtained from 30 individual measurements, was 17 filaments. It is accepted that some of the filaments may have changed their spatial orientation during impregnation.

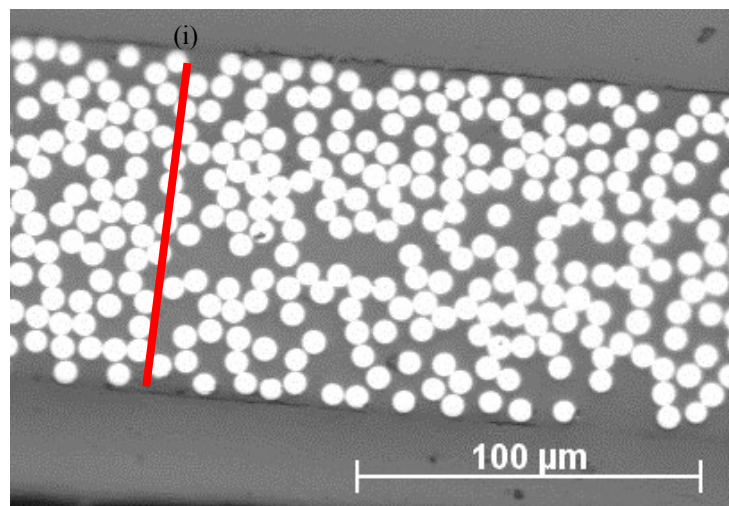


Figure 4.24 A microscope image of the as-received type-IIC carbon fibre used in the current study; (i) is a representative line along which filaments were counted.

Bearing in mind the segmentation shown in Figure 4.21(ii), Figure 4.22(ii) and Figure 4.23(ii), Figure 4.25 shows a series of micrographs of spread single-layer type-II carbon fibre composites. It is emphasised that the degree of fibre spreading can be controlled and the variations in the V_f shown in Figure 4.25(i-vi) is not an issue. A fine balance is required between the maximum degree of fibre spreading, the potential damage and segmentation, and the ease of hybridisation. In other words, the greater the extent of spreading the easier it would be to achieve a highly dispersed intra-filament hybrid composite. This is discussed further in Section 4.5.

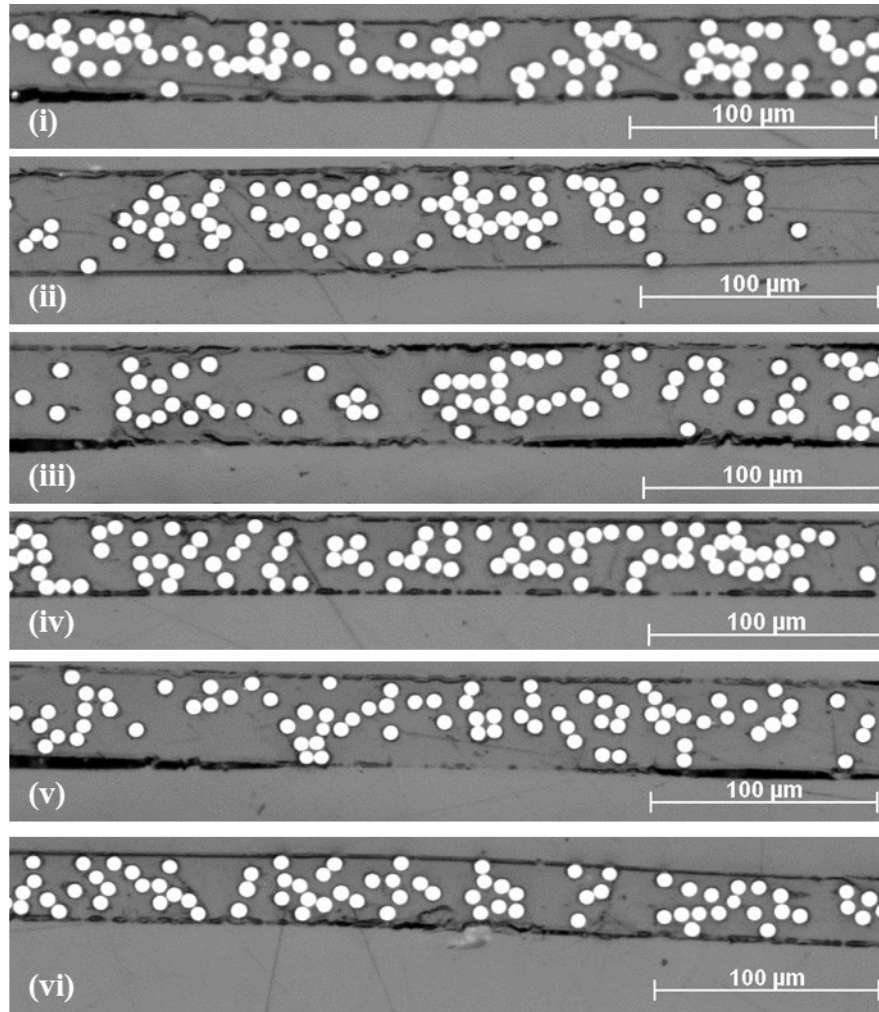


Figure 4.25(i-vi) Representative micrographs showing the variation in V_f in single-layer spread type-II carbon fibre composites.

4.3 Mechanism of Fibre Spreading

4.3.1 Tension-Release

The intermittent application of tension to the fibre bundle was a key factor for the spreading of E-glass and carbon fibre bundles. The cyclic application of tension was created by traversing the fibre bundle over the rollers on the rotating carrier-hubs. The highest tension was induced in the fibre bundle when the rollers were at their maximum position as shown schematically in Figure 4.26(i). As the roller carrier-hub rotated, the tension was progressively released as the rollers reached their minimum position as shown schematically in Figure 4.26(ii). The rotation of the roller carrier-hubs resulted in a sinusoidal application of the tension to the fibre bundle; this is referred to as the “tension-release” (Irfan *et al.*, 2012). In other words, as the fibre bundle traversed through the fibre spreading rig, it experienced periodic high and low-tension.

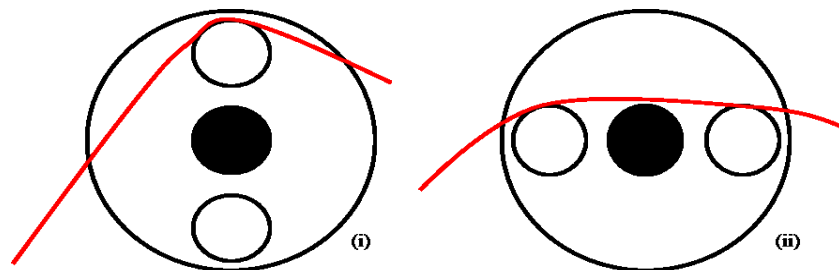


Figure 4.26 A schematic illustration showing the roller carrier-hub positions resulting in the (i) maximum and (ii) minimum tension respectively.

4.3.2 Mechanisms Associated with Spreading E-glass Fibre Bundles

The mechanisms of fibre spreading associated with E-glass fibre bundles will be discussed here with reference to Figure 4.27. This Figure was presented previously as Figure 3.1 in the Experimental Method chapter. However, in Figure 4.27 representative photographs of the degree of fibre spreading at different stages have been included.

In Figure 4.27(a), the creel stand is represented by item-(i). Item-(ii) represents the motorised-(iii) E-glass fibre creel where the pay-out was via drawing the fibre bundle from the outer circumference. The as-received fibre-(iv) was then traversed, via a D-eye ring-(v) into a pre-tension system-(vi) which housed a series of rollers. The function of this pre-tension system was to induce the desired tension in the fibre bundle and to aid the initial de-cohesion of the binder. In addition, the pre-tension system-(vi) and the exit roller-(vii) enabled a uniform fibre trajectory to be maintained. Upon traversing the pre-tension system exit roller-(vii), the fibre bundle was doubled back around the fibre creel to minimise the traversing action as it was unspooled. This was necessary because the creel was produced by the manufacturer by winding the fibre on to a mandrel where it is traversed left and right as it is wound. Hence, unwinding the creel resulted in the fibre bundle traversing left and right as it was unwound.

The fibre bundle was then traversed through a spring-arm-(viii) which maintained uniform tension on the bundle, as the sections of fibre bundle upstream were subject to the cyclic tension-release. Item-(ix) is a set of rollers whose position was set to enable the fibre bundle to traverse to the first roller carrier-hub in the desired trajectory. Figure 4.27(b) shows the fibre spreading rig containing the three roller carrier-hubs-(xiii). Item-(xvi) is a U-shaped device fashioned from a copper bar with a diameter of 5 mm. Its function was to control the width of the spread fibre bundle before it was wound on to the mandrel (item-xx).

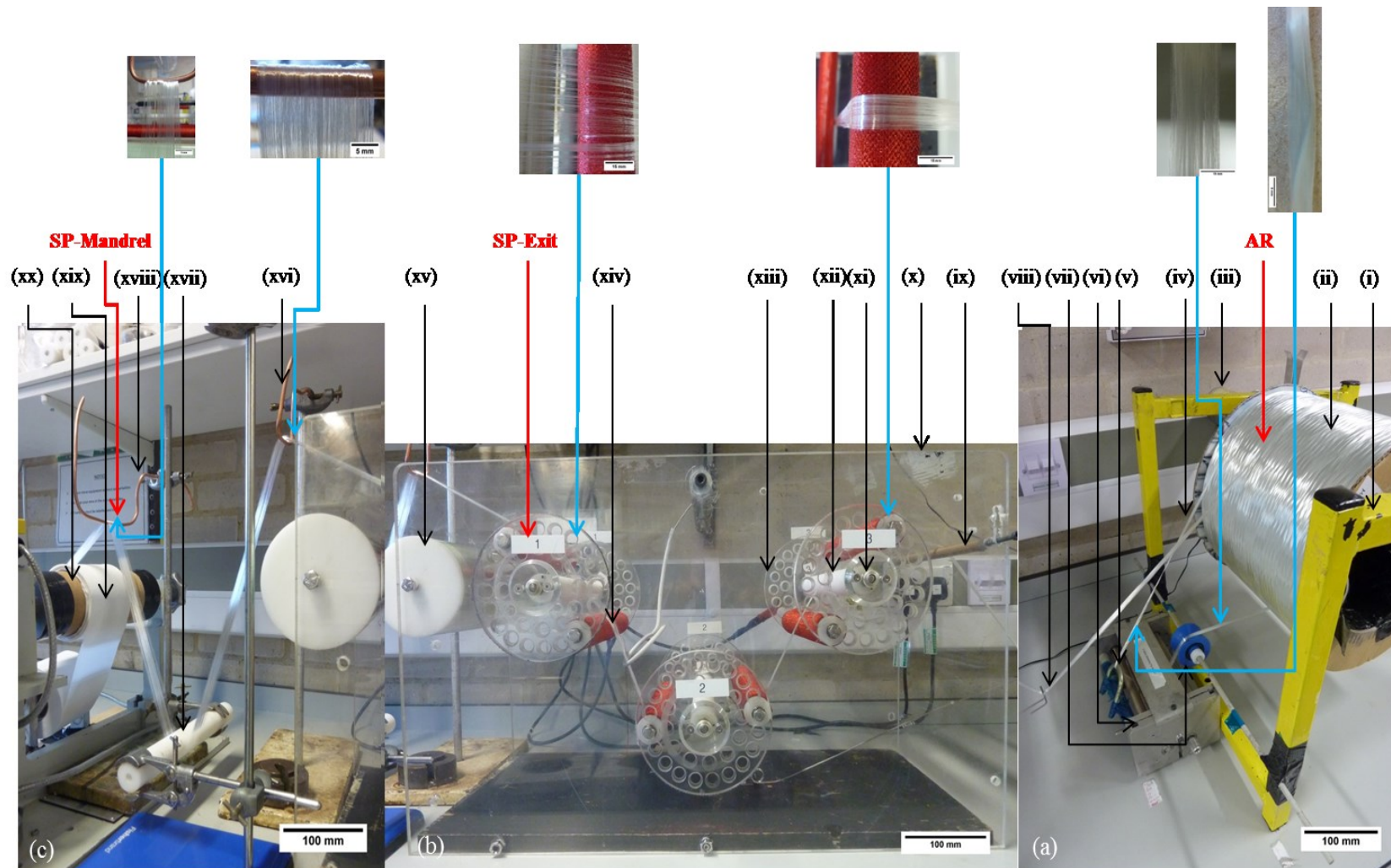


Figure 4.27 A photograph showing the fibre spreading rig for E-glass along with representative images of the degree of fibre spreading achieved at specified positions during a fibre spreading operation.

The following section proposes a mechanism to account for the spreading of the type-II E-glass fibre bundles.

The average width of the as-received type-II E-glass fibre was discussed previously. The width of the fibre bundle upon exiting the pre-tension system was 8.13 mm. The serpentine trajectory of the fibre bundle in the pre-tension system enabled partial de-cohesion of the binder, and, the contact of the rollers in tandem with the intermittent tension from the upstream bundle enabled a small degree of spreading, as some of the filaments on the top layer were forced into the interstitial spaces below. As the fibre bundle traversed through the spreading rig (Figure 4.27(b)), the fibre bundle width increased as a result of the combined influence of the cyclic tension-release, and the combing action of the micro-fibre fabric.

The cyclic contact, created by the tension-release, resulted in periodic combing where the micro-fibre fabric brushed the fibre bundle intermittently. This had four major effects. Firstly, the micro-fibres penetrated the bundle as shown in Figure 4.28. Since the contact was intermittent and momentary, the possibility of filament entanglement and snagging on the roller was minimised. This intermittent combing action tended to gently tease apart the filaments in the bundle. Secondly, the combing action enabled further de-cohesion of the binder. Thirdly, it straightened some of the meandering and off-axis filaments, creating a more homogenous fibre distribution and spatial architecture. Finally, the cyclic tension-release enabled the filaments on the top layers of the fibre bundle to drop into the interstitial spaces of the filament layers below; this is presented schematically in Figure 4.29.

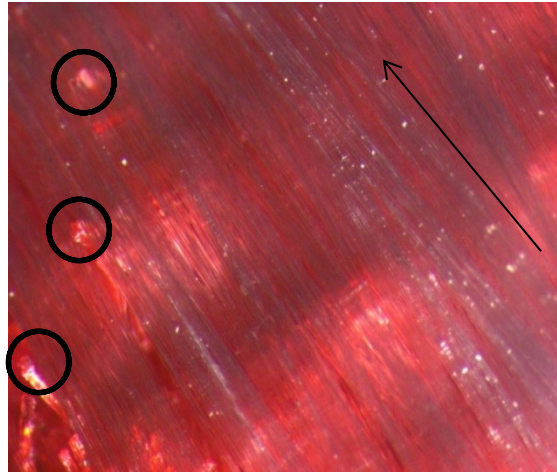


Figure 4.28 A spread type-II E-glass fibre bundle traversing over a micro-fibre fabric covered roller. The black circles indicate selected regions where the micro-fibre filaments had penetrated the fibre bundle.

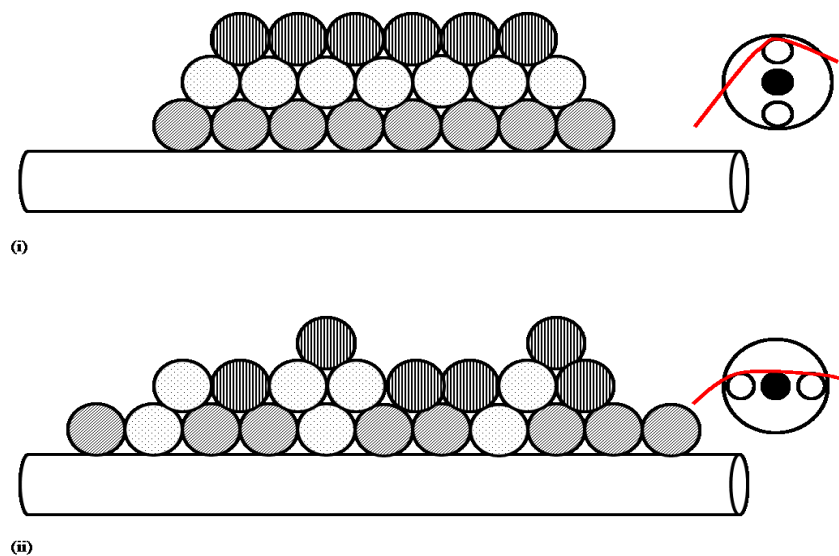


Figure 4.29 A schematic illustration showing one of the mechanisms of fibre spreading caused by tension-release: (i) high-tension; and (ii) low-tension.

Figure 4.30(i-iii) show an illustration of the mechanism of fibre spreading caused by the combing action of the micro-fibre fabric as the bundle was traversed over it, at the first (i), second (ii) and third (iii) roller carrier-hubs.

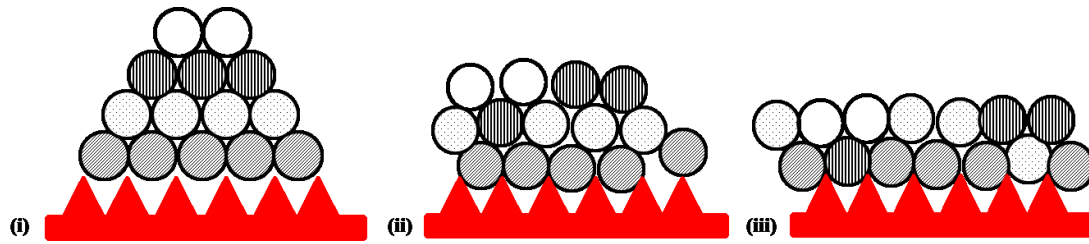


Figure 4.30(i-iii) Schematic illustrations of the fibre spreading mechanism associated with the micro-fibre fabric at the first (i), second (ii) and third (iii) roller carrier-hubs.

As three roller carrier-hubs were used, each of which housed two micro-fibre fabric covered rollers, the degree of spreading was observed to increase from the first to third roller carrier-hub. A maximum fibre bundle width of 80.19 mm could be achieved however, the fibre bundle exhibited extensive segmentation between the individual filaments. As the degree of fibre spreading increased, it became more difficult to produce a spread fibre bundle with the filaments in a linear array. In other words, if a diverging array was presented from the first to the third roller carrier-hub, this divergence will be carried through to the mandrel. This will result in different tensions in the filaments. To prevent this, the width-control bar-(xvi) was introduced along with two bars representing the post-tension system; see Figure 4.27(c).

4.3.3. Mechanism Associated with Carbon Fibre Spreading

With reference to Figure 4.31 the mechanism of spreading for type-IIC carbon fibre will be discussed. This was presented previously as Figure 3.17, however in this instance representative photographs to demonstrate the degree of fibre spreading at specified positions along the rig have been added.

Item-(i) shows the creel stand, item-(ii) represents the carbon fibre creel from which the as-received fibre bundle-(iii) with an average width of 6.97 mm was fed from the outer

circumference. The as-received fibre bundle then traversed to a pre-tension system-(iv) consisting of a pulley. This pulley enabled the as-received fibre bundle to be doubled back around the fibre creel, and minimised the traversing effect during unspooling. The carbon fibre was fed through a spring arm which maintained uniform tension, as the sections of fibre bundle upstream were subjected to the tension-release cycle.

Item-(vi) represents a series of rollers over which the fibre bundle traversed to ensure that it was presented to the first roller carrier-hub-(viii) in the desired trajectory. Presented in Figure 4.31(b) is the fibre spreading rig consisting of a total of three roller carrier-hubs; in the case of carbon fibre spreading the cyclic tension-release (previously described) was achieved through the rotation of the third roller carrier-hub only.

Item-(xiii) shows the prototype-II vacuum spreading device in which the sinusoidal tension cycle and air-flow resulted in lateral spreading of the carbon fibre bundle. The maximum average spread fibre bundle width achieved was 84.15 mm. This could be controlled by controlling the magnitude of the tension and air velocity experienced by the fibre bundle. A proposal for the mechanism of spreading carbon fibre is presented in the next section.

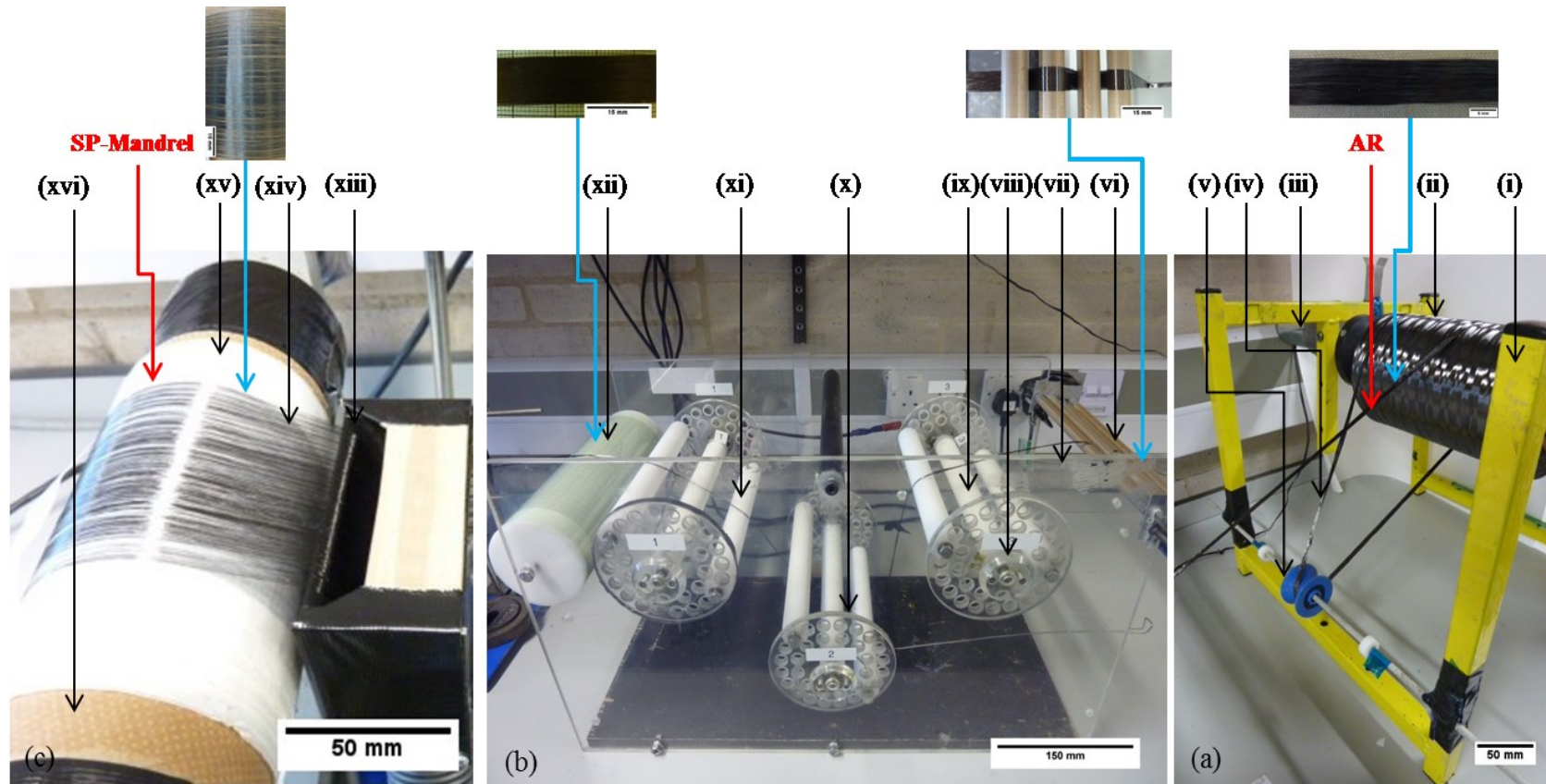


Figure 4.31 The fibre spreading rig for carbon fibre bundles:(a) the pay-out system; and (b) the fibre spreading rig; and (c) the vacuum spreading device and haul-off unit. Representative images of the degree of fibre spreading throughout the rig have been added.

The varying tension in the fibre bundle in relation to the position of the roller carrier-hub created periods in which the filaments were tension-free. Figure 4.32, Figure 4.33 and Figure 4.34 shows the vacuum-assisted spreading when using prototype-I along with type-IC carbon fibre bundles. At the maximum roller position (Figure 4.32), the tension in the fibre bundle was high as it traversed across the aperture. It can be seen that the bundle is straight and taught across the aperture.

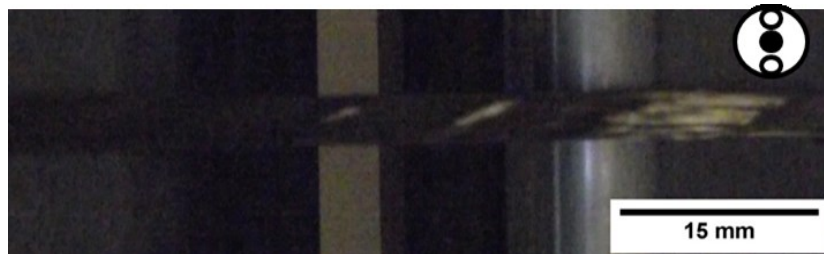


Figure 4.32 A representative image of the fibre bundle during the high-tension period as the rollers are positioned vertically (see insert).

As the roller carrier-hub rotated, there was a progressive decrease in the tension. The consequence of this on the trajectory on the fibre bundle over the aperture is shown in Figure 4.33. As the tension started to decrease, the fibre bundle began to be sucked into the aperture. Furthermore, the filaments moved sideways (laterally).

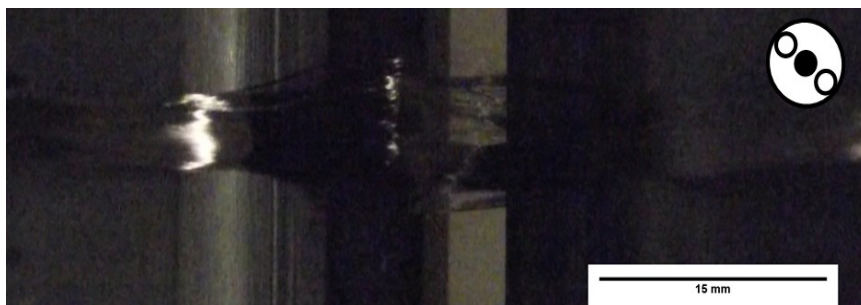


Figure 4.33 A representative image of the fibre bundle beginning to relax as the tension begins to fall.

As the tension was decreased to its lowest magnitude, the fibre bundle was sucked deeper into the aperture. The extent of lateral spreading increased as seen in Figure 4.34. As the tension is reapplied (due to the rotation of the roller carrier-hub) the spread fibre bundle was hauled up to the top of the aperture. The net effect of this was a decrease in the observed width when compared to the situation when the bundle was at the bottom of the aperture.



Figure 4.34 A representative image of the low tension state of the type-IC carbon fibre during spreading experiments with prototype-I.

This decrease in the extent of spreading as the fibre bundle was hauled back to the top of the aperture was addressed in prototype-II with the introduction of a “floating” bar. The addition of floating bar to prototype-II enabled the capture of the maximum spreading, at the point at which the tension was at its minimum. This will be discussed later. Figure 4.35 presents the position of the bar, with relation to the position of the roller carrier-hub at its maximum (i) and minimum (ii) positions.

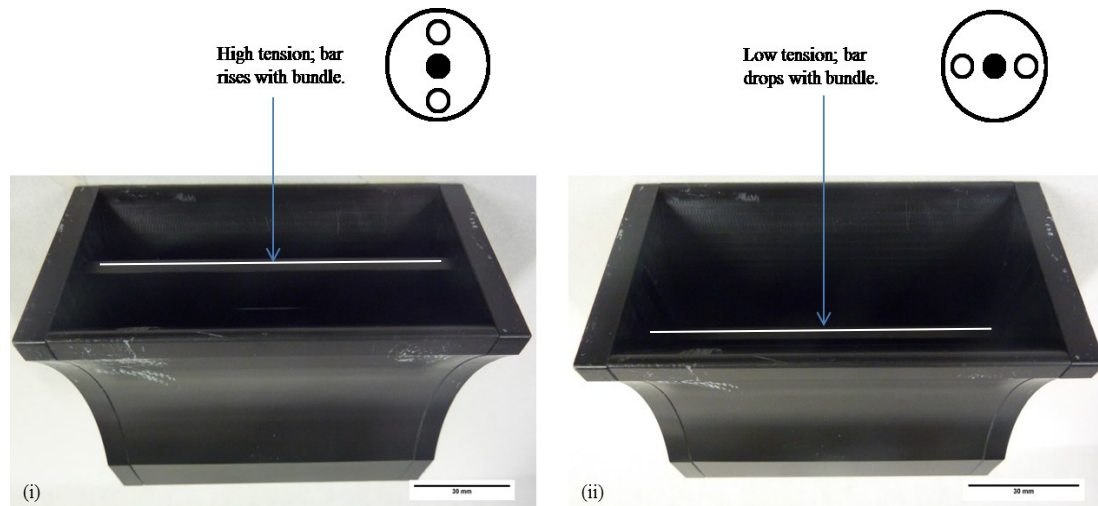


Figure 4.35 Photographs of the position of the floating bar in prototype-II with respect to the position of the roller carrier-hub during: (i) maximum tension: and (ii) minimum tension in the fibre bundle. The superimposed white lines highlight the relative positions of the bar.

The proposed mechanism for carbon fibre spreading using the two vacuum-spreading devices is discussed in the next section.

4.3.3.1 Differential Pressure

A series of experiments were conducted to determine the differential pressure profiles of prototype-I and prototype-II under four conditions; (i) an open aperture, (ii) a solid substrate across the aperture in the direction of fibre bundle traverse, (iii) a tensioned fibre bundle, and (iv) a spread fibre bundle.

The experimental method for measuring the differential pressure was previously outlined in the Experimental Method chapter. The vacuum inlet for prototype-I was positioned to one side (measurement point 1) and for prototype-II it was located at the centre (measurement point 4). Figure 4.36 presents the differential pressure profiles for prototype-I and prototype-II with an open aperture. It was observed that the differential pressure across prototype-I fluctuated by around 5 Pa. In contrast, the average differential pressures measured at the edges (point 1 and 7) were -76.1 Pa and -79.5 Pa

respectively. This was considerably lower than the average differential pressure for the rest of the aperture which was between -33.9 Pa and -26.4 Pa.

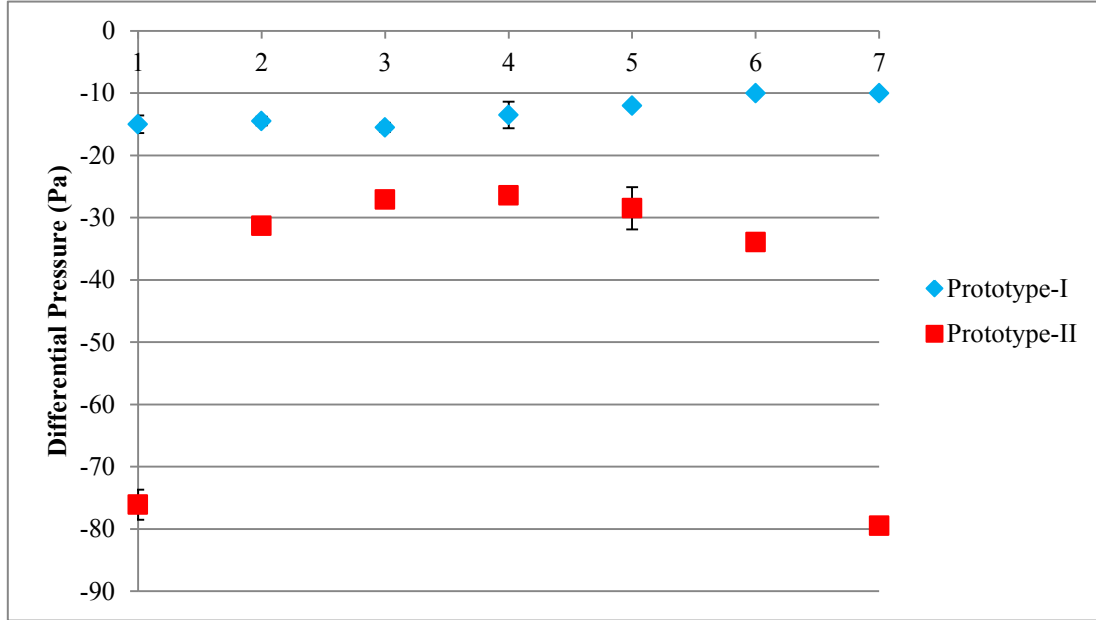


Figure 4.36 Differential pressure profiles for prototype-I and prototype-II under condition (i): an open aperture.

Figure 4.37 presents the results for differential pressure measurements with a solid substrate positioned centrally across the aperture in the direction of the fibre bundle traverse. A small change was observed in the differential pressure profile for prototype-I. At the central measurement point-4, the average differential pressure decreased to -7 Pa with the average differential pressure across the rest of the aperture being measured at -19.75 Pa. By contrast, a large change in the differential pressure profile was observed for prototype-II. No difference in the pressure was observed at the central measurement point-4. In contrast to the open aperture condition, there were lower partial pressures at the edges of the aperture and the edges of the substrate. The differential pressures measured at the edges of the substrate were -85.2 Pa and -81.8 Pa.

In the region between the substrate and the sides of the aperture, the partial pressure was slightly lower than the previous condition.

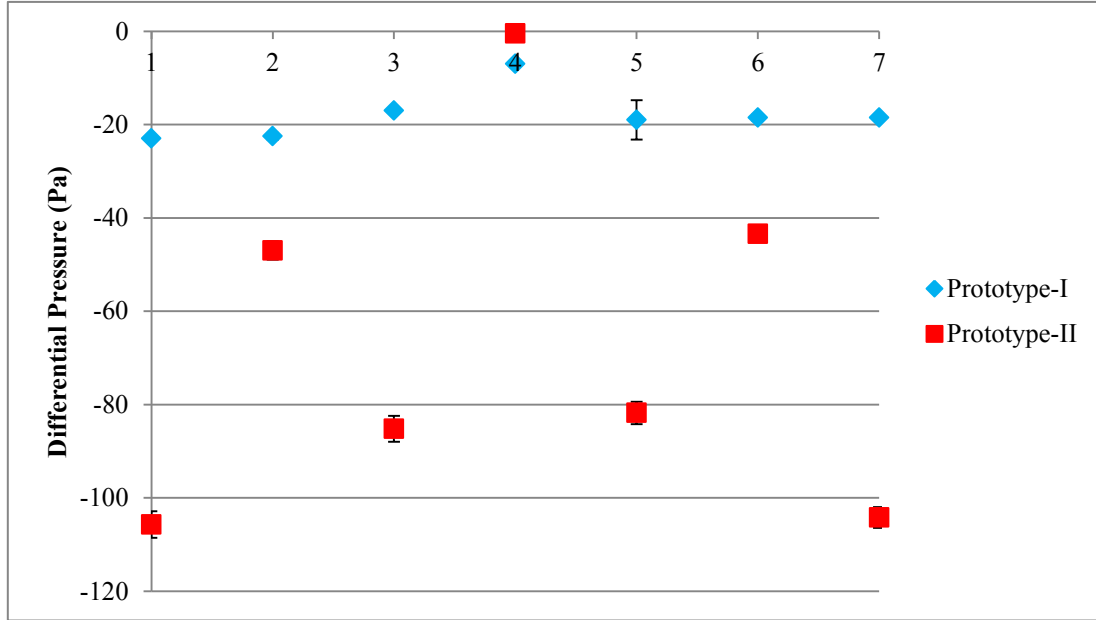


Figure 4.37 Differential pressure profiles for prototype-I and prototype-II with a solid substrate positioned across the aperture.

In order to determine the differential pressure profile during fibre spreading the measurements were made with a tensioned fibre bundle or a spread fibre bundle across the aperture and the results are presented in Figure 4.38 and Figure 4.39. In the case of prototype-I there was little difference observed between the profiles for a tensioned and spread fibre bundle. However in the case of prototype-II, it was observed that the differential pressure profile measured for the tensioned bundle condition was similar to that observed with the solid substrate. The pressures measured at the edges of the tensioned bundle were marginally lower than those measured at the centre. This was also the case for measurements taken in at the sides of the aperture.

The profile measured for the spread fibre bundle was seen to be very similar to the open aperture condition.

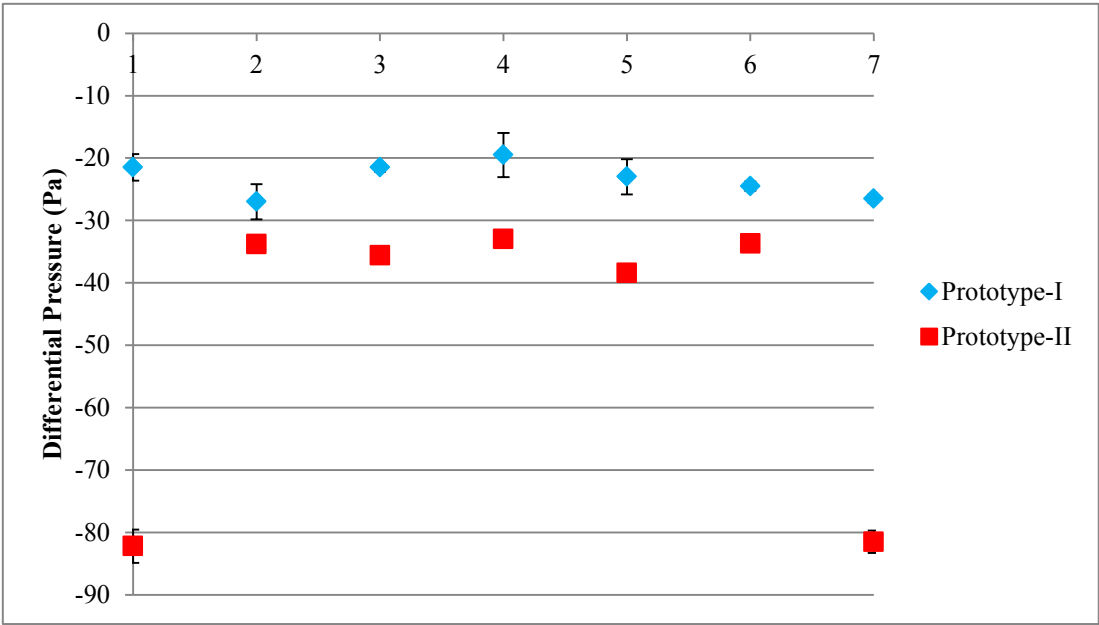


Figure 4.38 Differential pressure profiles for prototype-I and prototype-II with a tensioned fibre bundle positioned across the aperture.

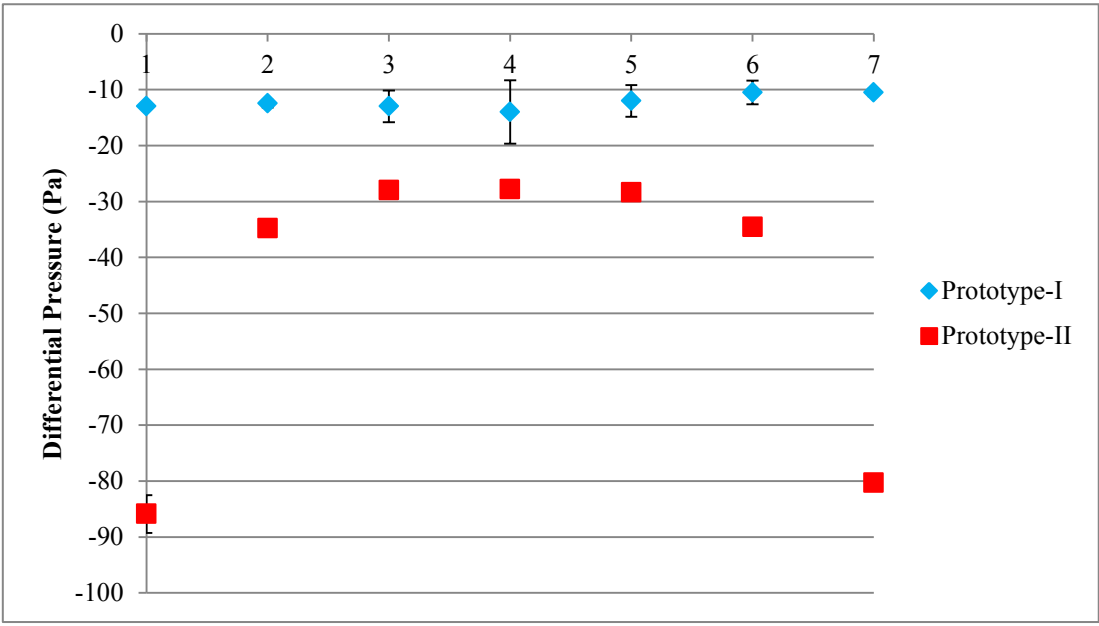


Figure 4.39 Differential pressure profiles for prototype-I and prototype-II with a spread fibre bundle positioned across the aperture.

With reference to the data presented in Figure 4.36, Figure 4.37, Figure 4.38 and Figure 4.39, the lower pressures measured at the sides of the apertures can be related to Bernoulli's principle of fluid dynamics. Bernoulli's principle states that when there is an increase in fluid flow velocity, there will be a corresponding pressure drop in the fluid. It is also understood that air flowing around an obstruction will flow at a greater velocity. Therefore, the air flowing around the sides into the aperture will be travelling at a greater velocity inducing a lower pressure at these points. This also explains the change in the pressure profile when a solid substrate was positioned across the aperture. The air velocity at the edges of the substrate would have been greater than in the space between the substrate and the aperture sides.

When a tensioned bundle was used, a slight change in the pressure profile was observed. The difference in pressure at the edges of the bundle was not as pronounced, and this was most likely due to the porous nature of the fibre bundle.

The proposed mechanism of spreading is based on differential pressure profile across the width of the aperture. As the fibre bundle traversed through the aperture and experienced maximum tension, the air flowing around the fibre bundle would have a higher velocity (as observed in Figure 4.38 when considering the sides of the aperture). Thus a differential pressure would be created between the edge of the fibre bundle and the sides of the aperture. This will result in lateral movement of the filaments – giving rise to fibre spreading. As the tension progressively decreased, the ease with which the filaments can move laterally increases, therefore this is the proposed mechanism for vacuum-assisted spreading of carbon fibre bundles. The presence of the floating bar enabled the maximum spreading created at the bottom of the aperture to be captured when the tension was reapplied (when the floating bar began to rise).

Previous studies, using the same 12k carbon fibres as used in the current work, have reported spread fibre bundle widths corresponding 18-22 mm (Diao *et al.*, 2014) and 25 mm (El-Dessouky & Lawrence, 2013). In the current study, using prototype-II and type-IIC carbon fibre, the average degree of fibre spreading achieved was 84.15 mm; this is three times greater than that reported in the literature to date.

Sihn *et al.* (2007) described the mechanism of spreading for their experimental set-up using 24k carbon fibre type and a vacuum-assisted technique. According to the authors, the differences in air velocity in close vicinity to the fibre bundle, and away from the fibre bundle, resulted in pressure differences between those two areas. In their description they stated that the pressure near the fibre bundle was greater than it was further away; in contrast to the work carried out by the current author, Sihn *et al.* (2007) stated that “The pressure difference created an aerodynamic force that helps the filaments to lose tension momentarily”. Sihn *et al.* (2007) did not report any differential pressure measurements or any practical mechanism associated the momentary loss of tension in the filaments. Their proposed mechanism of fibre spreading was previously discussed in the Literature Review.

In summary, two unique methods were developed to enable to controlled spreading of 2400 Tex E-glass and 12K carbon fibre bundles. Micro-fibre fabric was used with E-glass fibre bundles and a vacuum device was used for carbon fibre bundles. Unique mechanisms were proposed for the two types of reinforcing fibres.

Type-II E-glass and type-IIC carbon fibre bundles were chosen to manufacture and evaluate hybrid composites. One of the reasons for selecting these two fibre types was their lower binder content; 0.5% and 0.3% for type-II E-glass and type-IIC carbon fibre

bundles respectively. This study also demonstrated that it was possible to manufacture a single-layer E-glass composite of a mono-layer of type-II E-glass filaments. Although the extent of spreading achieved for the carbon fibres was, on average 1121%, this did result in some segmentation. It is anticipated that this will have an influence on the fibre volume fraction of the composite and the resultant mechanical properties.

4.4 Fibre Bundle Tensile Tests

Dry fibre bundle tensile tests were conducted on 2400 Tex E-glass and 12K carbon fibre bundles in the as-received and spread states, at two gauge lengths (50 mm and 100 mm). The fibre types used and the state in which they were tested are shown in Table 4.1.

Table 4.1 A summary of the samples types and gauge lengths used for the dry fibre bundle tensile tests.

Fibre Type	Fibre Bundle State	Gauge Length (mm)
Type-I E-glass	As-received	50
Type-I E-glass	As-received	100
Type-II E-glass	As-received	50
Type-II E-glass	As-received	100
Type-II E-glass	Spread	50
Type-II E-glass	Spread	100
Type-IIC carbon	As-received	50
Type-IIC carbon	As-received	100
Type-IIC carbon	Spread	50
Type-IIC carbon	Spread	100

4.4.1 E-glass Fibre Bundle Tensile Tests

The tensile strength of 2400 Tex type-I and type-II E-glass fibre bundles in the as-received state were evaluated and the results are shown in Figure 4.40. It can be seen that: (i) type-I E-glass fibres had, on average, a higher failure stress when compared to type-II E-glass fibres at both gauge lengths; and (ii) an increase in gauge length resulted in a decrease in the average failure stress for both type-I and type-II E-glass fibre bundles. The effect of gauge length on the tensile properties of fibre bundles has been extensively reported in the literature for E-glass; Pardini & Manhani (2002) reported a 3.96% drop in the tensile strength of 750 Tex E-glass fibres when going from a 50 mm gauge length to a 100 mm gauge length. In the current study type-I and type-II E-glass fibre bundles exhibited a reduction in average failure stress of 49.8 MPa (5.19%) and 74.2 MPa (8.20%) respectively. The statistical significance of these reductions will be discussed later.

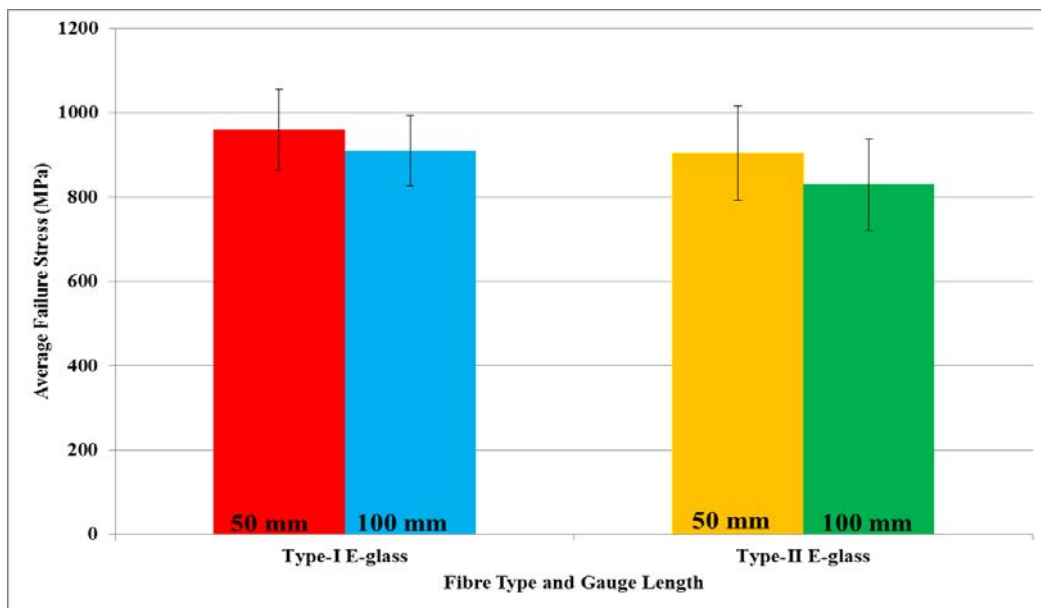


Figure 4.40 Comparison of the average failure stress for type-I and type-II 2400 Tex E-glass dry fibre bundles at gauge lengths of 50 mm and 100 mm.

Figure 4.41 presents the average failure stress for type-II E-glass fibre, as-received and spread, at the two gauge lengths. It was observed that spreading the fibre bundle resulted in a decrease in the average failure stress; this was calculated to be 15.02% and 18.04% at gauge lengths of 50 mm and 100 mm respectively. There are a number of reasons suggested for the observed decrease in average failure stress: (i) the mechanical-based fibre spreading could have induced unintentional damage that was not observed visually; (ii) It could be that the improvement of the filament alignment in the bundle, as a result of the spreading process, consequently led to an increase in the number of initially loaded filaments; (iii) the influence of inter-fibre friction is more pronounced in spread fibre bundles; this will be discussed with respect to the acoustic emission data.

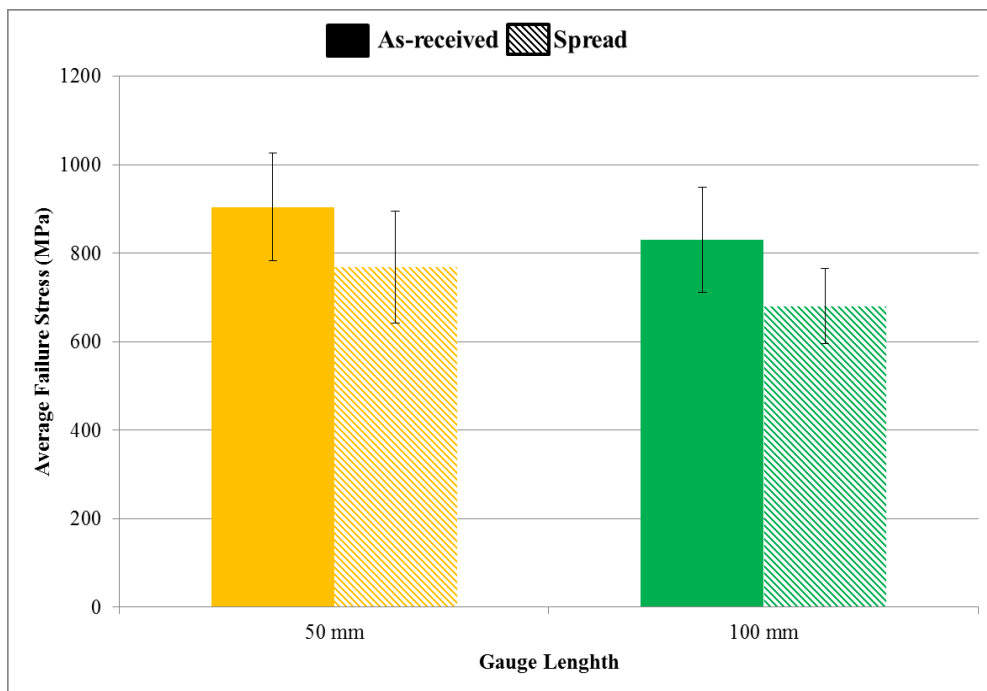


Figure 4.41 The effect of spreading, on the average failure load, of 2400 Tex type-II E-glass fibre bundles at gauge lengths of 50 mm and 100 mm.

Presented in Figure 4.42 are the average tensile moduli obtained for the as-received and spread 2400 Tex type-II E-glass fibre (50 mm and 100 mm gauge lengths). It can be seen that: (i) the modulus was higher for the samples tested at a 100 mm gauge length; and (ii) the modulus was higher for the spread samples when compared to the as-received samples of the same gauge length. With regards to (i), Pardini & Manhani (2002) reported varying Young's moduli, when assuming Hookean behaviour, for E-glass fibres tested at 25, 50, 75 and 100 mm gauge lengths. At a 25 mm gauge length the Young's modulus was 78.0 GPa whereas at a 50 mm gauge length the modulus increased to 95.6 GPa, an increase of 22.56%. In the current study, increases of 16.31% and 7.24% were observed from as-received to spread fibre bundles at 50 mm and 100 mm gauge lengths respectively. The as-received and spread 100 mm gauge length samples showed increases of 41.08% and 30.08% respectively compared to the 50 mm gauge lengths samples. The as-received and spread 100 mm gauge length samples showed increases of 41.08% and 30.08% respectively compared to the 50 mm gauge lengths samples.

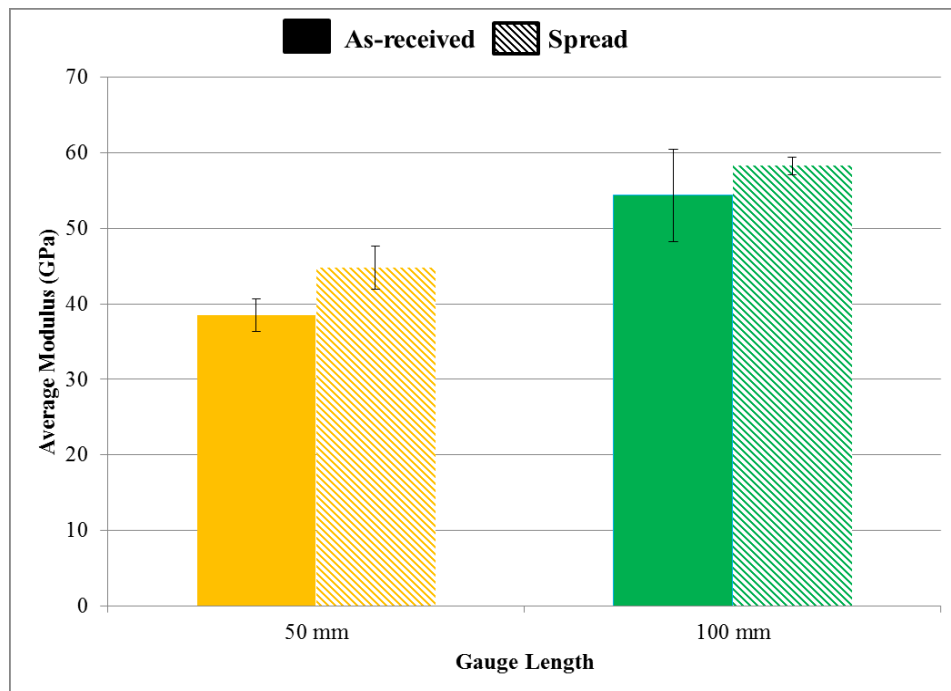


Figure 4.42 The average tensile modulus for as-received and spread 2400 Tex type-II E-glass fibre bundles tested at gauge lengths of 50 mm and 100 mm.

No explanation for this observed change in modulus was provided by Pardini & Manhani (2002). The current author is also unable to provide an explanation other than to suggest that the machine compliance needs to be considered. With reference to observation (ii): the improvement in spatial architecture following spreading was discussed in Section 4.4.2; therefore the suggestion is that the change in modulus was likely due to an improvement in the filament alignment and a reduction in off-axis and meandering filaments.

Figure 4.43 presents three representative stress/strain curves from the 50 mm as-received tensile tests of dry type-II E-glass fibre bundles. Linear loading behaviour was observed in the samples that showed maximum (1143 MPa) and mid-range (903 MPa) failure stresses respectively. The minimum observed failure stress was 537 MPa. It is possible that the minimum load sample was an anomaly. The next lowest observed failure stress was 734 MPa, almost 200 MPa higher. The sample that exhibited the lowest failure stress, did not load linearly up to failure; it is possible that this non-linear behaviour was a result of filament misalignment and/or uneven tension in the bundle due to the undulations previously mentioned in section 4.1.1. The ends of each fibre bundle, 20 mm outside of the gauge length, were impregnated with UV-curable resin to ensure the filaments were ‘locked’ in place prior to tensile specimen preparation. This should have prevented the filaments in the bundle slipping during testing.

Presented in Figure 4.44 are representative load displacement curves for spread type-II E-glass fibre. In each case, the fibre bundle followed Hooke’s law up to initial failure. The loads represented are 981 MPa, 860 MPa and 525 MPa. By contrast to the as-received fibre bundles, a greater proportion of spread fibre bundles exhibited a lower stress. In both conditions, as-received and spread, it was noted that the failure in the

fibre bundles that had a higher peak load was more catastrophic than the more gradual failure exhibited by the samples failing at lower loads.

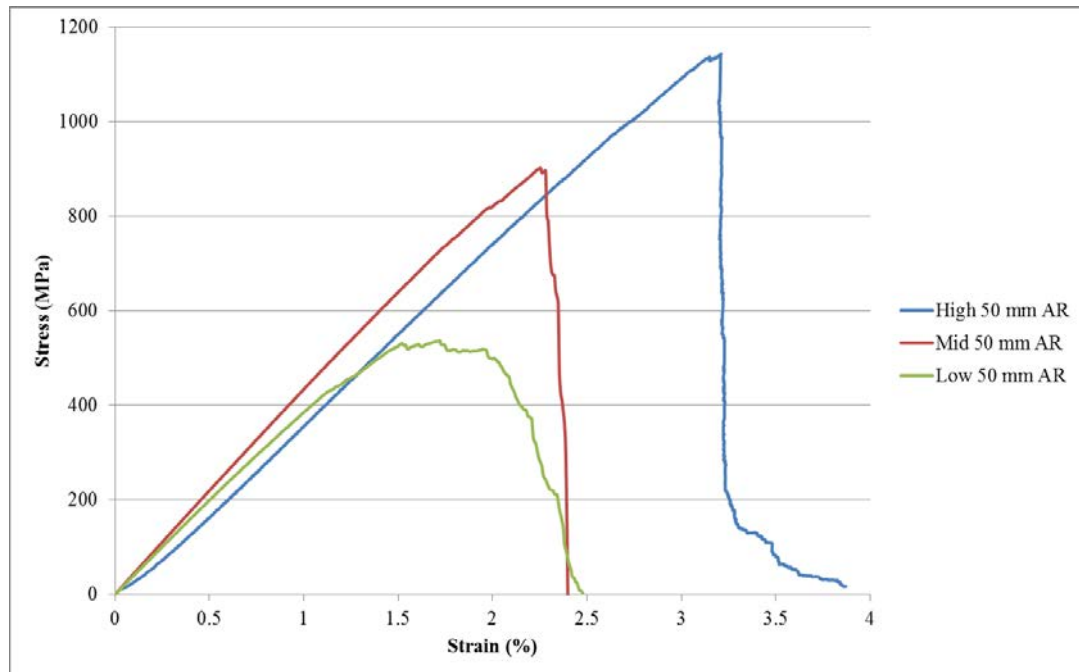


Figure 4.43 Representative stress/strain curves for 50 mm as-received type-II E-glass fibre.

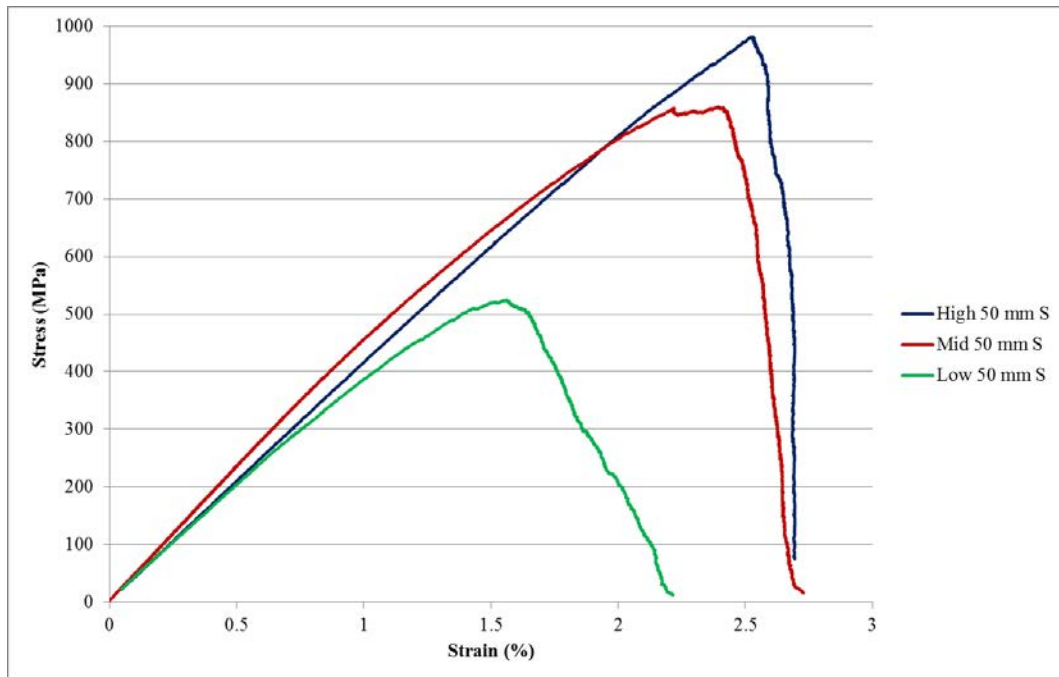


Figure 4.44 Representative stress/strain curves for 50 mm spread type-II E-glass fibre.

Figure 4.45 and Figure 4.46 present the representative load displacement curves for the as-received and spread 100 mm gauge length type-II E-glass fibre bundle tests respectively. The highest stress recorded in the as-received fibre bundles was 982 MPa compared to 794 MPa for the spread fibre bundles. This is a drop of around 188 MPa. The lowest recorded value of the as-received 100 mm gauge length fibre bundles was 611 MPa, compared to 563 MPa for the spread 100 mm gauge length bundles a drop of over 110 MPa. The difference in the median failure stresses was over 150 MPa. As with the 50 mm as-received samples, only the fibre bundle that recorded the lowest load did not load linearly. All of the 100 mm spread E-glass samples loaded linearly up to failure.

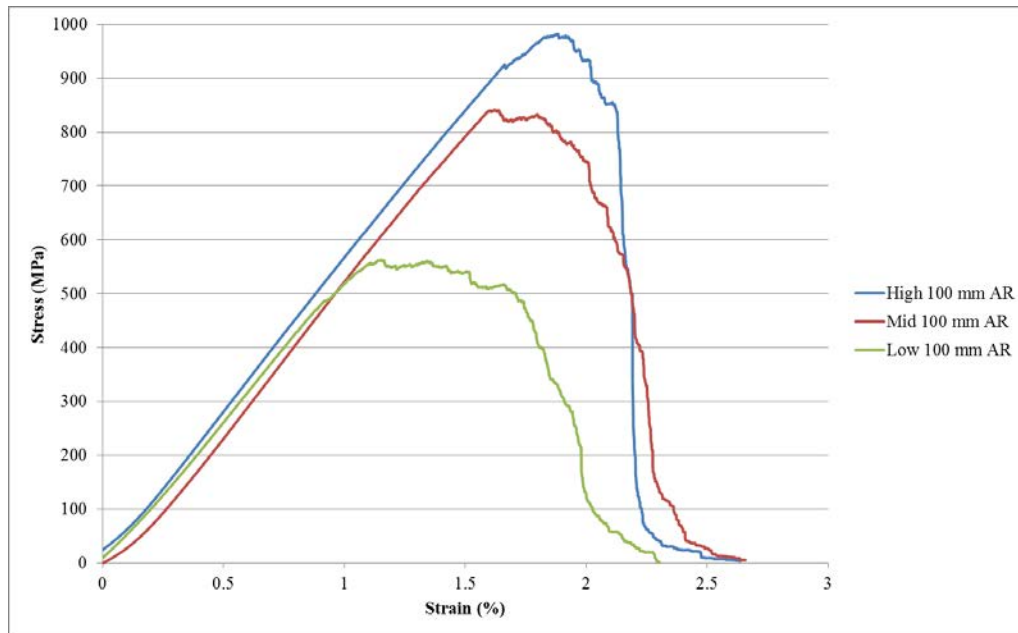


Figure 4.45 Representative load displacement curves for 100 mm gauge length as-received type-II E-glass fibre bundle tests.

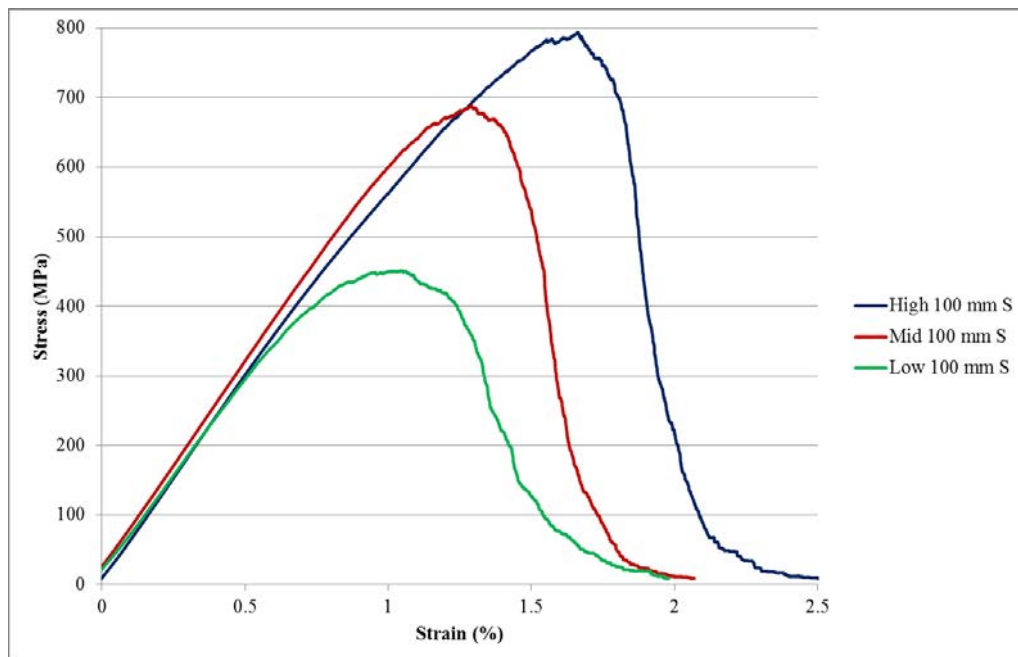


Figure 4.46 Representative load displacement curves for 100 mm gauge length spread type-II E-glass fibre bundle tests.

At the time of writing there was no record found in the literature of fibre bundles being tensile tested in the spread state. The decrease in average peak load seen in the spread fibre bundles could be a result of a number of factors: (i) when a filament fails in a fibre bundle, the load it was carrying is transferred to its neighbouring surviving filaments. In the case of dry fibre bundles, the load transfer reportedly occurs through inter-filament interactions (Calard & Lamon, 2004); the most commonly attributed mechanism is through inter-fibre friction (Hitchon & Phillips, 1979). In the spread fibre bundles, there were fewer filaments in close proximity to each other, reducing the number of filaments available for load transfer through inter-fibre interaction when a filament failed. In a spread fibre bundle, the load transferred through local load sharing (LLS) would have been redistributed among fewer filaments; this could have resulted in overloading of neighbouring filaments, leading to their premature failure.

In addition, spreading a fibre bundle increased the filament alignment and made it easier to evenly tension all of the filaments in the bundle. It has been reported in the literature that the filaments in the bundle can be misaligned due to different filament lengths and subsequently are under different tensions as load is applied. This is observed in a load-trace, where-by the initial portion of the curve is non-linear (presented in Figure 2.25, Section 2.2). The curve becomes linear when all of the filaments have been ‘straightened’ and are under the same tension. This mismatch in tension could result in a greater peak displacement and filaments surviving to a higher load.

4.4.1.2 Acoustic Emission – E-glass

The acoustic emission (AE) data was analysed in order to determine any patterns in the fibre bundle tensile behaviour. Figure 4.47 presents the amplitude distribution for as-received type-II E-glass fibre with a 50 mm gauge length; the example shown is the

bundle that had a median peak load. It can be seen that there are two distinct amplitude distributions; one distribution was observed ranging from 45-60 dB and a higher amplitude distribution in the range of 85-100 dB. With reference to the literature, the lower amplitude distribution is related to noise and inter-fibre friction (R'Mili, Moevus & Godin, 2008). The higher amplitude distribution is related to individual filament breaks (Oskouei & Ahmadi, 2010). It is important to note that the AE data was unfiltered. The decision was made not to filter the data as, due to the number of parameters recorded, it was not possible to tell whether some filament breaks were being lost during the filtering. The most commonly used parameters for filtering include: amplitude, energy, frequency and duration. Studies have suggested that through filtering, each individual filament break was captured. However, little information is given on the filtering method and, due to the number of variables it would be possible to filter to a point to collect the desired number of events.

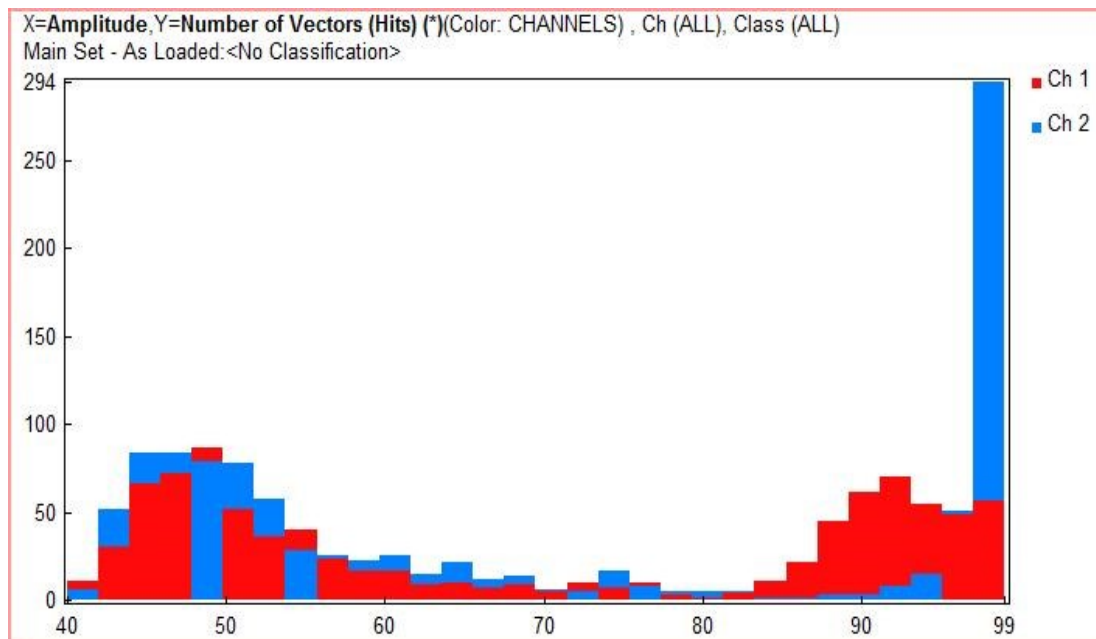


Figure 4.47 The amplitude distribution for an average type-II E-glass fibre bundle tested at a gauge length of 50 mm.

For example, presented in Figure 4.48 and Figure 4.49 is representative stress/strain curve for an as-received type-II E-glass at a gauge length of 50 mm. In Figure 4.48 all of the recorded AE events have been superimposed. In contrast to Figure 4.48, the AE events superimposed on Figure 4.49 were filtered first. An advantage of presenting the data in this manner is the ability to correlate each individual hit with its unique stress and strain.

From Figure 4.48 it can be seen that there were two distinct amplitude distributions. A low distribution, 40-60 dB, that was present throughout the test and a higher distribution (> 80 dB) that began at a load of ~ 600 MPa. In total there were 1934 AE events recorded during this test. Figure 4.49 presents the same stress/strain curve where the AE hits have been filtered, based on the distribution observed in Figure 4.47, to remove any events that had an amplitude below 80 dB. The number of AE events remaining after filtering was 762. The number of filaments in this bundle according to the manufacturer, is 2400, therefore if only 762 filaments in the bundle failed then 1638 filaments would be surviving at the end of the test. The fact that the bundle failed catastrophically after peak load would suggest that this was not the case.

As can be seen from Figure 4.49 the number of recorded AE hits increased dramatically at peak load. This increased the chance that filament failures were occurring in rapid succession leading to potential multiple filament failures. In order to determine whether this was the case, some waveforms from the AE data were analysed.

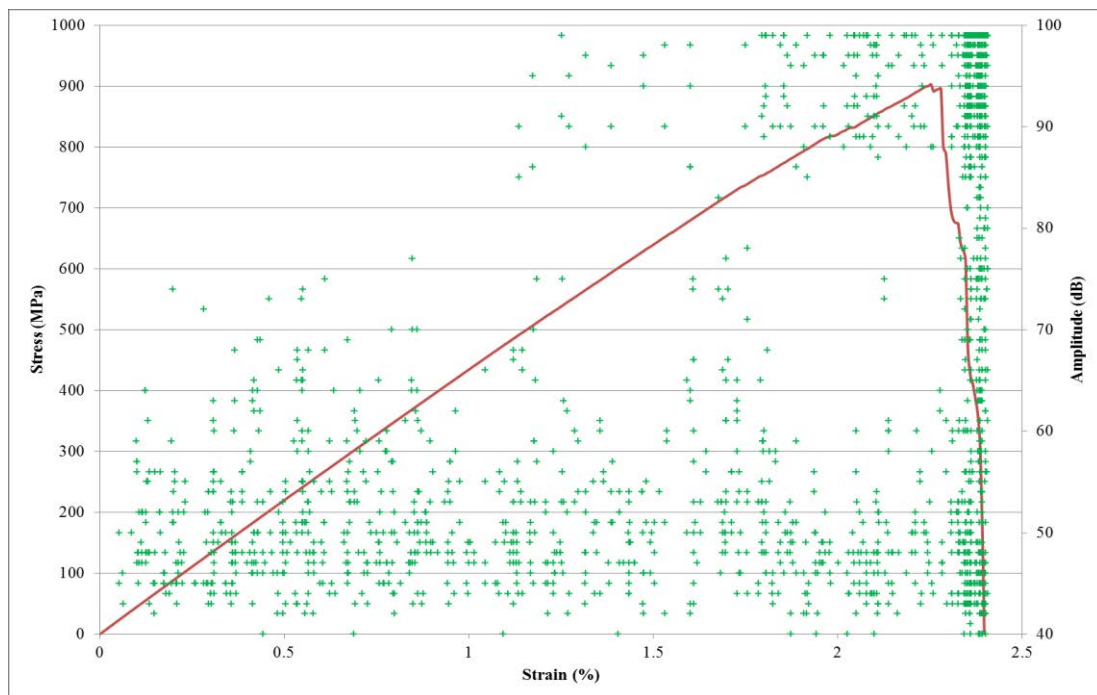


Figure 4.48 A stress/strain curve with AE hits superimposed for an as-received type-II E-glass fibre bundle tested at a gauge length of 50 mm.

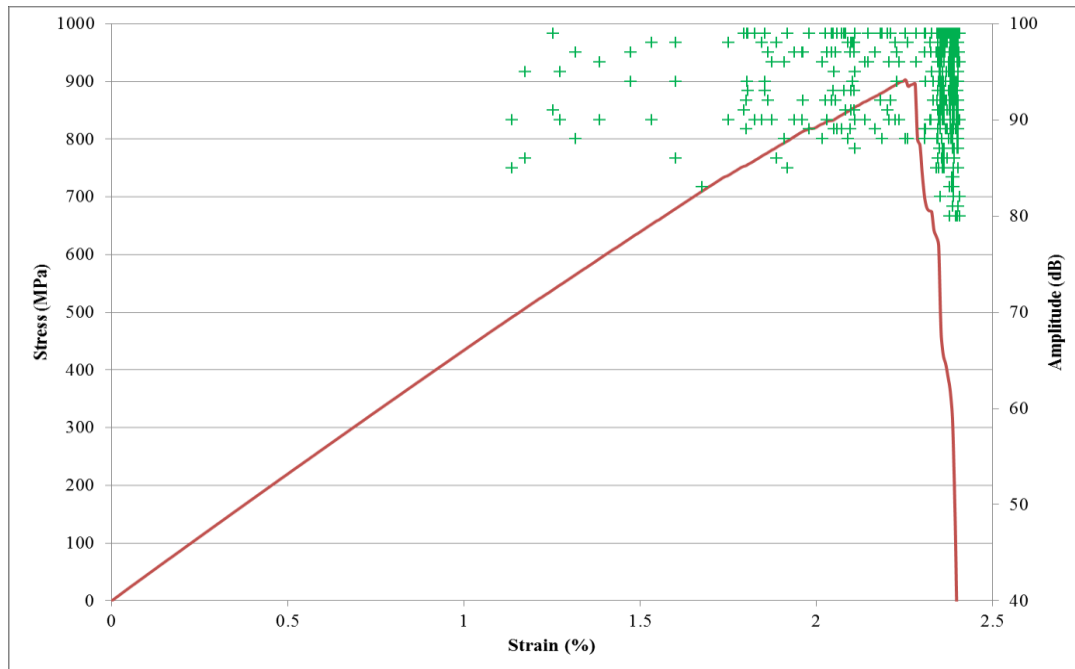


Figure 4.49 A stress/strain curve for an as-received type-II E-glass fibre bundle tested at a gauge length of 50 mm with filtered AE hits (> 80 dB) superimposed.

Figure 4.50 and Figure 4.51 present single AE event waveforms associated with a filament failure and ‘noise’ or inter-fibre friction prior to peak load respectively. The filament failure waveform had a rapid rise to high voltage (greater than 2) from zero and a rapid decay to a low voltage. By contrast it can be seen that the voltage of the waveform associated with noise was considerably lower (less than 0.02) and the signal lasted much longer at that voltage.

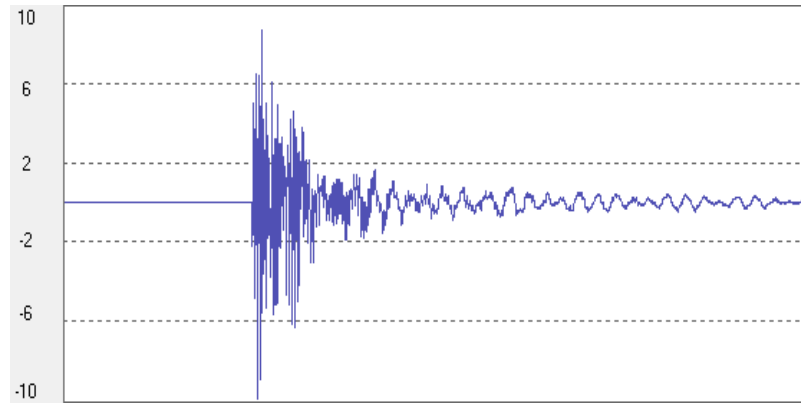


Figure 4.50 A representative waveform of a filament failure in a 50 mm as-received type-II E-glass fibre bundle.

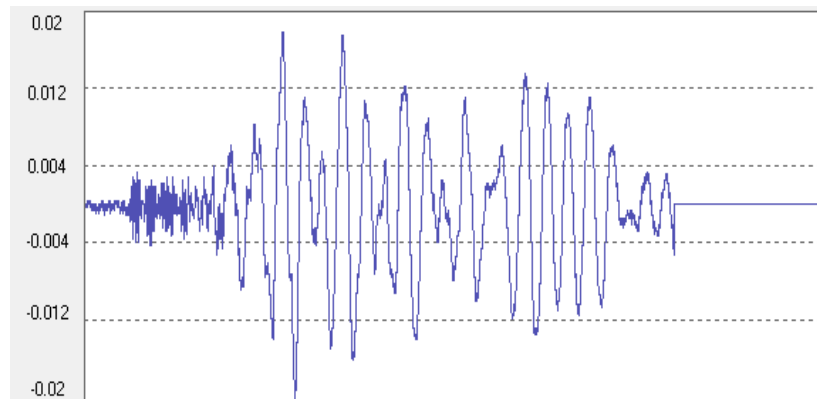


Figure 4.51 A representative waveform of 'noise' or inter-fibre friction in a 50 mm as-received type-II E-glass fibre bundle.

Figure 4.52(i-iii) presents representative waveforms from after the peak load, in which there are potential multiple filament failures recorded in the same event. The voltages of the initial portion of the waveforms were nearly identical to that of the filament failure in Figure 4.50. The subsequent part of the waveforms show at least one more high voltage peak; in Figure 4.52(i) a significant number of high voltage peaks are present.

The instance of multiple high peaks in the waveforms suggests a number of filament failures occurred in rapid succession and were all recorded in the one event.

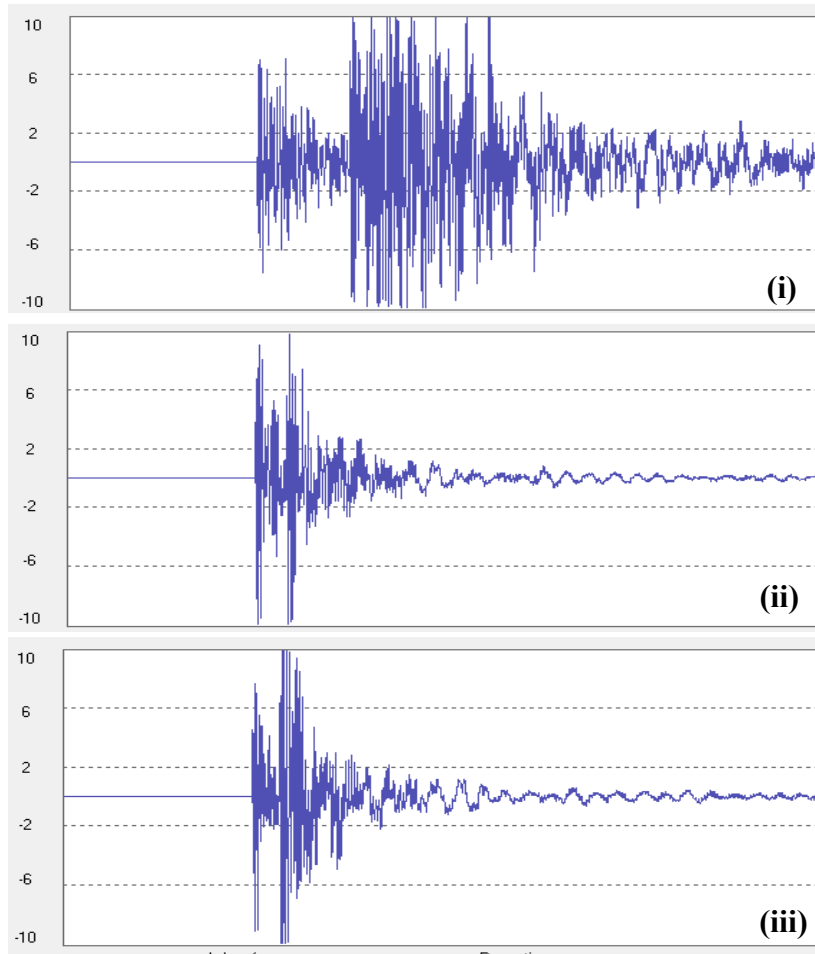


Figure 4.52 (i-iii) representative waveforms for AE events after peak load in a 50 mm as-received type-II E-glass fibre bundle.

Figure 4.53 presents the amplitude distribution for an as-received type-II E-glass fibre bundle tested at 100 mm gauge length. Two amplitude distributions in the same regions as seen with the 50 mm gauge length sample were observed. A greater number of low and high amplitude events were recorded in the 100 mm gauge length sample. The increase in low amplitude hits is due to the increase in gauge length.

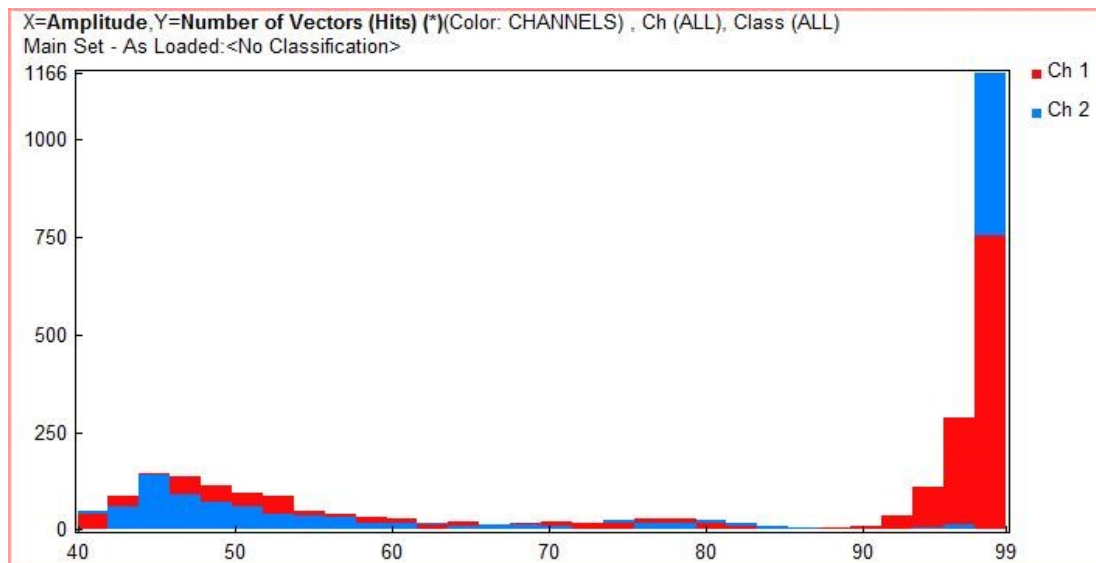


Figure 4.53 The amplitude distribution for an average type-II E-glass fibre bundle tested at a gauge length of 100 mm.

Presented in Figure 4.54 and Figure 4.55 are the stress/strain curves for a representative as-received type-II E-glass fibre bundle tested at 100 mm gauge length with raw and filtered AE events superimposed. With reference to Figure 4.54 a total number of 4258 events were recorded. This is significantly more than the number of filaments than in the fibre bundle (2400). The higher amplitude hits, associated with filament failures, began to occur at ~ 400 N.

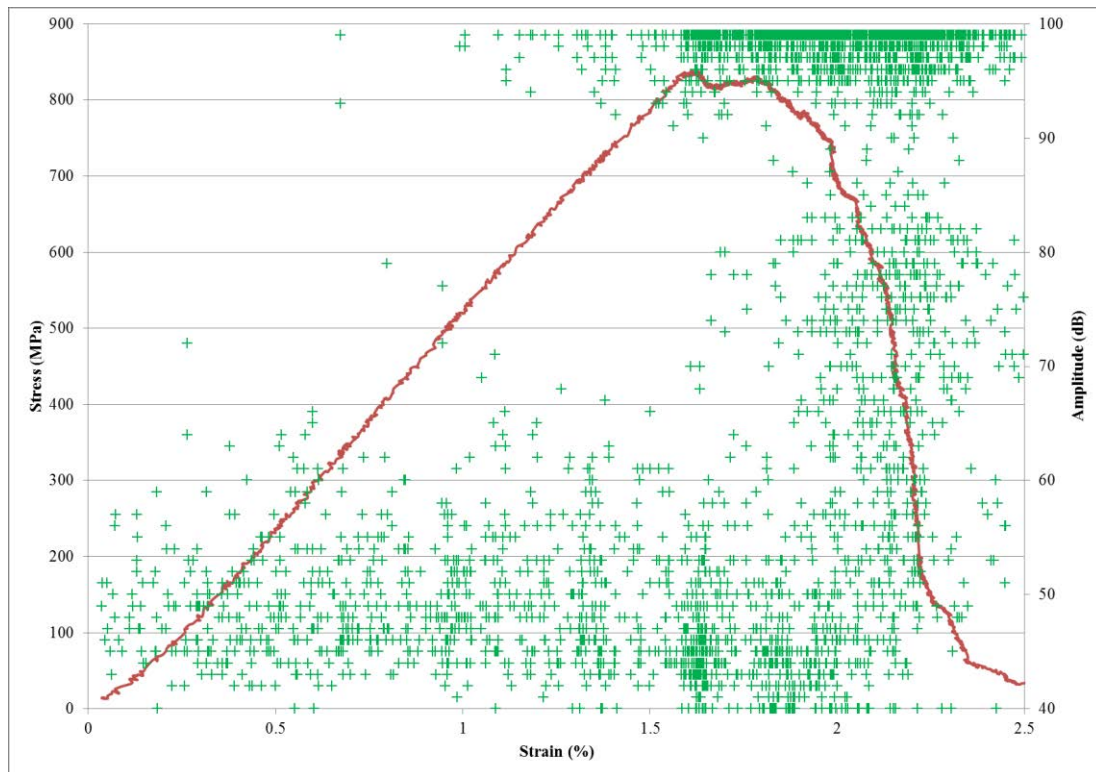


Figure 4.54 The stress/strain curve, with AE hits superimposed, for an as-received type-II E-glass fibre bundle tested at a gauge length of 100 mm.

With reference to Figure 4.55, filtering the AE events to an amplitude range > 80 dB reduced the number of AE events to 2459. This is still more than the number of filaments in the bundle. Therefore it could be said that all of the filament failures were recorded. However, as shown previously (Figure 4.52) it is possible that multiple failures are recorded in one event. For this reason it is not being suggested here that each individual failure was recorded.

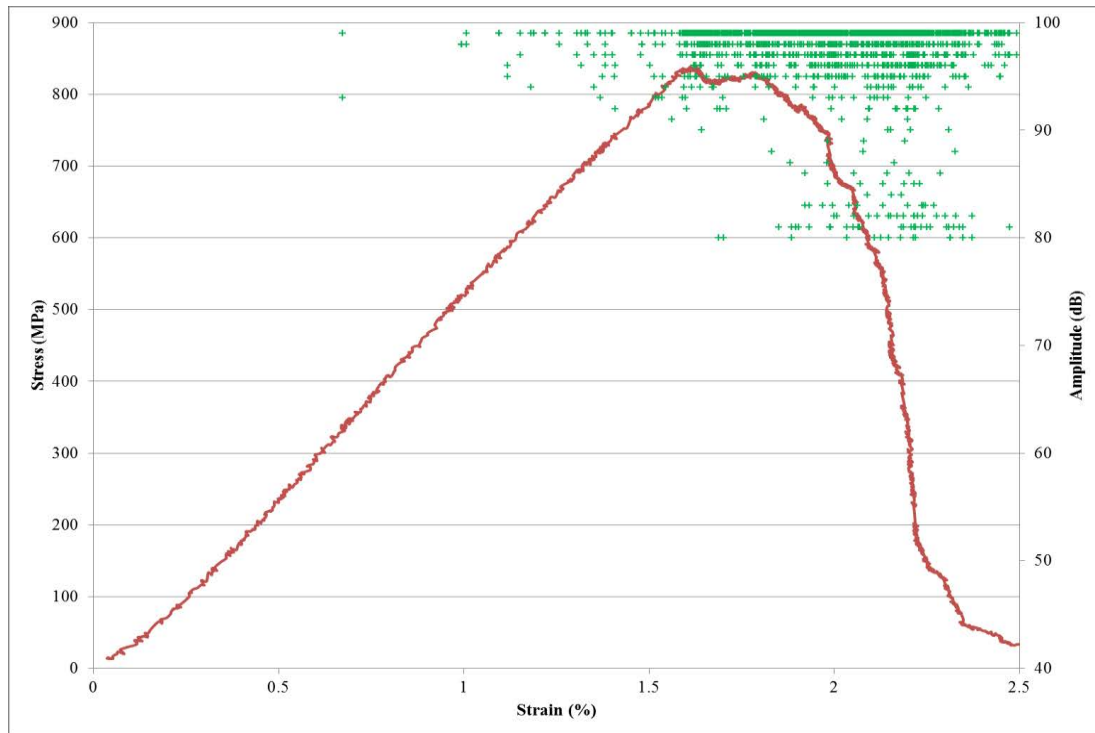


Figure 4.55 The stress/strain curve, with filtered AE hits (> 80 dB) superimposed, for an as-received type-II E-glass fibre bundle tested at a gauge length of 100 mm.

The AE data was also analysed for spread type-II E-glass fibre bundles in order to determine whether there was any difference in the failure behaviour and amplitude distributions. The AE data presented from now will all be raw unfiltered data.

Figure 4.56 and Figure 4.57 present representative stress/strain curves with superimposed AE events for average spread type-II E-glass fibre bundles tested at a gauge length of 50 and 100 mm. In both cases two amplitude distributions were observed. A greater number of filament failures were recorded after peak load as the strongest filaments began to fail. A total of 3444 and 5032 AE events were recorded in the 50 mm and 100 mm gauge length spread type-II E-glass samples. Higher AE events were recorded in the spread samples compared to the as-received samples. It is suggested that the increase number of AE events is due to an increase in the inter-fibre

friction in the spread samples. One of the effects of spreading the fibre bundles was to cause fractures in the binder content. Therefore, the presence of groups of filaments bound together would be decreased meaning more filaments were able to move and hence slide against each other as the load was applied.

In both the 50 mm and 100 mm gauge length spread E-glass fibre bundles, the weaker filaments began to fail at a lower load. This provides some evidence to the influence of spreading, and the resultant local increase in redistributed load, among surviving neighbouring filaments. The weaker filaments were more susceptible to the redistributed load upon filament failure than in an as-received fibre bundle. Therefore, when local load sharing occurred, the redistributed load was shared among fewer neighbouring filaments. If one of the filaments to which load was redistributed was a weaker filament or had more flaws present, it would be more likely to fail under a lower load.

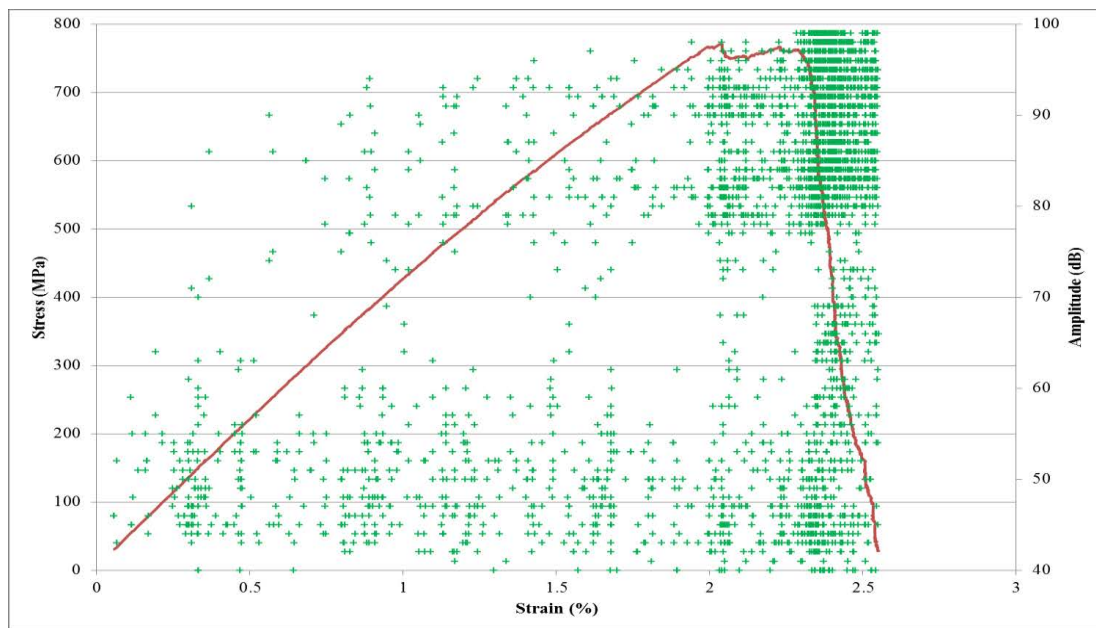


Figure 4.56 The stress/strain curve, with AE hits superimposed, for a spread type-II E-glass fibre bundle tested at a gauge length of 50 mm.

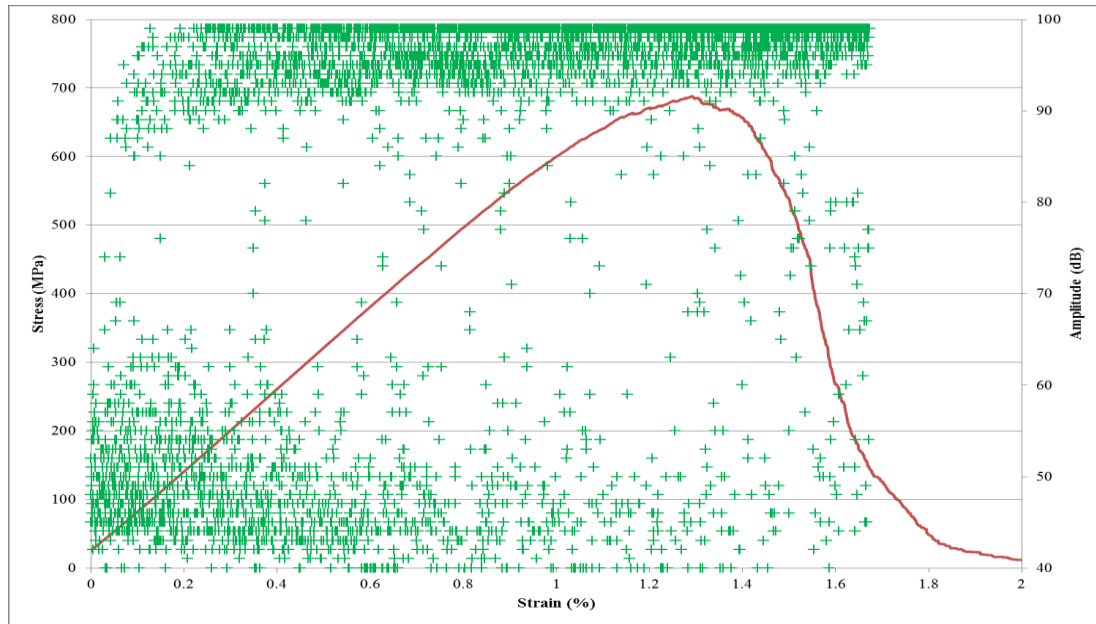


Figure 4.57 A stress/strain curve, with AE hits superimposed, for a spread type-II E-glass fibre bundle tested at a gauge length of 100 mm.

Presented in Figure 4.58(i) is an AE event in which a single filament break was recorded; this event was recorded after the peak load. It has very similar characteristics to representative waveforms observed previously i.e. rapid rise time and decay. Figure 4.58(ii) presents another waveform from an AE event after the peak load. This shows that multiple failures were recorded in this one event. Therefore if the data was to be filtered and a number of events matching the number of filaments remained then some of those events would not necessarily be filament failures. A number of the events could contain multiple failures, something that is difficult to account for when filtering data without analysing each individual AE event.

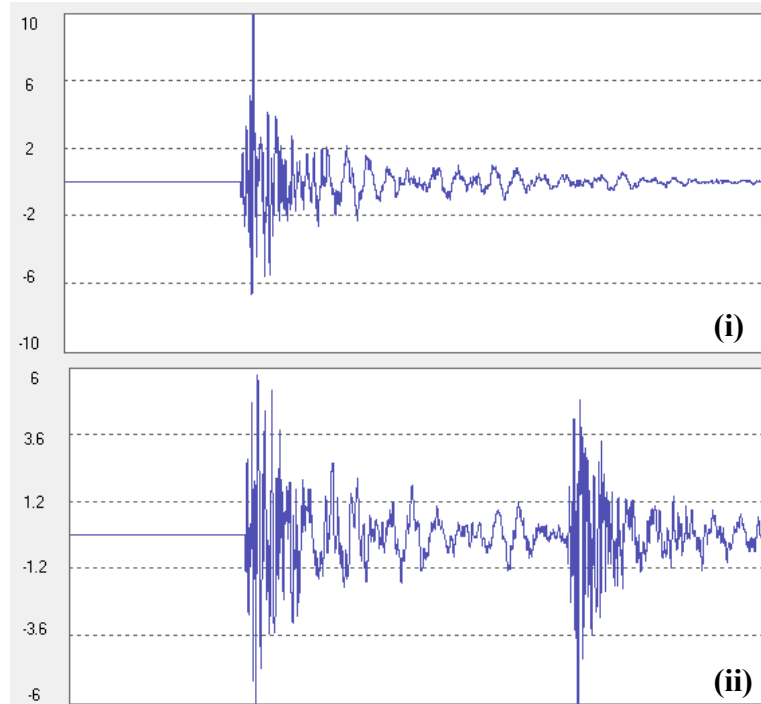


Figure 4.58 Representative waveforms of filament breaks in a spread type-II E-glass fibre bundle after peak load; (i) single failure and (ii) multiple failures; at 100 mm gauge length.

4.4.2 12K Carbon Fibre Bundle Tensile Testing

Figure 4.59 shows the average failure stress of fibre type-IIC carbon fibre bundles, in the as-received and spread state, at 50 mm and 100 mm gauge lengths. With reference to Figure 4.59 it can be seen that at both gauge lengths, 50 mm and 100 mm, the spread fibre bundles exhibited a greater average peak load than the as-received fibre bundles. It can also be seen that the standard deviation was smaller for the spread fibre bundles; this suggested that the spreading enabled the material to perform more consistently.

The average failure stress of the type-IIC carbon fibre bundles was 2594 MPa and 2332 MPa. (as-received) and 2631 MPa and 2466 MPa (spread) at gauge lengths of 50 and 100 mm respectively. These values equated to percentage increases in average failure stress of 1.44% and 5.77% respectively. The statistical significance of these differences in average tensile failure stress will be discussed later. These initial results suggest that

spreading the type-IIC carbon fibre bundles did not have a detrimental effect on the tensile properties.

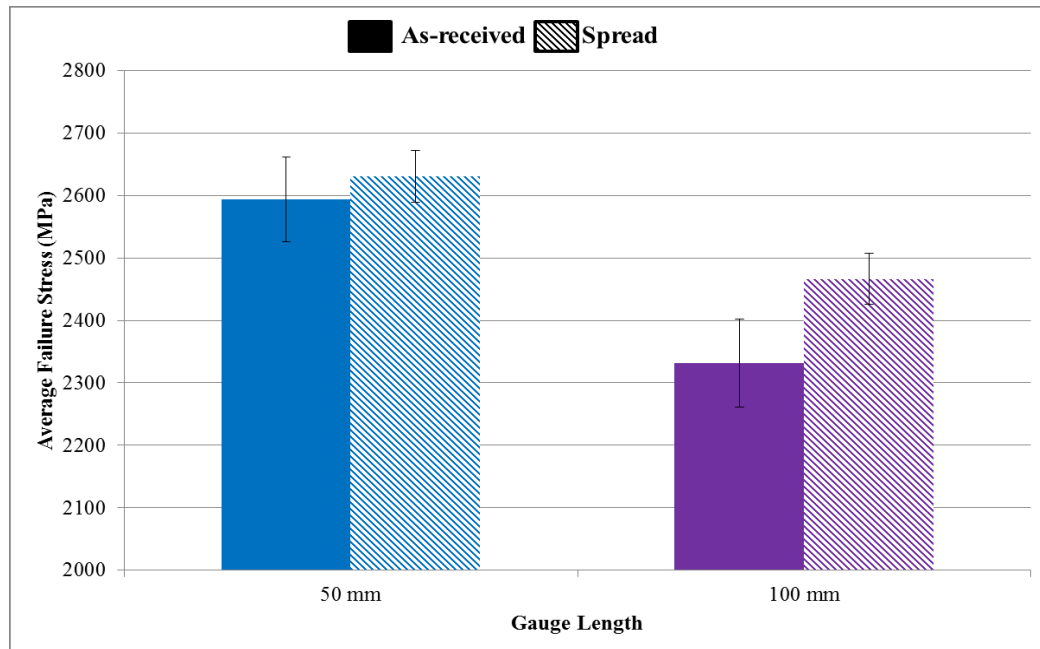


Figure 4.59 The effect of spreading on type-IIC carbon fibre bundles at 50 mm and 100 mm gauge lengths.

Figure 4.60 presents the average tensile moduli for type-IIC carbon fibre bundles, as-received and spread, for gauge lengths of 50 mm and 100 mm. It was observed that the spread fibre bundles had a higher modulus. There was also a small increase in modulus observed when going testing at a gauge length of 100 mm compared to 50 mm. The explanation for the increase in modulus for spread fibre bundles was previously discussed with respect to type-II E-glass fibre bundles.

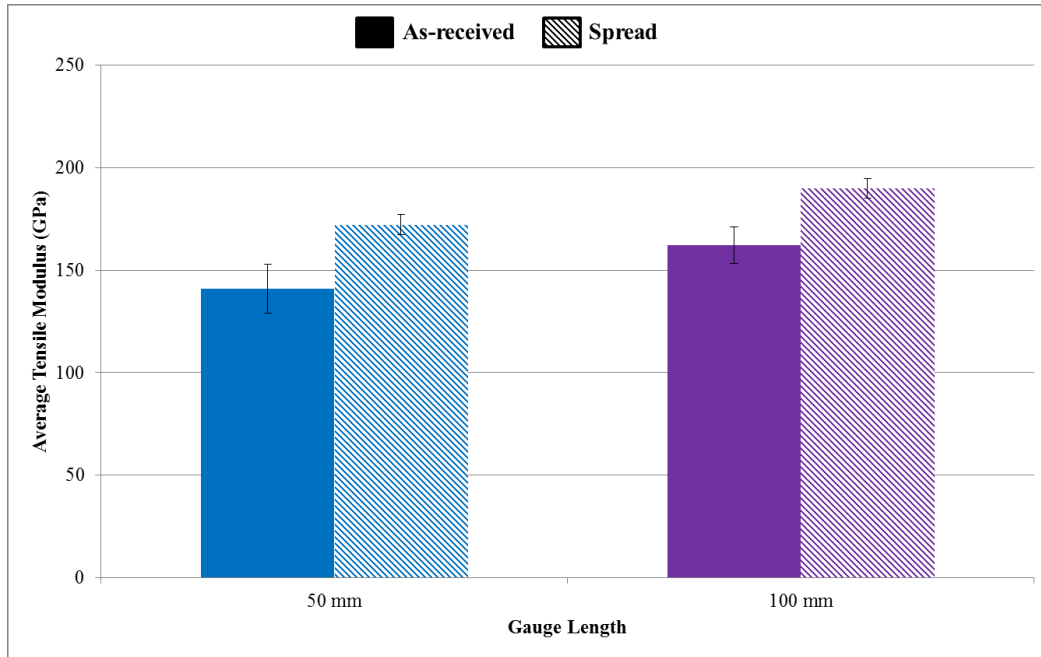


Figure 4.60 The average tensile modulus for as-received and spread 2400 Tex type-II E-glass fibre bundles tested at gauge lengths of 50 mm and 100 mm.

For type-IIC carbon fibre bundle tests there was a smaller range in the minimum and maximum loads recorded. Figure 4.61 and Figure 4.62 show the representative stress/strain curves for as-received and spread type-IIC carbon fibre bundles at a 50 mm gauge length. The maximum, mid-range and minimum loads were 2828 MPa, 2621 MPa and 2193 MPa and 2788 MPa, 2631 MPa and 2453 MPa for the as-received and spread fibre bundles respectively. The range from the maximum to minimum tensile failure stress for the as-received and spread type-IIC carbon fibre bundle was 635 MPa and 336 MPa respectively.

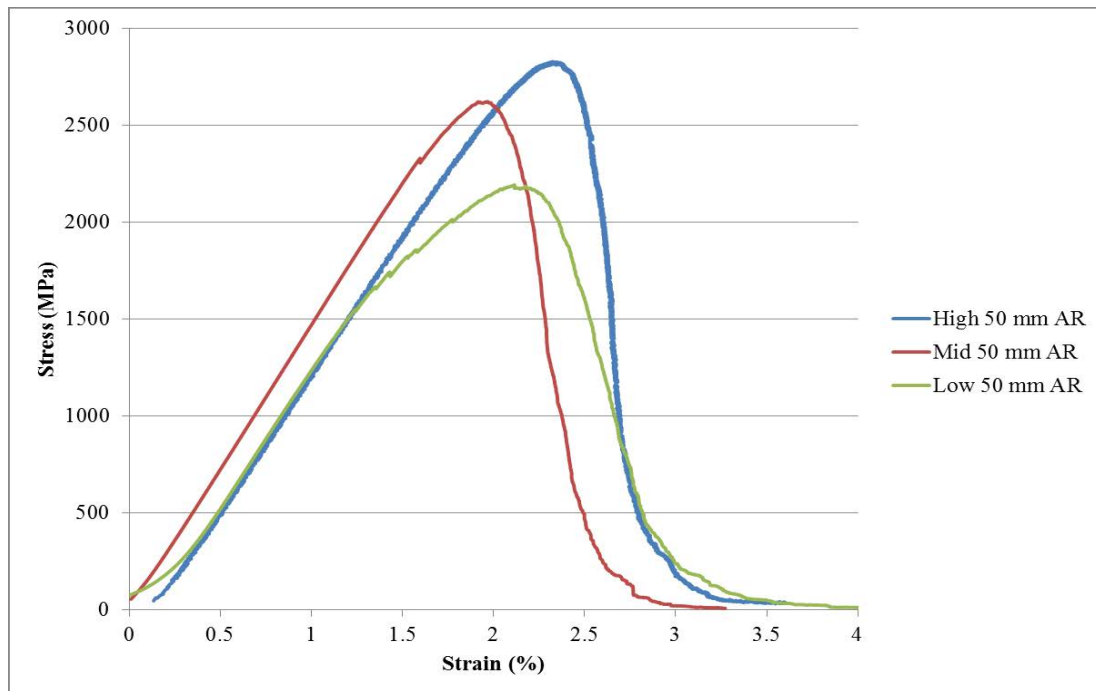


Figure 4.61 Representative stress/strain curves for as-received type-II C carbon fibre bundles tested at a gauge length of 50 mm.

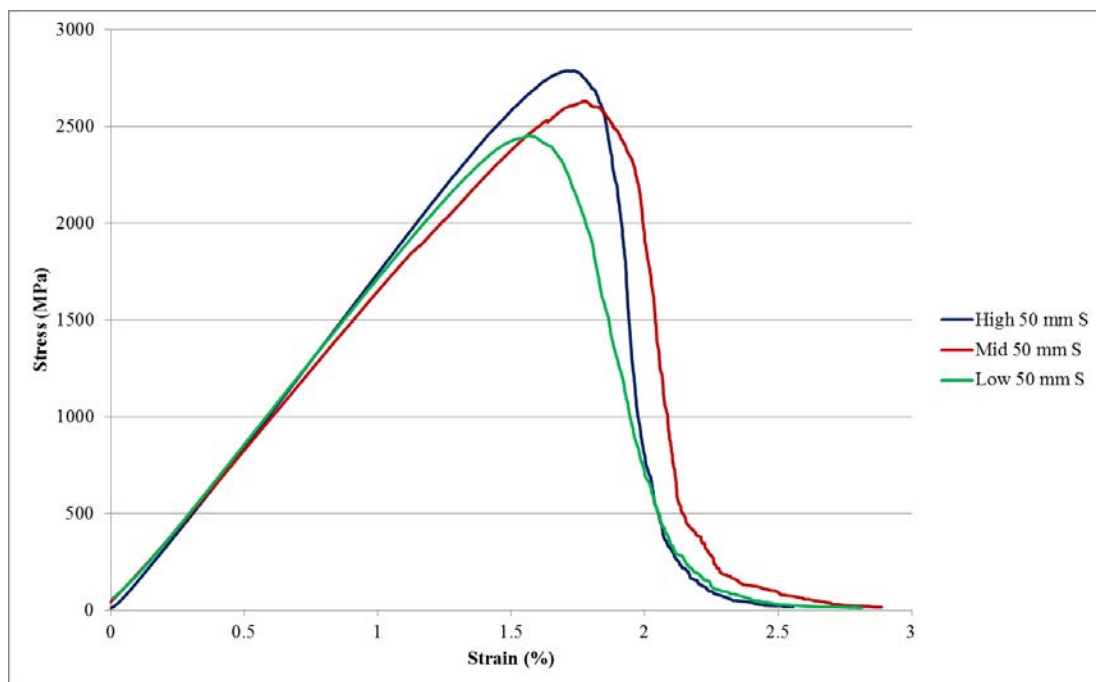


Figure 4.62 Representative stress/strain curves for spread type-II C carbon fibre bundles tested at a gauge length of 50 mm.

A similar trend was seen in the 100 mm gauge length fibre bundles. The ranges from maximum to minimum load were 302 N and 170 N for as-received and spread type-IIC carbon fibre bundles respectively. This is nearly a 50% reduction in scatter. The maximum recorded load for spread type-IIC carbon fibre bundles was also higher at 1211 N compared to 1200 N for as-received type-IIC carbon fibre bundles.

Figure 4.63 and Figure 4.64 present the representative load displacement curves for as-received and spread type-IIC carbon fibre bundles tested at a gauge length of 100 mm. It can be seen that the samples all loaded in a linear fashion up to initial failure. Once failure began it progressed quickly in all fibre bundles as the load being redistributed among the surviving filaments became too great and they all eventually failed.

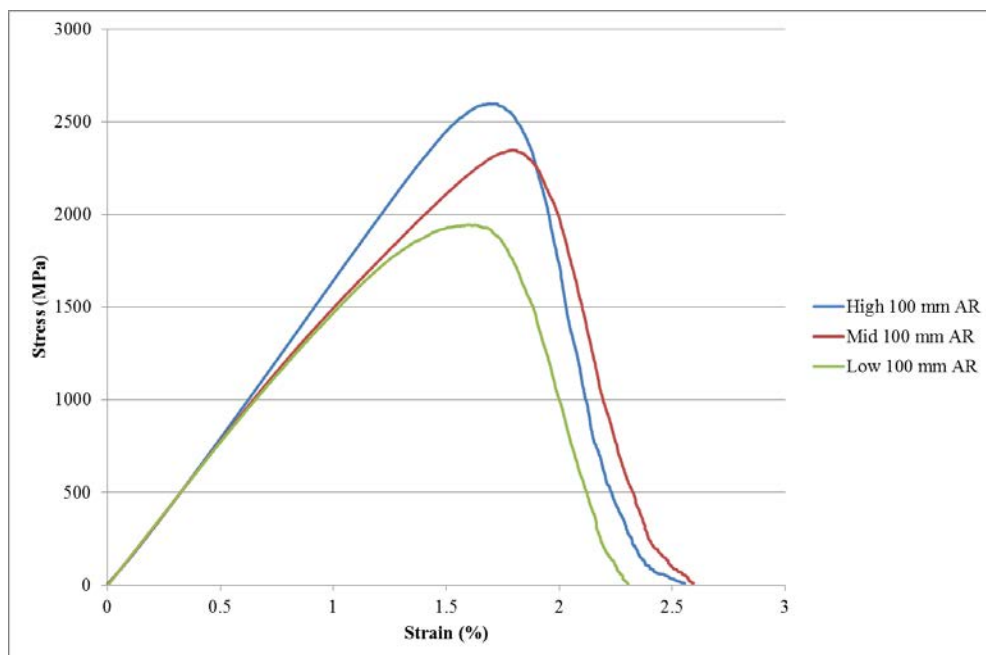


Figure 4.63 Representative stress/strain curves for as-received type-IIC carbon fibre bundle tested at a gauge length of 100 mm.

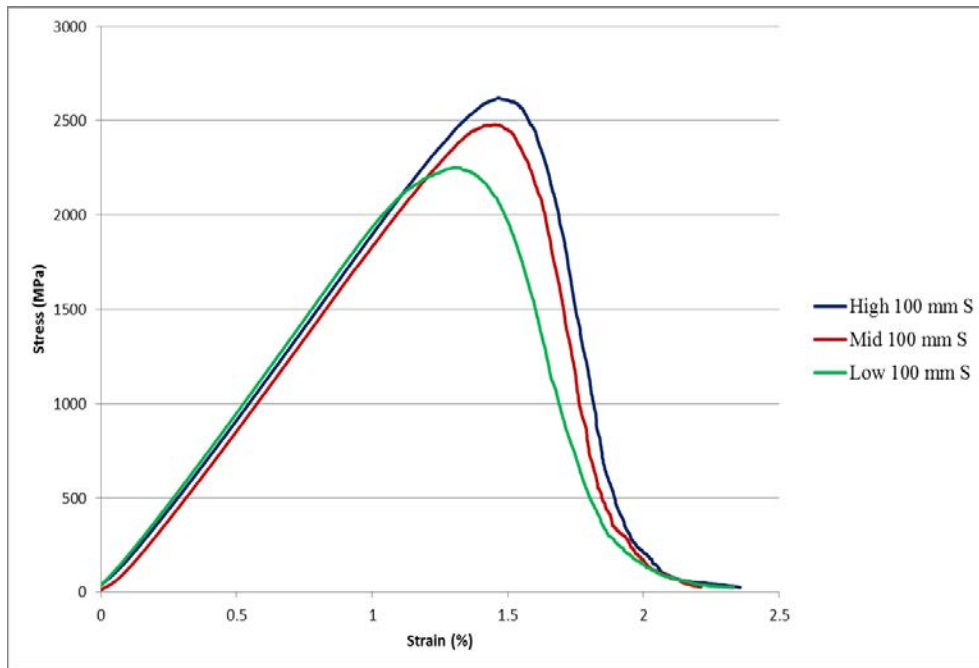


Figure 4.64 Representative stress/strain curves for spread type-IIC carbon fibre bundle tested at a gauge length of 100 mm.

The observed reduction in scatter in the spread type-IIC carbon fibre bundles may be due to an improvement in the alignment of the filaments within the bundle. However, it is thought that, as the carbon fibre bundles were only spread by approximately 200% there would not have been large changes to the fibre bundle architecture. By contrast, the type-II E-glass fibre bundles for tensile testing were spread by 400%. This would have caused more significant changes to the fibre bundle architecture, especially with respect to the number of neighbouring filaments a failed filament would have had in close proximity.

4.4.2.1 Acoustic Emission – Carbon Fibre Bundles

AE data was analysed to determine failure characteristics of the type-IIC carbon fibre bundles tested in different conditions. Figure 4.65, Figure 4.66, Figure 4.67 and Figure 4.68 present representative samples for fibre bundles tested in the following conditions;

50 mm gauge length as-received, 50 mm gauge length spread, 100 mm gauge length as-received and 100 mm gauge length spread. The unfiltered AE data has been superimposed.

In each example it can be seen that two amplitude distributions were present: a low amplitude distribution and a high amplitude distribution. The majority of high amplitude events occurred around the failure stress as the stronger filaments began to fail and the redistributed load became greater for each individual surviving filament. In the two spread samples, seen in Figure 4.66 and Figure 4.68, it was observed that filaments failures started to occur at a lower load compared to the as-received samples.

For the sample presented in Figure 4.65, there were 11705 AE events recorded during the test. This number of events is less than the number of filaments in the bundle (12000 according to the manufacturer). If the data was to be filtered using specific parameters such that only filament failures remained, the number of AE events would be 10108. Thus not all of the filament failures were recorded individually during this test. This could be due to limits in the hardware. Another issue was that, in some AE events, more than one filament failure was recorded, as was seen with the AE data for E-glass. This would reduce the number of overall AE events.

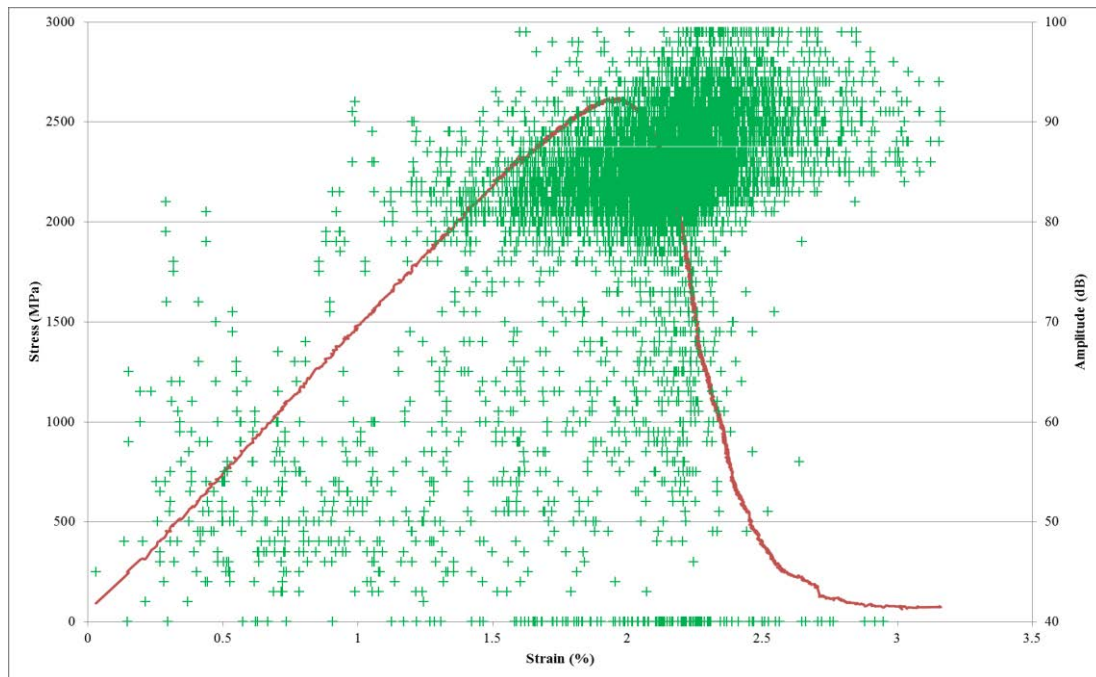


Figure 4.65 A stress/strain curve, with AE hits superimposed, for an as-received type-IIIC carbon fibre bundle tested at a gauge length of 50 mm.

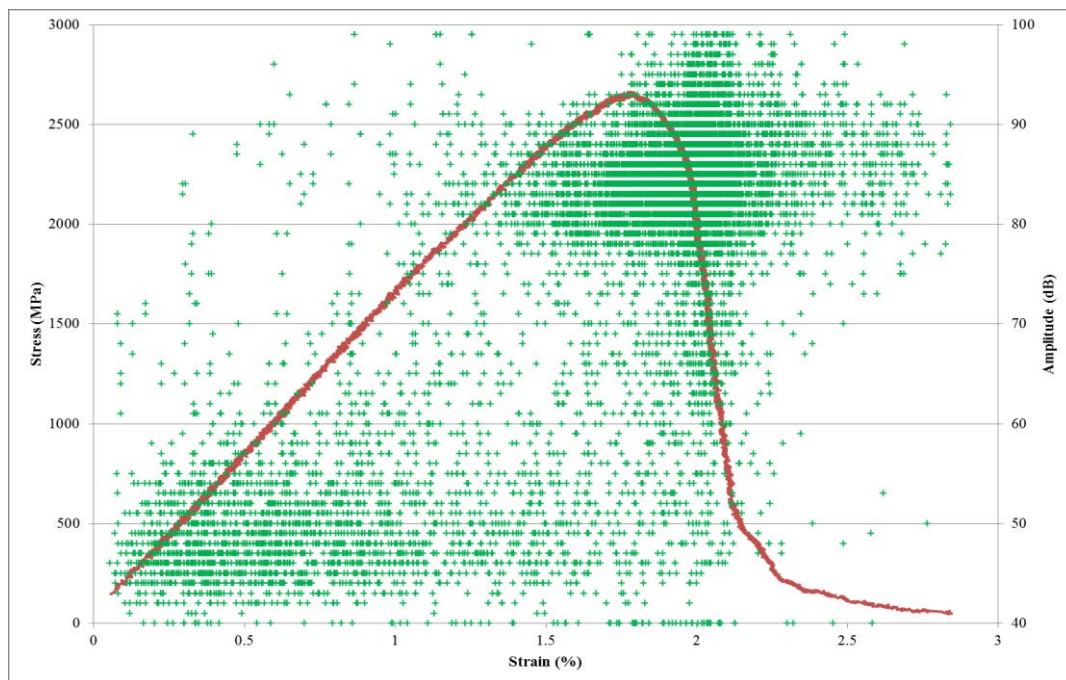


Figure 4.66 A stress/strain curve, with AE hits superimposed, for a spread type-IIIC carbon fibre bundle tested at a gauge length of 50 mm.

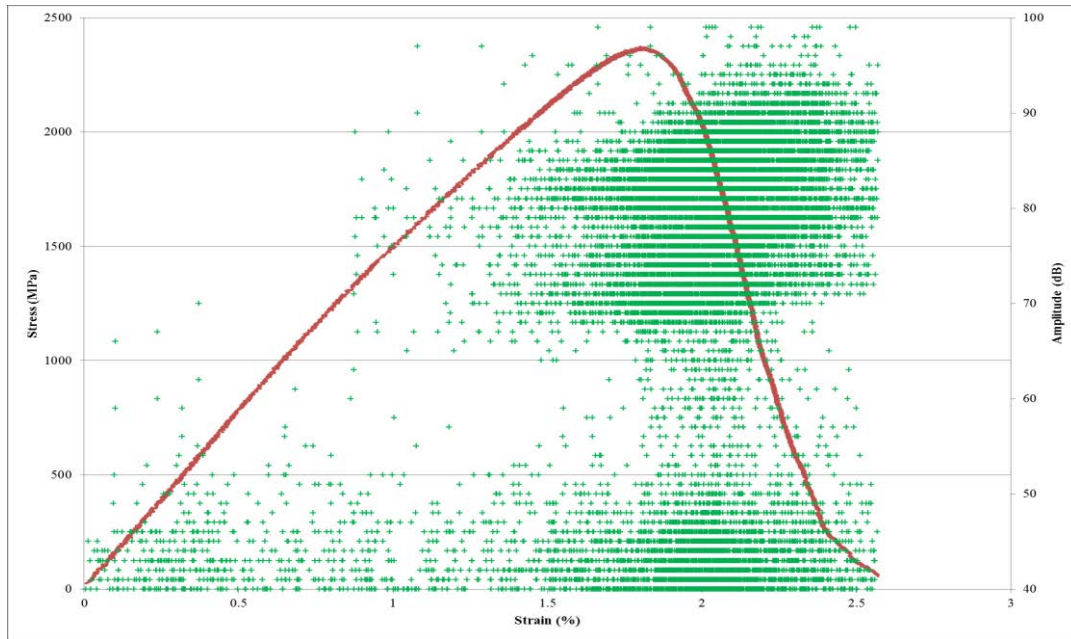


Figure 4.67 A stress/strain curve, with AE hits superimposed, for an as-received type-II C carbon fibre bundle tested at a gauge length of 100 mm.

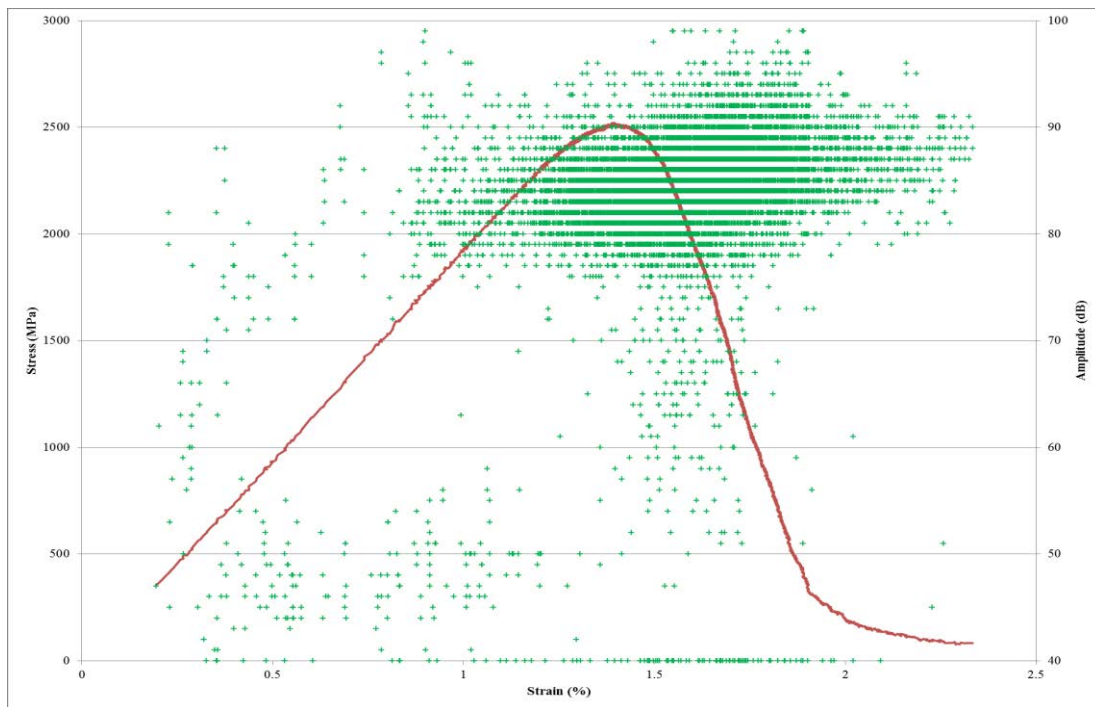


Figure 4.68 A stress/strain curve, with AE hits superimposed, for a spread type-II C carbon fibre bundle tested at a gauge length of 100 mm.

Representative waveforms, recorded after peak load in an as-received and spread type-IIC carbon fibre bundle tested at a gauge length of 50 mm, are presented in Figure 4.69 and Figure 4.70. With reference to the Figures, (i) presents one AE event in which a single filament failure was recorded and (ii) presents one AE event in which two filament failures were captured. In this particular sample a number of AE events were recorded that exhibited two distinct waveforms associated with filament failures.

Comparing Figure 4.69 and Figure 4.70, it can be seen that the waveforms are very similar in all of the AE events presented. For the type-IIC carbon fibre, no difference was seen in the failure of as-received and spread fibre bundles.

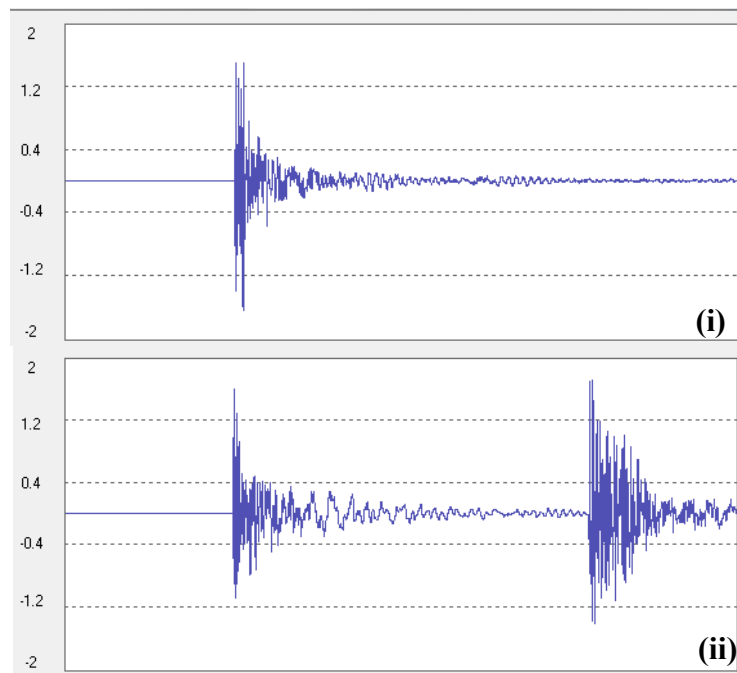


Figure 4.69 Representative waveforms from AE events recorded in an as-received type-IIC carbon fibre bundle after peak load; (i) single filament failure and (ii) multiple filament failures.

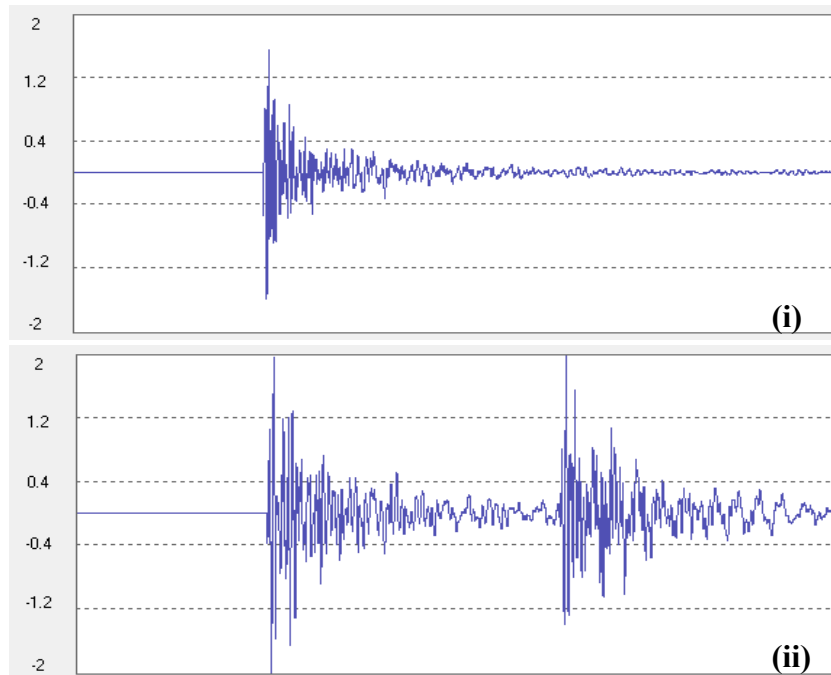


Figure 4.70 Representative waveforms from AE events recorded after peak load; (i) single filament failure and (ii) multiple filament failures. Spread fibre type-IIC carbon.

With regards to tensile behaviour of the fibre type-IIC carbon bundles, it must be noted that the suggestion is not that spreading improved the properties of the fibre. It is believed that changes to the fibre bundle architecture, such as improvements in filament alignment and straightening of meandering filaments, enhanced the loading behaviour. This resulted in more efficient loading and more evenly distributed load among filaments.

4.4.3 Weibull Distribution

A two-parameter Weibull distribution was calculated for both as-received and spread type-II E-glass and type-IIC carbon fibre bundles, at the different gauge lengths, using the peak loads of each sample. The Weibull distribution gives the failure or survival probability for a population of fibre bundles. For a two-parameter Weibull distribution, the two parameters are the shape parameter (also known as the Weibull modulus), m , and the scale parameter, α . The effect of gauge length is assumed to be negligible. In the

literature there are differing definitions of the Weibull parameters. Hill & Okoroafor (1995) defined the scale parameter as the failure strain of the fibre, for the shape parameter they suggest it is not only a measure of flaw distribution but also ‘determines the coefficient of variation and the magnitude of the size effect at normalised fibre length’. Creasy (2000) defined the shape parameter as a spread in strain to failure, and the scale parameter as corresponding to the mean failure strain of the fibre. In this study, the shape parameter was defined as a measure of the flaw distribution in the material. Therefore a larger shape parameter indicated a smaller flaw distribution and a more homogenous material. The scale parameter was defined as the ultimate tensile strength (UTS) at a survival probability of 36.8%.

The shape and scale parameters were determined respectively from a slope analysis of the peak loads of each of the fibre bundles i.e. for each fibre type, gauge length and as-received or spread. Presented in Figure 4.71 and Figure 4.72 are the slope analysis for the fibre type-II E-glass and fibre type-IIC carbon fibre bundles respectively. The equations for the slope analysis are positioned in the legend on the right hand side. The y value corresponds to the shape parameter and the scale parameter was determined by calculating the exponent of the minus value from the slope equation divided by the y value.

In each case, for the type-II E-glass and type-IIC carbon fibre bundles, it can be seen that a single linear trend line could be used to fit the data. This means that there was a unimodal flaw distribution in the fibre types used. In other words, the failure was influenced mainly by only one type of flaw in the two fibre types respectively (R’Mili, Moevus & Godin, 2008). In the literature the majority of studies reported a bimodal flaw distribution for E-glass fibres (Hill & Okoroafor, 1995; Jihan, Siddiqui & Sweet,

1997; Oskouei & Ahmadi, 2010). However, although E-glass was used in each of those studies it was not the same E-glass as used in this study. Therefore a direct comparison is difficult. For carbon fibres, Hill & Okoroafor (1995) found a bimodal distribution, although again, this was for a different fibre type and the fibre bundles were lubricated, not dry.

Presented in Figure 4.71 and Figure 4.72 are the shape (m) and scale (α) parameters for the type-II E-glass and type-IIC carbon fibre bundles respectively. The highest shape parameters, 34.22 and 32.89, were calculated for the spread type-IIC carbon fibre bundles tested at gauge lengths of 50 mm and 100 mm respectively. The two lowest shape parameters, 7.94 and 8.16, were calculated for the as-received and spread type-II E-glass fibres, tested at a gauge length of 50 mm, respectively.

From Figure 4.72 it can also be seen that, in the case of type-IIC carbon fibre, the shape parameter in the spread bundles was higher compared to the as-received bundles. This is interesting as the shape parameter defines the flaw distribution within the material. It is impossible that spreading the fibre has reduced the number of flaws or altered the distribution, as the material is the same. However, the data suggests that by spreading the fibre, it was possible to reduce the sensitivity of the material to the flaws. In addition to this, the scale parameter was larger for the spread type-IIC carbon fibre compared to as-received carbon. Therefore the survival probability was slightly higher for spread type-IIC carbon fibre bundles, compared to the as-received type-IIC carbon fibre bundles.

The results for type-I E-glass fibre bundles varied. For as-received fibre type-I E-glass there was an increase in the shape parameter with an increase in gauge length, however

there was an expected corresponding decrease in the scale parameter. This would suggest the flaw sensitivity was lower in 100 mm gauge length bundles. Nevertheless, as is well reported in the literature, an increase in gauge length results in a decrease in fibre properties, therefore the survival probability decreased.

For fibre type-II E-glass different results were obtained for the as-received and spread fibre bundles respectively. For the shape parameter there was a decrease for as-received fibre bundles with an increase in gauge length. Conversely, there was an increase in the shape parameter, with an increase in gauge length, for spread fibre bundles. When comparing the effect of spreading at the same gauge lengths, there was a decrease at 50 mm, but an increase at 100 mm.

Therefore, with respect to type-II E-glass fibre bundles in the spread state, the results suggest that, as the gauge length increased the sensitivity of the fibre to flaws was reduced. However, there was no improvement in the tensile properties, as highlighted by the consistent drop in the scale parameter with an increase in gauge length.

Table 4.2 presents collated shape and scale parameters for carbon and E-glass fibres from the literature. Not all papers used the same definitions and the exact fibre bundles used differ making it difficult to draw direct comparisons.

For E-glass fibre bundles, the values obtained in the current study were, in general, towards the higher end of those reported in the literature. By contrast, aside from Mosur *et al.* (2003), the reported shape parameters for carbon fibre are significantly lower than those obtained in the current study. With regards to the scale parameter, the experimentally derived values in the current study are within the spread of values reported in the literature.

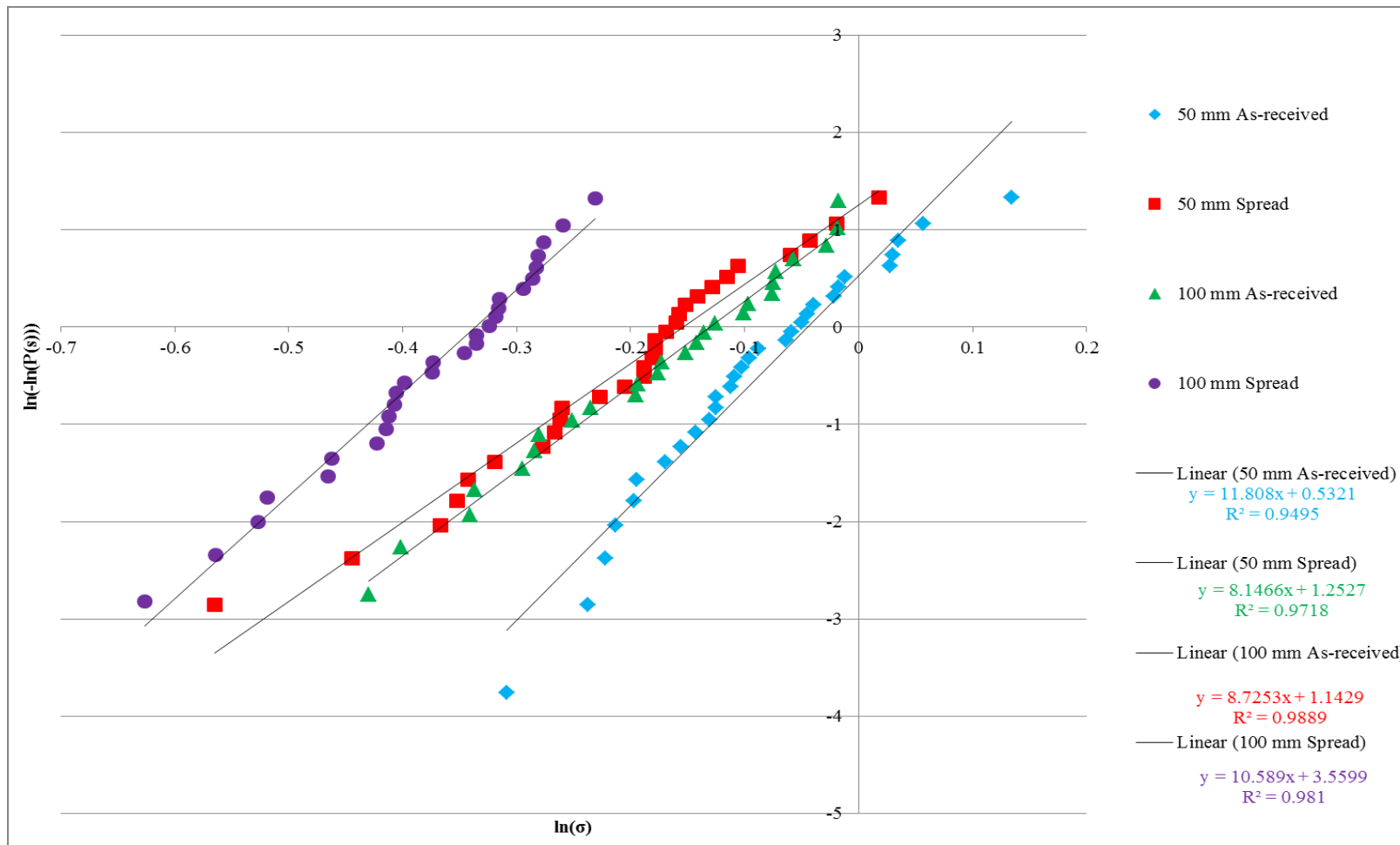


Figure 4.71 The slope analysis graph for the as-received and spread type-II E-glass fibre bundles tested at the two gauge lengths.

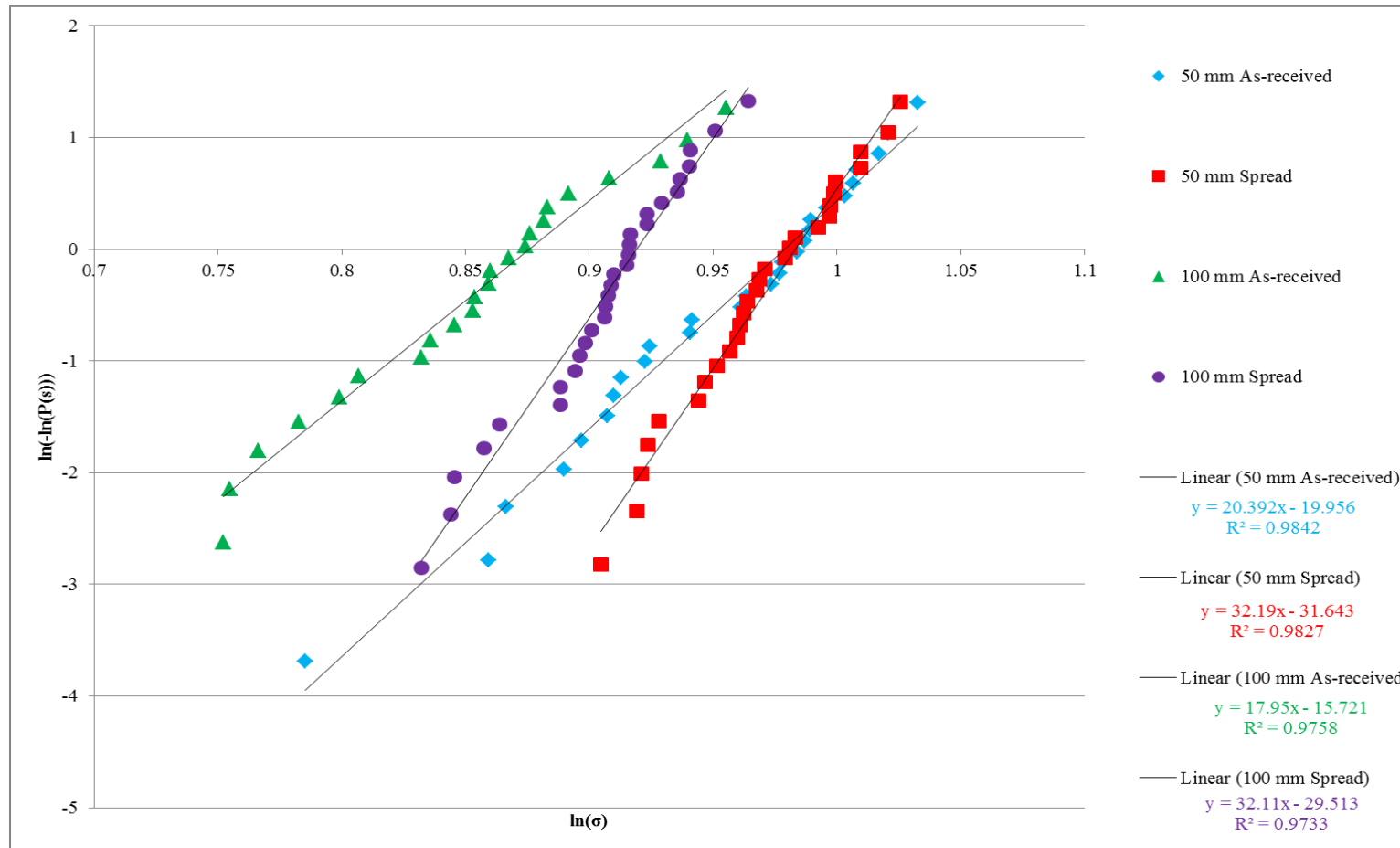


Figure 4.72 The slope analysis graph for the as-received and spread type-II carbon fibre bundles tested at the two gauge lengths.

Table 4.2 Weibull shape and scale parameters reported in the literature for E-glass and carbon fibres.

Author(s) (Date)	Test	Fibre Type: Gauge Length	Shape parameter (m)	Scale parameter (α) (GPa)
Hill & Okoroafor (1995)	FBT	E-glass fibre: 70 mm Dry (Lubricated)	9.4 (6.4)	2.437 (3.074)
		Carbon fibre: 70 mm Dry (Lubricated)	4.5 (4.25)	1.243 (1.424)
Okoroafor & Hill (1995)	FBT	Lubricated E-glass fibre 70 mm:	6.7	3.07
		Lubricated carbon fibre (9007C) 70 mm:	4.5	1.62
Ma & Sines (1995)	SFT	Pitch-based carbon fibres		
		E130:		
		1.5 mm	5.74	-
		3 mm	6.07	-
		6 mm	4.66	-
		12 mm	5.42	-
		24 mm	4.68	-
		C700:		
		1.5 mm	-	-
		3 mm	4.81	-
R'Mili, Bouchaour & Merle (1996)	SFT	T300 carbon fibre:		
		30 mm	5.5	3200 (MPa)
		60 mm	7.6	2970 (MPa)

Gurvich, DiBenedetto & Pegoretti (1997)	SFT	E-glass fibres (various suppliers, filament diameters and sizing):		
		14.8 μm Ø: 20 mm	3.18	2020
		15 mm	5.13	1793
		10 mm	6.61	1768
		5 mm	4.16	2017
		14.7 μm Ø: 20 mm	7.07	2565
		15 mm	7.76	2558
		10 mm	6.85	2640
		5 mm	5.52	2628
		25.1 μm Ø: 40 mm	2.76	4218
		25 mm	6.47	2341
		10 mm	8.14	2207
		5 mm	5.65	2184
		19.9 μm Ø: 20 mm	7.94	2602
		15 mm	6.50	2703
		10 mm	9.38	2742
		5 mm	8.74	2400
		16.8 μm Ø: 20 mm	4.44	2146
		15 mm	3.67	3220
		10 mm	3.17	3364
		5 mm	3.44	2777
		Carbon fibres μm 7 Ø: 25 mm	5.72	3764
		20 mm	5.80	3967
		10 mm	6.00	3945
		5 mm	9.81	3765

Pickering & Murray (1999)	SFT	12k HTA 5131 800 Tex carbon fibre: 1 mm 2 mm 5 mm 20 mm 200 mm 500 mm	5.65 6.06 6.67 7.86 6.29 6.95	- - - - - -
Pardini & Manhani (2002)	SFT	E-glass 700 dTex fibres: 25mm 50 mm 75 mm 100 mm PAN-based 400 dTex carbon fibres: 25 mm 50 mm 75 mm 100 mm	6.56 4.74 5.63 5.89 3.25 3.56 3.14 3.10	
Andersons <i>et al.</i> (2002)	FBT SFT	E-glass fibre: 80 mm 160 mm 320 mm E-glass fibre: 5 mm 10 mm 20 mm	5.38 3.98 4.37 5.12 5.48 5.50	4120 (MPa) 5660 (MPa) 5280 (MPa) 3380 (MPa) 3620 (MPa) 3810 (MPa)

		40 mm	5.54	3880 (MPa)
		80 mm	5.18	4440 (MPa)
Moser <i>et al.</i> (2003)	FBT	T300 carbon fibres	15	3.5
Brown <i>et al.</i> (2005)	FBT	Epoxy-sized Glass Fibre 25 mm:		
		10% humidity	13	-
		40% humidity	14	-
		80% humidity	14	-
		100% humidity	17	-
R'Mili, Moevus & Godin (2008)	FBT	E-glass fibre:		
		30 mm	3.0	2.75(%)
		60 mm	3.6	2.14(%)
		100 mm	2.8	2.07(%)

Presented in Figure 4.73 and Figure 4.74 are the survival probability graphs for the as-received and spread type-II E-glass and type-IIC carbon fibre bundles respectively.

Figure 4.73 showed that for type-II E-glass fibre bundles, the greatest survival probability was in the as-received state, at a gauge length of 50 mm. On the other hand, the lowest survival probability was shown in the spread fibre bundles at a gauge length of 100 mm. Interestingly, the survival probabilities for the as-received and spread fibre bundles, tested at gauge lengths of 100 mm and 50 mm respectively, were very similar.

By contrast, the survival probabilities of the type-IIC carbon fibre bundles were extremely close (Figure 4.74). The as-received and spread fibre bundles exhibited the highest survival probabilities, at a gauge length of 50 mm. The as-received fibre bundles, tested at a 100 mm gauge length, exhibited the lowest survival probability.

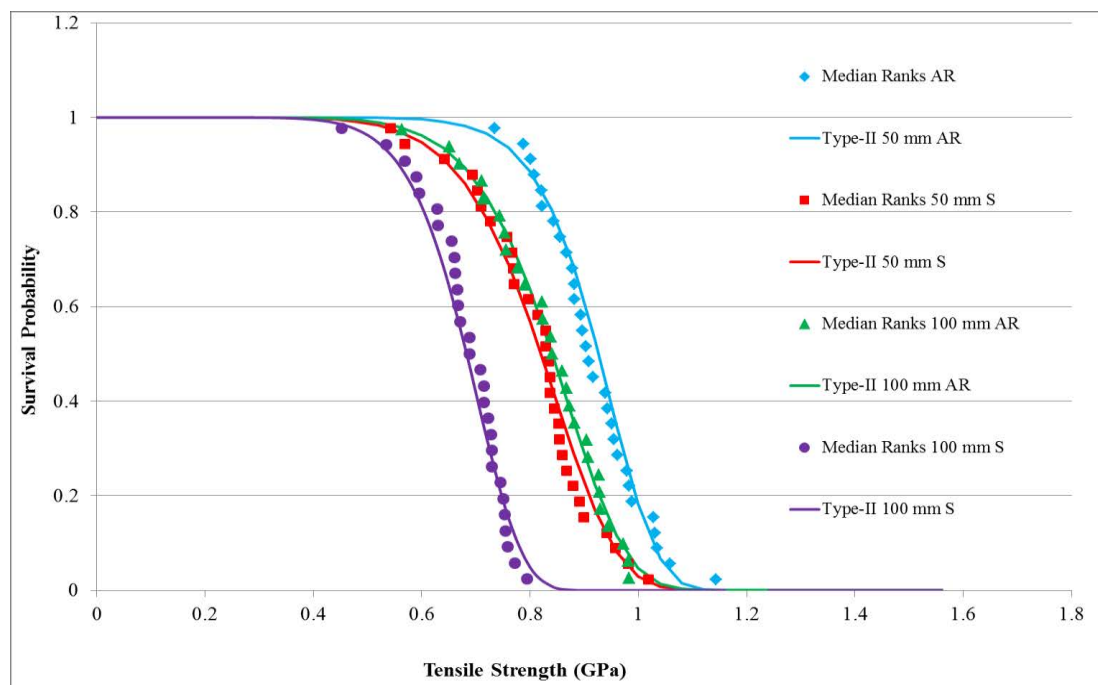


Figure 4.73 The Weibull survival probabilities for the as-received and spread type-II E-glass fibre bundles tested at the two gauge lengths of 50 mm and 100 mm.

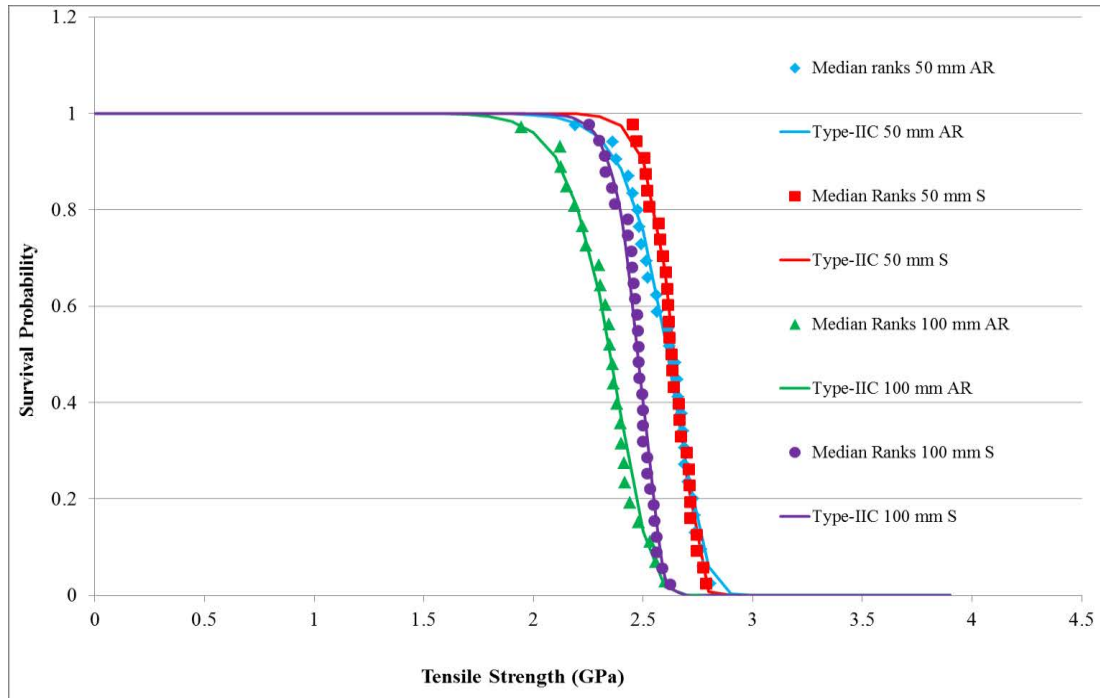


Figure 4.74 The Weibull survival probabilities for the as-received and spread type-IIC carbon fibre bundles tested at gauge lengths of 50 mm and 100 mm.

Presented in Table 4.3 are the tensile stress values for survival probability of the two reinforcing fibre types. In other words, each value corresponds to a tensile stress at which 36.8% of a population of fibre bundles would survive. For example, 100% of bundles in a population of type-II E-glass fibre bundles would survive at a tensile stress of 0.52 GPa (in the as-received state at a gauge length of 50 mm). However, all of the bundles in the population would be expected to have failed at a tensile stress of 1.12 GPa.

The survival probability of the type-IIC carbon fibre bundles was higher. For comparison, a population of as-received fibre bundles, tested at a gauge length of 50 mm, would have 100% survival at a tensile stress of 1.80 GPa. For the same population, the tensile stress at which all fibre bundles would have failed is predicted to be 2.90 GPa.

Table 4.3 The calculated survival probabilities for fibre type-II E-glass and fibre type-IIC carbon.

Fibre Type	Gauge Length (mm)	State	Stress at failure (GPa)		
			100%	50%	0%
Type-II E-glass	50	As-received	0.52	0.96	1.12
		Spread	0.40	0.84	1.10
Type-II E-glass	100	As-received	0.40	0.84	1.10
		Spread	0.32	0.68	0.88
Type-IIC Carbon	50	As-received	1.80	2.60	2.90
		Spread	2.20	2.70	2.80
Type-IIC Carbon	100	As-received	1.70	2.40	2.60
		Spread	2.00	2.50	2.70

4.4.4 Statistical Analysis

Statistical analysis was conducted in order to further investigate the influence of the gauge length and the spreading of type-II E-glass and type-IIC carbon fibre bundles. In order to compare one set of data with another, a T-test was performed. A range of paired data sets were considered; the results are presented in

Table 4.4 P-values were calculated for the t-test to determine whether or not to accept or reject the null hypothesis: there is no effect of gauge length and/or spreading on the average peak failure load of E-glass and carbon fibre. The P value determines the probability of getting a result greater than or equal to the experimental observations when the null hypothesis is true. In the context of this study: to accept the null hypothesis, the P value has to be greater than or equal to 0.05 (with a confidence of 95%). Conversely, the null hypothesis will be rejected if the P value is less than 0.05 (with a confidence of 95%). The P-value was calculated via an open-source statistical software package: ‘QuickCalcs’ (GraphPad Software, Inc. by Dr. Harvey Motulsky. <http://graphpad.com/quickcalcs/PValue1.cfm>).

From the T-test analysis the general observation was that an increase in gauge length resulted in a statistically significant difference in the average failure load of the as-received and spread fibre bundles. This fits with the reports in the literature of gauge length dependence (Pardini & Manhani, 2002; Andersons *et al.*, 2002, Hitchon & Phillips, 1976; Naito *et al.*, 2012). However, this was not the case for the as-received type-I E-glass fibre bundles. The change from as-received to spread fibre bundles, for type-I E-glass fibre was found to be significant at both gauge lengths of 50 mm and 100 mm. A search of the relevant literature did not find a report on the tensile testing of spread fibre bundles; hence the findings reported here are new to the field.

The T-test also highlighted, that the change in fibre bundle properties observed in spread type-II E-glass and type-IIC carbon fibre bundles, did not result in a significant difference at a gauge length of 50 mm when paired with their respective as-received data. Conversely, at a gauge length of 100 mm, there was a significant difference in the data sets for spread type-II E-glass and type-IIC carbon fibre bundles when compared to as-received fibre bundles.

Table 4.4 The results of student T-test statistical analysis, on paired data sets from tensile testing of as-received and spread, type-II E-glass and type-IIC carbon dry fibre bundles. *denotes data from tests conducted by S. Ojo, University of Birmingham (2016).

Comparison Parameters	T ₀	Degrees of Freedom	P-value	Conclusion
Fibre Type-I E-glass				
As-received (50 vs 100 mm)	0.954	56	0.3440	Not statistically significant
Spread (50 vs 100 mm)*	7.570	58	0.0001	Statistically significant
As-received Vs Spread (50 mm)*	-4.368	58	0.0001	Statistically significant
As-received Vs Spread (100 mm)*	-2.710	58	0.0088	Statistically significant
Fibre Type-I Vs Fibre Type-II E-glass				
As-received 50 mm	2.583	58	0.0123	Statistically Significant
As-received 100 mm	3.863	53	0.0003	Statistically Significant
Fibre Type-II E-glass				
As-received (50 vs 100 mm)	3.356	55	0.0014	Statistically Significant
Spread (50 vs 100 mm)	5.213	57	<0.0001	Statistically Significant
As-received Vs Spread (50 mm)	0.746	58	0.4584	Not Statistically Significant
As-received Vs Spread (100 mm)	3.850	51	0.0003	Statistically Significant
Fibre Type-II Carbon				
As-received (50 vs 100 mm)	6.781	50	<0.0001	Statistically Significant
Spread (50 vs 100 mm)	7.175	57	<0.0001	Statistically Significant
As-received Vs Spread (50 mm)	-1.193	55	0.2379	Not Statistically Significant
As-received Vs Spread (100 mm)	-2.096	52	0.0409	Statistically Significant

To summarise, the influence of spreading on tensile behaviour, of type-II E-glass and type-IIC carbon fibre bundles, was analysed. It was observed that, in the case of type-II

E-glass fibre bundles, there was a reduction in the average peak load in spread fibre bundles, in comparison to as-received fibre bundles. A t-test analysis determined that this was a significant difference at a gauge length of 100 mm. This is likely to be due to an increase in the influence of friction, as well as an increase in the locally redistributed load. Put simply, the spread fibre bundle was more sensitive to filament failures. The difference in average peak load, between as-received and spread type-II E-glass fibre bundles at a gauge length of 50 mm, was determined to not be statistically significant.

By contrast, the average peak load in type-IIC carbon fibre bundles exhibited a small increase in the average peak load. This is not due to the spreading improving fibre properties, but more likely due to an improvement in fibre bundle architecture, leading to more efficient loading of the filaments. This was determined to be statistically significant at a gauge length of 100 mm. However, at a gauge length of 50 mm it was not statistically significant.

In line with the current literature, an increase in gauge length resulted in a decrease in the average peak load; this was true for both as-received and spread fibre bundles. In addition, this change was highlighted in the survival probability analysis. The survival probability reduced as the gauge length increased. It was also observed that there appears to be a threshold for the sensitivity of a fibre bundle, to its respective flaw distribution, depending on the gauge length. This was highlighted by an increase in the shape parameter as the gauge length increased.

4.5 Tensile Testing of Composites

Subsequent to developing unique techniques for spreading E-glass and 12k carbon fibres, attention was given to manufacturing and evaluating mono-fibre and hybrid

composites. A summary of the types of composite configurations that were manufactured and evaluated, along with the thicknesses and fibre volume fraction (V_f) of each class of composite are presented in Table 4.5.

4.5.1 Composite Lay-up and Fibre Volume Fraction (V_f)

The thicknesses of the composites that were manufactured using the spread fibres were lower, between 68% and 84%, when compared to those manufactured using the as-received fibres. The reduction in the thicknesses of the hybrid composites when manufactured using spread fibres was between 78% and 81% when compared to those produced using the as-received reinforcements. The average thickness for the single-layer E-glass composites was 0.238 mm and this decreased to an average thickness of 0.037 mm in the case where spread fibre bundles were used to manufacture the composite. The thickness of single-layer carbon composites manufactured using as-received and spread fibre bundles were 0.128 mm and 0.041 mm respectively.

Table 4.5 Average thickness and V_f for composites manufactured using as-received and spread fibre bundles. AR and S stand for as-received and spread respectively and the % change refers to the difference in thickness and V_f for composites manufactured using the as-received and spread fibres.

Fibre Type	Lay-up (Number of Layers)	Average Thickness (mm)			Fibre Volume Fraction (V_f)		
		AR	S	% Change	AR	S	% Change
E-glass Type-II	Mono-fibre (1)	0.238	0.037	-84	58.13	64.03	10
Carbon Type-IIC	Mono-fibre (1)	0.128	0.041	-68	44.69	19.41	-57
E-glass Type-II	Mono-fibre (3)	0.400	0.102	-75	51.87	62.33	20
Carbon Type-IIC	Mono-fibre (3)	0.284	0.052	-82	42.47	27.51	-35
E-glass Type-II/Carbon Type-IIC	Hybrid [GCG] (3)	0.396	0.085	-79	52.14	63.14	21
E-glass Type-II/Carbon Type-IIC	Hybrid [CGC] (3)	0.334	0.065	-81	54.75	49.60	-9
E-glass Type-II	Mono-fibre (6)	0.718	0.190	-74	54.03	65.40	21
Carbon Type-IIC	Mono-fibre (6)	0.440	0.085	-81	41.66	42.31	2
E-glass Type-II/Carbon Type-IIC	Hybrid [GCG] _{2s} (6)	0.762	0.168	-78	51.46	58.93	15
E-glass Type-II/Carbon Type-IIC	Hybrid [CGC] _{2s} (6)	0.635	0.141	-78	53.24	51.34	-4

Czél *et al.* (2012) reported thicknesses of 0.067 mm and 0.037 mm for two types of preregs consisting of spread carbon fibres (Simgatex IMS65 E23 and Oxeon UTS50 F22S). In a further study, Czél & Wisnom (2013) reported the thickness for a three-layer hybrid composite to be 0.597 mm. This hybrid was manufactured using spread carbon fibres in the central ply with as-received E-glass preregs forming the outside layers. The thickness of the E-glass layer was reported to be 0.125 mm; this is thinner than the as-received E-glass fibre composites manufactured in the current study. However, the three-layer [GCG] hybrid composite that was manufactured in the current study, using spread fibres, had an average thickness of 0.085 mm. This is 85% thinner than that reported by Czél & Wisnom (2013). The three-layer [GCG] hybrid composites manufactured using as-received fibres in the current study, were 34% thinner than that presented by Czél & Wisnom (2013).

Figure 4.75(i-iv) shows representative micrographs, of individual as-received type-II E-glass fibre bundles, that were impregnated without changing the fibre architecture. In other words, the as-received bundles were immersed in the resin system which was permitted to permeate into the bundle naturally. It is clear from these micrographs that the shapes of the as-received E-glass bundles show significant variations from bundle-to-bundle.

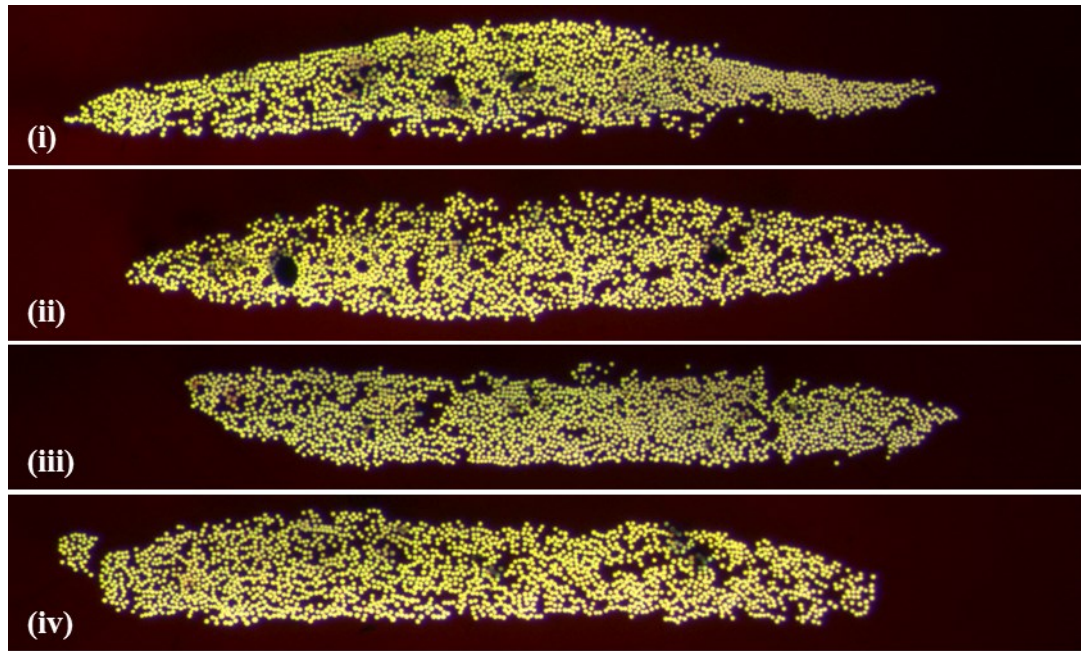


Figure 4.75 (i-iv) Micrographs illustrating the general shape and fibre architecture of the as-received type-II E-glass fibre bundles. The fibre architecture was maintained during impregnation and subsequent curing. (Micrographs supplied by T Ma, University of Birmingham, 2016).

It is also clear that these bundles will distort when manual impregnation and consolidation techniques are used to manufacture the composite. The same can be said when these fibre bundles are subjected to spreading. However, the width-control bar that was used in the current study was implemented to overcome this problem and to control the width and the general fibre orientation. Furthermore, the ends of the preform were secured using adhesive, after the post-process to ensure that the relative fibre orientation was maintained during impregnation.

Figure 4.76(i-ii) show typical micrographs obtained for composites that were manufactured using as-received type-II E-glass composites; these composites were manufactured by three independent researchers, including the author. Here, the resin was massaged into the bundle using conventional techniques prior to curing. Significant effort was expended in developing processing techniques to minimise the movement of the filaments during impregnation. The researchers who were involved in

this pro-active and collaborative effort include the author, T Ma and R Mindell of the Sensors and Composites Research Group. As it was a joint venture, some data and associated micrographs were shared. However, in all cases due credit was given to the originator of the material.

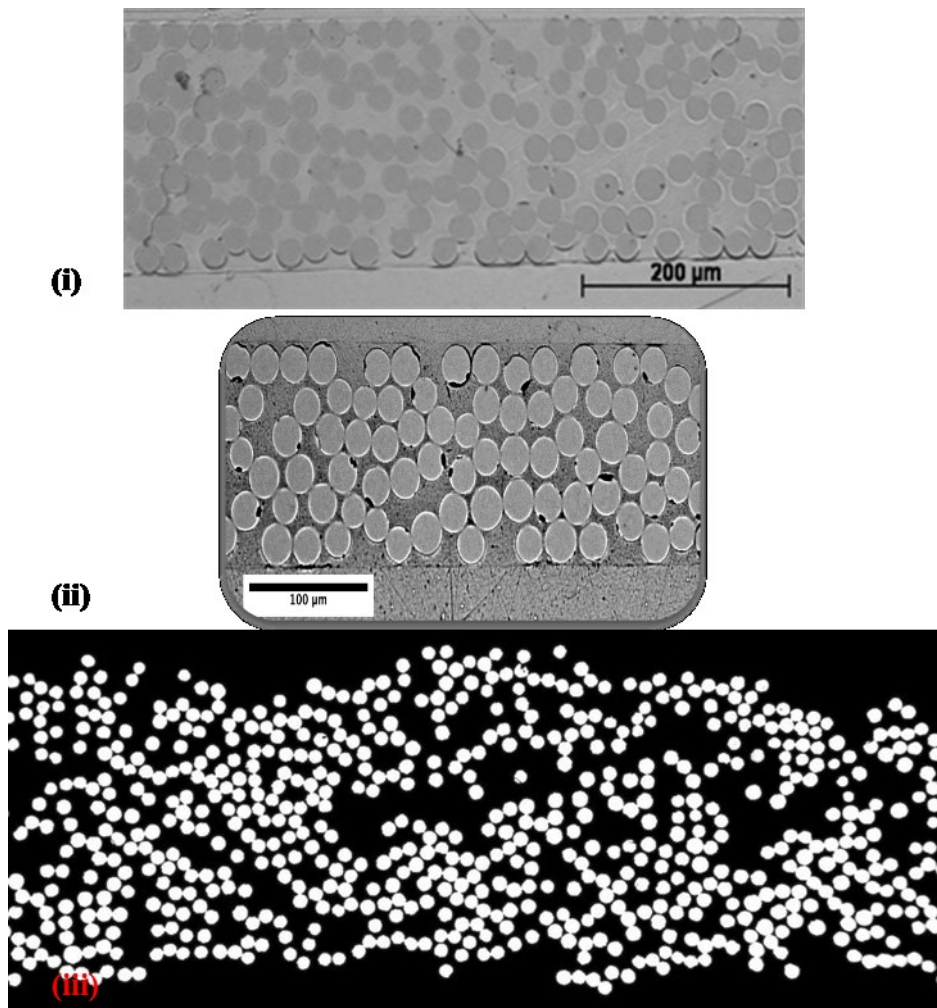


Figure 4.76 (i-iii) Typical transvers sections of composites manufactured from as-received type-II E-glass fibres. The micrographs were manufactured by: (i) the author; (ii) R Mindell (University of Birmingham, 2016); and (iii) T Ma (University of Birmingham, 2016).

On inspecting Figure 4.76(i-iii), it is apparent that there is significant variation in the three micrographs. This may be indicative of operator-dependence with regard to the

quality and the consistency of the composites manufactured by manual impregnation. Time constraints did not permit a detailed investigation into the use of resin films to impregnate the preforms.

The in-house process was inspected and then improved in a sequential manner whereby the procedures developed enabled a mono-layer of E-glass fibres to be produced; see Figure 4.77. This mono-layer of E-glass was obtained by post-processing the E-glass that was spread using the fibre spreading rig, the fibre volume fraction of photographed area is 0.78.



Figure 4.77 Micrograph showing a mono-layer of post-spread 2400 Tex E-glass (T. Ma, 2016).

Although it was possible to produce mono-layer preforms, the retention of the fibre architecture during impregnation and curing was not assured per sample. As will be seen later, this variability may account for the scatter in the tensile properties of the single-layer composite. Significant effort was made to produce mono-fibre and hybrid composites where the void content and the presence of resin rich regions was minimised. However, due to the intrinsic variability in the as-received and spread reinforcements this was not always possible. It is emphasised that great care and attention was paid to the quality of the composites. The literature review indicated that a similar rigor was not applied universally to the quality of composites.

Figure 4.78(i) shows the situation where the filaments seem to take a “sinusoidal” position with the alternating fibres being displaced to the plane above, the fibre volume fraction of this area is 0.58. Close inspection of the perimeter of the fibres suggests some evidence for de-bonding possibly caused by resin shrinkage. The variability in the filament diameter can be seen in Figure 4.78(ii). This is an intrinsic feature of this fibre type. The distribution of the variability in the diameter of the fibres was not investigated in this study. Another feature seen in Figure 4.78(ii) is the variability in the fibre-to-fibre spacing. A selection of micrographs showing the variability in the fibre architecture after manufacturing the composite is shown in Figure 4.79(i-iv).

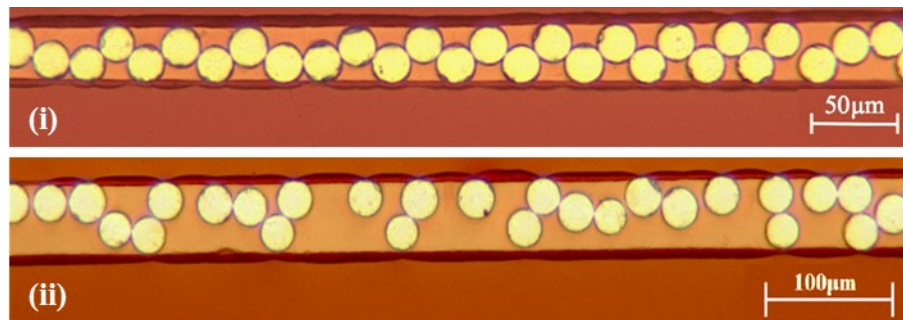


Figure 4.78 Micrographs showing: (i) alternating filaments being displaced above their neighbours; and (ii) the variability in the fibre diameter. (T. Ma, 2016).

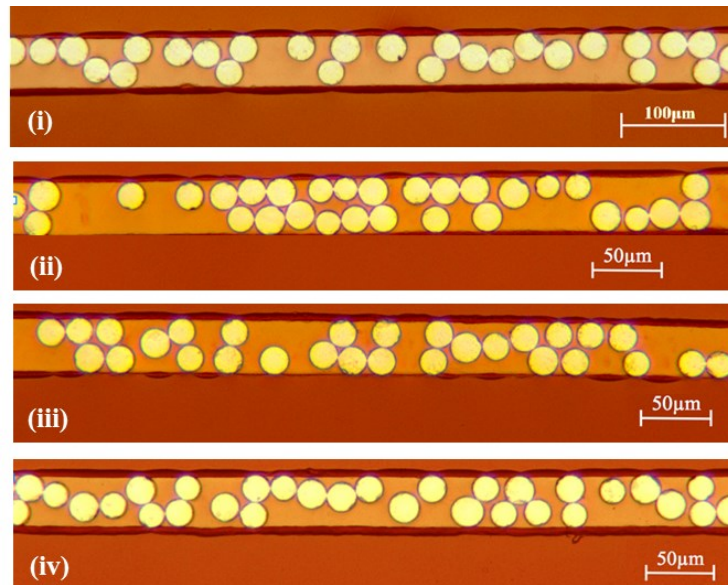


Figure 4.79 (i-iii) Micrographs showing the variability in the fibre-to-fibre distance and the relative fibre volume fractions in three specimens. (T. Ma, 2016).

As for the multiple layered E-glass fibre composites (Figure 4.80), the stacking configuration between two adjacent layers was also seen to be variable. For instance in three layered mono-fibre E-glass spread fibre composites, the filaments can be either on the top of other filaments or stack into the gaps between two filaments, shown in Figure 4.80, the red box (i) indicates filaments stacked one on top of the other, whilst the red circle (ii) shows the filaments stacking in the gaps between their neighbours.

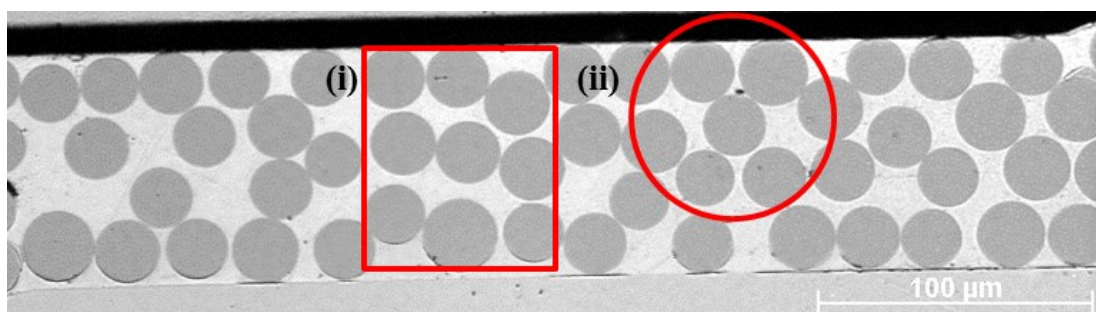


Figure 4.80 A micrograph of a three-layer, mono-fibre composite made from spread E-glass fibres showing: (i) filaments stacked one on top of the other; and (ii) filaments off-set into the space between neighbouring filaments.

With reference to Figure 4.78, Figure 4.79 and Figure 4.80, it is speculated that the following reasons may have contributed to the loss in some of the fibre architecture in the post-processed composites:

(i) Fibre tension: The tension in the individual filaments of the post-processed preform was achieved by bonding the ends with an adhesive. It is possible that the tension in each of the filaments was unequal, where visually the alignment of the post-processed E-glass bundle seemed uniaxial. Any variability in the tension would have caused fibre movement during impregnation.

(ii) Impregnation: It is probable that the impregnation sequences described previously may have resulted in some lateral fibre movement. Since only mono-layer preforms were considered, any minute gaps between the individual filaments would have had an adverse effect on the fibre architecture. This is because the surface tension of the resin would cause any segmentation to coalesce; this will result in the observed variability in the fibre-to-fibre spacing. It is proposed that a combination of variable tension in the filaments and filament movement during impregnation was probably the primary reason for the observed variability.

(iii) Resin shrinkage: It is known that thermosetting resins undergo shrinkage during cross-linking. Since the ends of the post-spread bundle were bonded with an adhesive and secured to the PTFE-coated aluminium plate, the effect of shrinkage would be in the lateral direction. The likely consequence of this would be the sideways displacement of the filaments as observed in Figure 4.78(i).

In the case of the E-glass fibres, it was possible to post-process it obtain mono-layer composites. However, this was not possible with the carbon fibre bundles primarily due to the presence of significant intrinsic meandering filaments.

Evidence for the presence of intrinsic meandering filaments within the bundle is shown in Figure 4.81

It is interesting to note that presence of intrinsic meandering of filaments within the bundle did not seem to affect the degree of spreading that could be achieved. Instead, it was observed that the original trajectory of the off-axis filaments was exaggerated during vacuum-assisted fibre spreading. However, these off-axis filaments prevented any significant post-processing to minimise segmentation in the spread bundle. Furthermore, any attempt to manipulate these off-axis or meandering filaments resulted in significant filament movement leading to more (unacceptable) segmentation and gaps being created in the spread bundle.

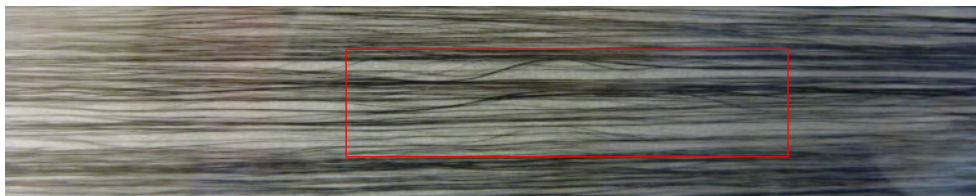


Figure 4.81 Evidence for the presence of intrinsic meandering in a spread type-II C carbon fibre bundle; the red box highlights areas of obvious inherent filament meandering.

Table 4.5 presented a summary of the average fibre volume fractions (V_f) for the composites manufactured in this programme. A higher V_f was observed for the composites that were manufactured using the spread mono-layer of E-glass when compared to those manufactured using the as-received fibres. The V_f in the single, three,

and six-layer spread composites manufactured using the spread fibres were 10%, 20% and 21% greater than those manufactured using the as-received reinforcement. Figure 4.82 shows representative micrographs for the three-layer composites that were manufactured using as-received and spread type-II E-glass fibre bundles.

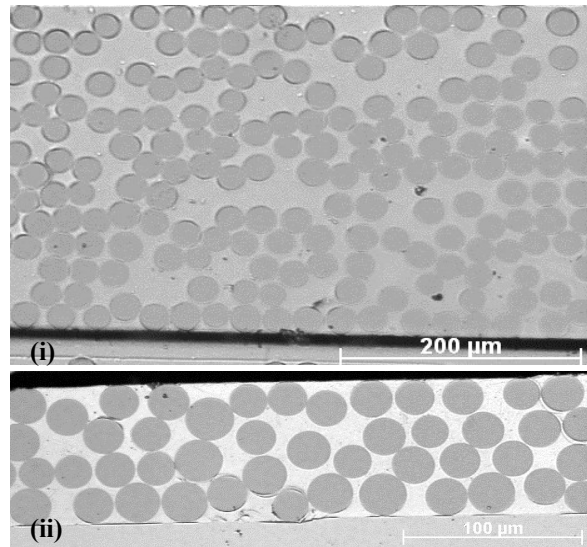


Figure 4.82 Representative micrographs of the mono-fibre, three-layer, type-II E-glass composites manufactured using: (i) as-received; and (ii) spread fibres.

The average V_f of the composites manufactured using single and three-layer spread carbon fibres, were 57% and 35% lower respectively when compared to those manufactured using the as-received fibres. By contrast, the composites manufactured using six layers of as-received and spread carbon fibres were similar (41% and 42% respectively). Figure 4.83 illustrates representative micrographs for carbon fibre composites manufactured using three-layers of as-received and spread carbon fibres.

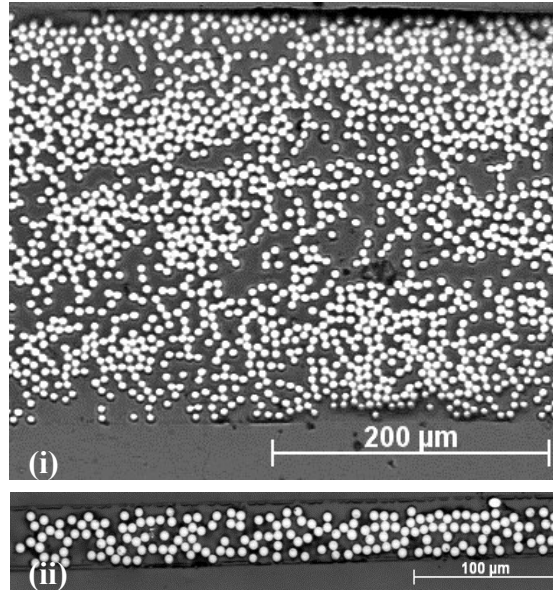


Figure 4.83 Representative micrographs of the mono-fibre, three-layer, type-II carbon composites manufactured using: (i) as-received; and (ii) spread fibres.

The average V_f of the three and six-layer [GCG] and [GCG]_{2s} hybrid composites manufactured using spread fibre bundles were 23% and 15% higher than those manufactured using as-received fibre bundles. On the other hand, the average V_f of the three and six-layer [CGC] and [CGC]_{2s} hybrid composites manufactured using spread fibre bundles were 9% and 4% lower than those manufactured using as-received fibre bundles.

Figure 4.84 and Figure 4.85 show representative micrographs of the [GCG] and [GCG]₂ hybrid composites manufactured using as-received and spread fibre bundles respectively. Figure 4.86 and Figure 4.87 illustrate representative micrographs of the [CGC] and [CGC]₂ hybrid composites using the as-received and spread fibre bundles.

Figure 4.84 highlights the dramatic change in thickness, as well as the improvement of the fibre architecture within the composite. In Figure 4.84(i) it is seen that the as-received carbon fibre bundle is not positioned at the centre of the three-layer [GCG] composite. This was possibly due to the original architecture of the E-glass bundle as

discussed previously. Some evidence for fibre-matrix de-bonding can be seen in the central region of the micrograph, this is surprising because the composites manufactured in this programme were cured at room temperature and post-cured at 80 °C for 6 hours. It is speculated that the variable binder content may have been a contributing factor. However, further research is required to identify the root cause of this shrinkage induced de-bonding. Another possibility, given the lower than average thickness of the composites manufactured in this programme, the observed fibre-matrix de-bonding may have been caused during handling and the preparation of samples for microstructural investigations via potting and polishing. By contrast Figure 4.84(ii), [GCG]_s composite manufactured using spread fibres exhibited highly ordered filaments of E-glass, with the carbon fibre layer lying centrally between the two E-glass fibre layers. The composites manufactured using spread reinforcements were nearly void-free. This was not necessarily the case for the composites manufactured using the as-received reinforcements. This is attributed to the variability in the as-received reinforcements as shown previously in Figure 4.75, where soaking the as-received bundle in the resin did not enable the resin to penetrate fully to the centre regions of the bundle.

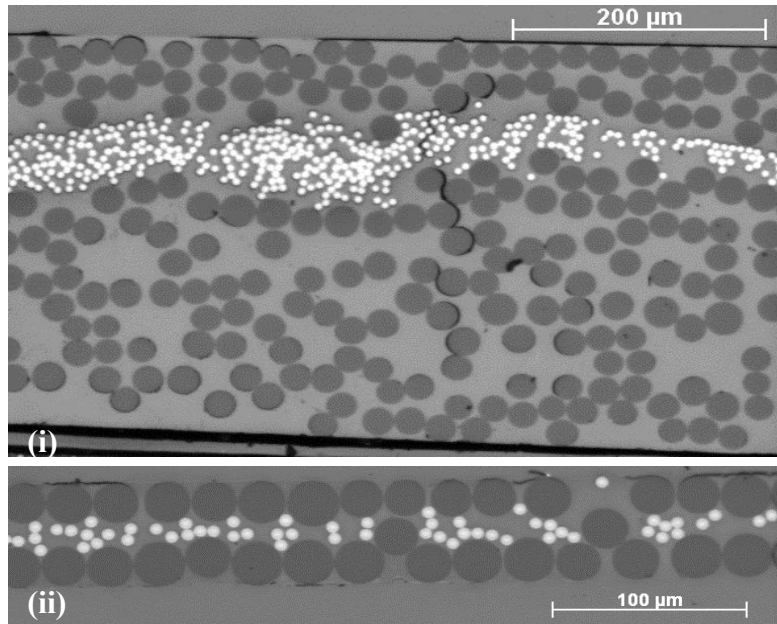


Figure 4.84 Representative micrographs of the three-layer [GCG] hybrid composites manufactured using: (i) as-received; and (ii) spread fibre bundles.

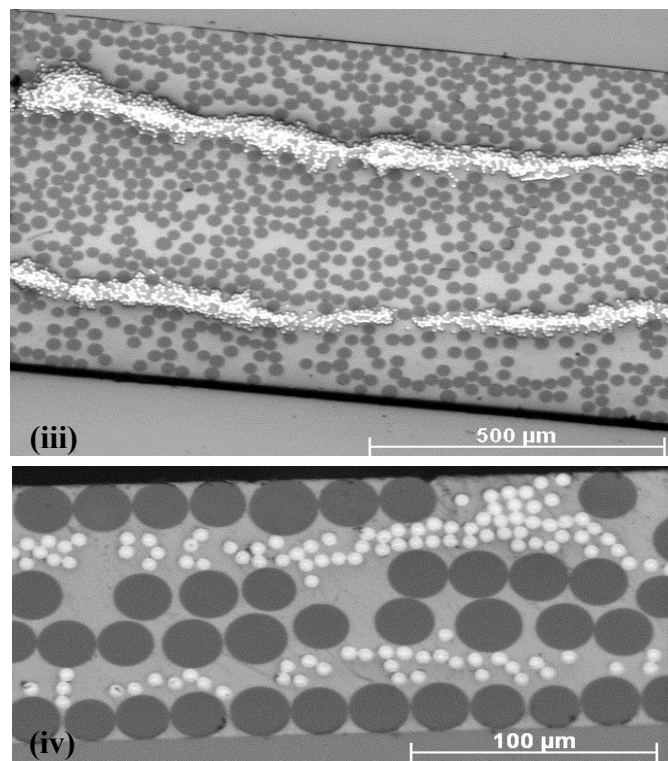


Figure 4.85 Representative micrographs of the six-layer [GCG]₂ hybrid composites manufactured using: (i) as-received; and (ii) spread fibre bundles.

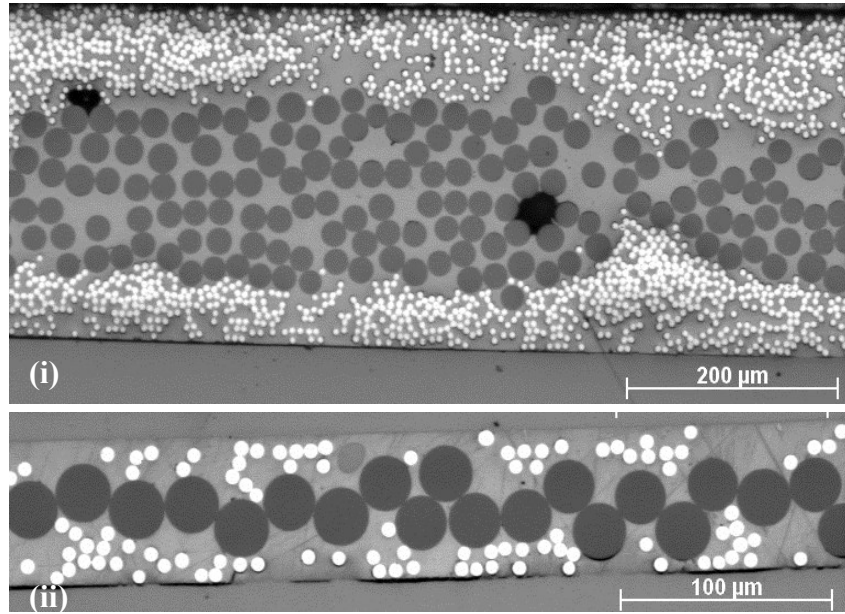


Figure 4.86 Representative micrographs of the three-layer [CGC] hybrid composites

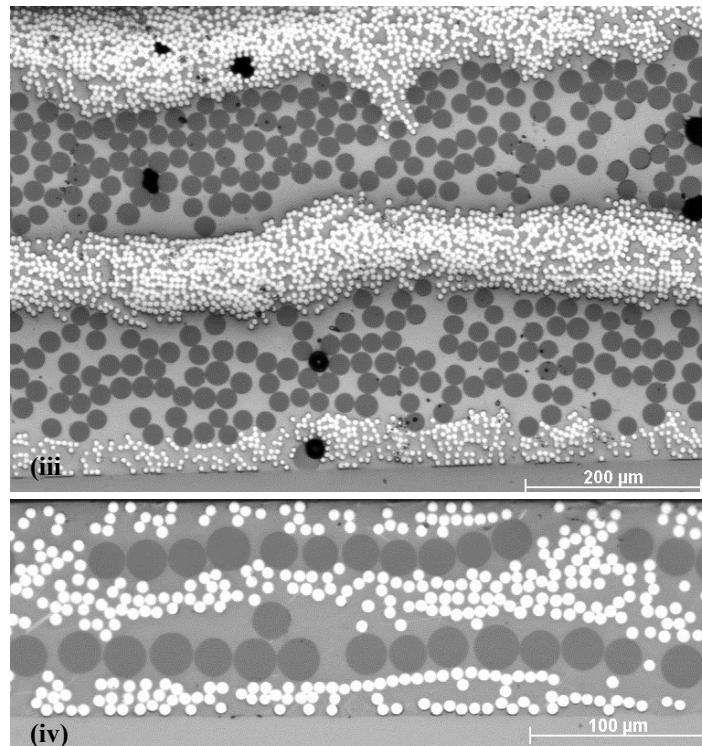


Figure 4.87 Representative micrographs of the six-layer [CGC]₂ hybrid composites manufactured using (i) as-received and (ii) spread fibre bundles.

In the hybrid composites manufactured using spread fibres, there was significant intimate intermingling between the E-glass and carbon filaments compared to the hybrid composites manufactured using the as-received fibres. Historically, the hybrid models were based on an idealised fibre architecture, in which the two types of reinforcing fibres alternated at the filament level (Zweben, 1977; Fukuda & Chou, 1982; Fukunaga, Fukuda & Chou, 1984).

Whilst this has not been achieved, there has been an increase in the intermixing of the filaments in the hybrid composites manufactured using spread fibres compared to the composites manufactured using the as-received fibres. There are regions in which two to four carbon filaments are surrounded by four E-glass filaments. In areas where the carbon filaments are surrounded by E-glass filaments the chance of cracks originating in the carbon filaments being arrested by the E-glass filaments would be greater. Furthermore, the dispersion of the two filament types, in the spread composites, was observed to be highly ordered single-layers of filaments; the ideal dispersion suggested in a model proposed by Swolfs *et al.* (2015).

The closest examples of layered and intimately mixed hybrids, in the literature to date, are found in Czél *et al.* (2012), Czél & Wisnom (2013) and Diao *et al.* (2014). Presented in Figure 4.88, is a representative micrograph of the three-layer [GCG] hybrid manufactured by Czél *et al.* (2012). In Figure 4.89, is the spread intra-mingled glass/carbon bundle hybrid presented in Diao *et al.* (2014).

It can be seen in Figure 4.88, that there were a large number of voids within the E-glass layers. The carbon layer was positioned centrally, however no inter-mixing of the two filament types was observed.

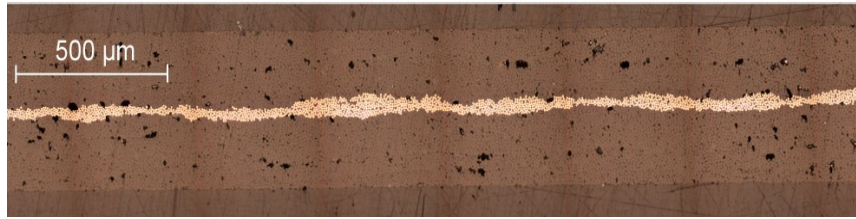


Figure 4.88 A representative micrograph of the [GCG] hybrid manufactured by Czel *et al.* (2012).

With reference to Figure 4.89, there are no observable voids in the material, and there is inter-mixing within the hybrid. However, according to Swolfs *et al.* (2015) a random dispersion was deemed not to be the most effective filament configuration for a hybrid composite. The hybrid composite presented by Diao *et al.* (2014) is best described as a random dispersion.

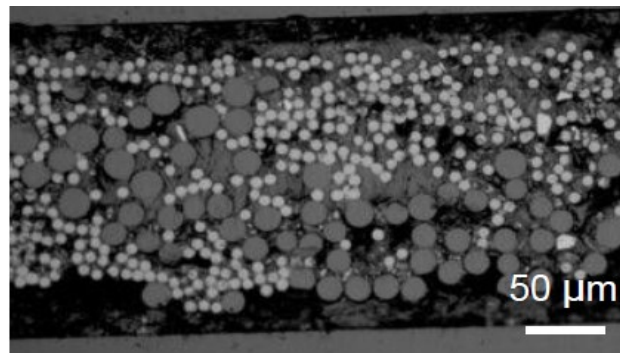


Figure 4.89 A representative micrograph of the spread E-glass fibre/ spread carbon fibre inter-mingled hybrid presented in Diao *et al.* (2014).

4.5.2 Mechanical Properties

The results of tensile testing the mono-fibre and hybrid composites manufactured using as-received and spread fibre preforms, will be presented in this section. The following nomenclature is used to describe the different types of composite manufactured and evaluated in this project.

- (i) As-received composite = a composite manufactured using as-received 2400 Tex E-glass or 12K carbon fibres
- (ii) Spread composite = a composite manufactured using spread 2400 Tex E-glass or 12K carbon fibres
- (iii) Mono-fibre: a composite manufactured using one type of reinforcement
- (iv) Hybrid composite: a composite manufactured using E-glass and carbon fibres

It is generally appreciated the unidirectional glass fibre composites fail by longitudinal splitting where the initial damage is thought to originate at transverse fibre fractures. This posed a problem in the current study because in some instances the surface mounted strain gauges failed before the ultimate failure stress was attained. Therefore, this meant that the failure stress and Young's modulus could be calculated but not the ultimate failure strain via the electrical resistance strain gauges.

The premature failure of the strain gauge can be seen in Figure 4.90 along with the data from the mechanical test machine (Instron). The modulus was calculated from the initial linear portion of the strain gauge trace and the stress was calculated from the load data.

In this case, using the modulus obtained from the strain gauge data, the strain was extrapolated using stress from the Instron. The resultant traces are presented in Figure 4.91; with reference to the Figure, the red trace is the translated Instron and the red trace is the extrapolated data. The failure strain calculated for the translated Instron data was 1.49% compared to 1.38% for the extrapolated strain.

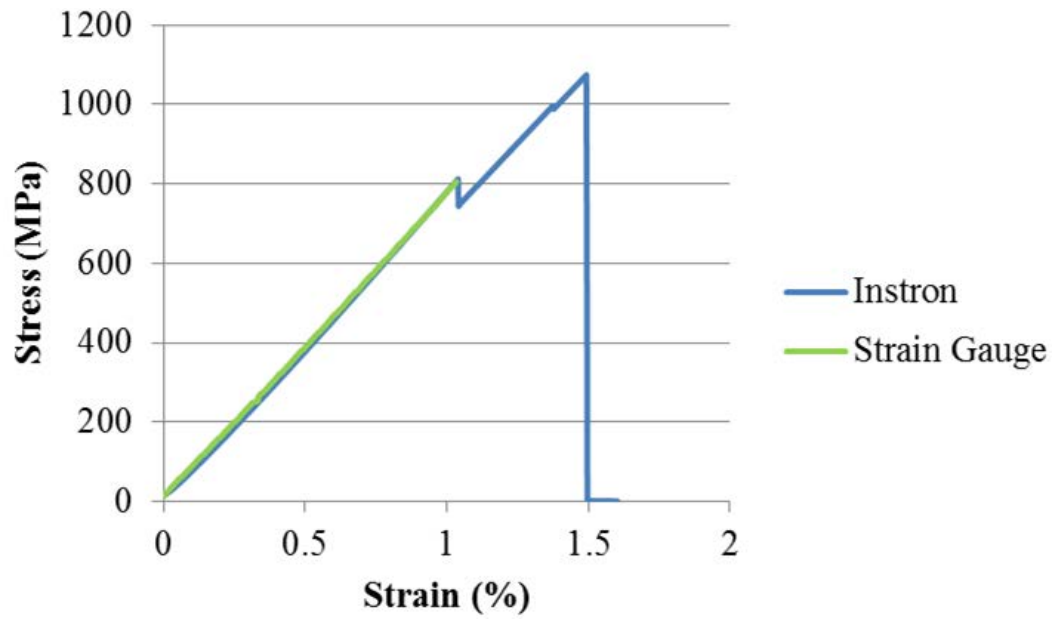


Figure 4.90 A representative stress/strain curve where the strain gauge failed at initial failure.

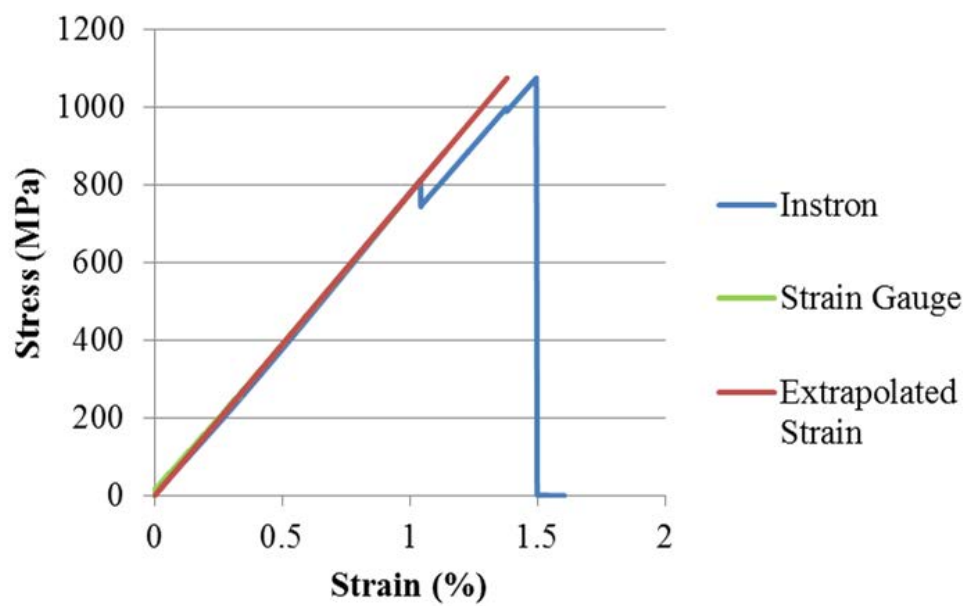


Figure 4.91 A representative stress/strain curve with extrapolated strain data where the strain gauge failed at initial failure.

Presented in Table 4.6, are the average results for each set of composites (mono-fibre and hybrid), tested in both the as-received and spread state; this data are not normalised. The results include the initial failure stress and strain, the final failure stress and strain, and the Young's modulus.

The highest failure stress, 2152 MPa, was observed in the six-layer as-received mono-fibre carbon composite; this set also had the highest modulus, 118 GPa. The lowest failure stress, 515 MPa, and strain, 1.11%, were observed in the single-layer spread mono-fibre carbon composites. The lowest modulus, 32.3 GPa, was observed in the single-layer as-received mono-fibre E-glass composites.

Interestingly, the highest initial stress, 1172 MPa, and strain, 1.57%, were observed in the six-layer mono-fibre carbon spread composites and mono-fibre E-glass composites respectively. On the other hand, the lowest initial stress, 125 MPa, and strain, 0.38%, were observed in the single-layer spread mono-fibre carbon composite.

In order to enable a comparison between data sets, each of the average values was normalised to a fibre volume fraction of 60%. The results of this normalisation are presented in

Table 4.7. The initial and final failure strains are not presented as they were not normalised. Therefore only the initial stress, failure stress and modulus are presented.

Table 4.6 The average data obtained for the mono-fibre and hybrid composites in the as-received and spread state.

Fibre/Lay-up	State	Stress at first failure (MPa)	Strain at first failure (%)	Ultimate failure stress (MPa)	Ultimate failure strain (%)	Young's Modulus (GPa)
1G	AR	483	1.22	637	1.63	32.3
	S	491	1.31	645	1.93	38.1
1C	AR	729	0.89	1487	1.77	83.7
	S	125	0.38	515	1.11	44.9
3G	AR	558	1.38	1000	2.50	41.7
	S	701	1.48	858	1.78	48.3
3C	AR	861	0.85	1857	1.84	98.9
	S	879	1.00	1198	1.35	88.7
[GCG]	AR	623	1.22	1052	2.04	50.4
	S	808	1.43	911	1.52	60.2
[CGC]	AR	814	1.07	1543	1.99	76.6
	S	987	1.30	1202	1.59	75.7
6G	AR	324	0.83	921	2.42	38.4
	S	777	1.57	984	1.98	50.1
6C	AR	1110	0.95	2152	1.80	117
	S	1172	1.14	1407	1.34	104
[GCG] _{2s}	AR	454	0.84	1151	2.09	55.5
	S	788	1.41	1020	1.80	56.7
[CGC] _{2s}	AR	508	0.67	1481	1.83	79.3
	S	871	1.31	1212	1.82	66.6

The ultimate failure stress was highest for the six-layer mono-fibre carbon as-received composites (3099 MPa). The following explanation is offered for this observation, with reference to the micrographs of the single-layer composites presented previously, it was

made clear that there was considerable variation in the architecture of the reinforcement. Moreover, the V_f as a consequence were also variable. Therefore, the single ply composite was significantly more sensitive to parameters such as resin rich regions and meandering filaments. As the thickness is increased the “nesting” of the different layers tends to homogenise the variability in the fibre architecture and V_f . Evidence for the homogeneity in the V_f of the thicker carbon fibre composites was presented in table Table 4.5. Whilst it was possible to attain relatively high V_f for the spread E-glass fibre composites, this was not the case for the spread carbon fibre material. The primary reason for this was attributed to meandering filaments in the as-received carbon fibre bundle.

The lowest ultimate failure stress, 604 MPa, was observed in the single-layer mono-fibre E-glass spread composites. The highest and lowest initial failure stress, were observed in the three-layer mono-fibre spread carbon composite (1916 MPa), and six-layer as-received mono-fibre E-glass (359 MPa) composites respectively. The single-layer spread E-glass fibre composite also exhibited the lowest modulus, 35.7 GPa. The highest modulus was calculated for the three-layer spread carbon fibre composite, 193 GPa.

Table 4.7 The normalised average data for initial and final failure stress and modulus of the composites tested.

Fibre/Lay-up	State	Stress at first failure (MPa)	Ultimate failure stress (MPa)	Young's Modulus (GPa)
1G	AR	499	657	33.3
	S	460	604	35.7
1C	AR	978	1996	112
	S	387	1592	139
3G	AR	646	1156	48.2
	S	675	826	46.5
3C	AR	1216	2624	140
	S	1916	2612	193
[GCG]	AR	717	1210	57.1
	S	768	866	57.2
[CGC]	AR	892	1691	83.9
	S	1194	1454	91.5
6G	AR	359	1023	42.7
	S	712	903	45.9
6C	AR	1599	3099	170
	S	1662	1995	148
[GCG] ₂	AR	530	1342	64.7
	S	802	1038	57.7
[CGC] ₂	AR	572	1669	89.3
	S	1018	1416	77.8

It was expected that the ascending order of strength would be: mono-fibre E-glass, hybrid composites ([GCG]/[GCG]₂) and ([CGC]/[CGC]₂) and mono-fibre carbon composites. This has been found in the literature in studies where E-glass fibre was added to carbon fibre composites in varying volume fractions (Khatri & Koczak, 1995; Pandya, Veerraju & Naik, 2011) and is based on the rule-of-mixtures. As more E-glass is added to a carbon composite the ultimate failure stress and modulus would be expected to decrease. This is because E-glass fibre is less strong and stiff compared to carbon fibre. There should however, be an increase in the failure strain of the composite as more E-glass fibre is added.

Presented in Table 4.8 and Table 4.9 are the average failure stress values, in ascending order, for as-received and spread composites respectively. For the as-received composites, the values do follow the rule-of-mixtures approach. The mono-fibre E-glass composites had the lowest failure stress, followed by the [GCG] and [GCG]₂ hybrid composites, the [CGC] and [CGC]₂ hybrid composites, with the mono-fibre carbon composites having the highest failure stress. The same trend was seen for the spread composites. However, the [GCG] hybrid composite, exhibited a lower stress than the six-layer E-glass composite. This is most likely related to the respective fibre volume fractions of the composites used in the current study. The modulus, using normalised data, was found to directly follow the assumed trend. In ascending order were the E-glass fibre, hybrid and carbon fibre composites. This was found to be true for both the as-received and spread composite configurations.

Table 4.8 The normalised failure stress for the as-received composites in ascending order.

Fibre/Lay-up	Failure σ (MPa)
1G	657
6G	1023
3G	1156
[GCG]	1210
[GCG] ₂	1342
[CGC] ₂	1669
[CGC]	1691
1C	1996
3C	2624
6C	3099

Table 4.9 The normalised failure stress for the spread composites in ascending order.

Fibre/Lay-up	Failure σ (MPa)
1G	604
3G	826
[GCG] _s	866
6G	903
[GCG] _{2s}	1038
[CGC] _{2s}	1416
[CGC] _s	1454
1C	1592
6C	1995
3C	2612

4.5.2.1 As-received Vs Spread Mono-fibre Composites

Further analysis was conducted on the normalised data, presented in Table 4.7, to determine the effect on the mechanical properties, of using spread fibres in the mono-fibre composites. Presented in Table 4.10 are the results. From Table 4.10, it can be seen that the initial stress in spread composites was different to that observed in the as-received composites. For the single-layer composites, using a spread fibre bundle resulted in a reduction in the initial failure stress. The largest reduction, 60.47%, was observed for the single-layer carbon composite. Conversely, for the three and six-layer composites, the spread composite had a higher initial failure stress. The increase in initial failure stress for three-layer E-glass fibre (4.54%) and six-layer carbon fibre composites (3.94%) were not significant increases. However, for three-layer carbon fibre and six-layer E-glass fibre composites, increases in the initial failure stress of 57.50% and 98.28% respectively were observed.

By contrast, the average ultimate failure stress of each of the composites was lower in all of the spread composite configurations. The smallest and largest changes of 0.45% and 28.27% were observed in the three-layer carbon fibre and three-layer E-glass fibre composites respectively.

It was also determined that using spread, as opposed to as-received fibre bundles, had an influence on the modulus of the composites. In each case, with the exception of three-layer E-glass fibre and six-layer carbon fibre composites, there was an increase in the modulus of the composite. The highest increase in the modulus of 38.42% was observed in the three-layer carbon composite.

Table 4.10 Normalised average mechanical properties highlighting the percentage change in initial failure stress, final failure stress and modulus when comparing as-received and spread composites.

Fibre/Lay-up	State	Initial Failure Stress (MPa)	Initial Failure Strain (MPa)	Young's Modulus (GPa)	Initial Failure Stress (MPa)	Initial Failure Strain (MPa)	Young's Modulus (GPa)
1G	AR	499	657	33.3			
	S	460	604	35.7	-7.82	-8.00	7.01
1C	AR	978	1996	112			
	S	387	1592	139	-60.47	-20.22	23.50
3G	AR	646	1156	48.2			
	S	675	826	46.5	4.54	-28.57	-3.58
3C	AR	1217	2624	140			
	S	1916	2612	193	57.50	-0.45	38.42
6G	AR	359	1023	42.7			
	S	712	903	45.9	98.28	-11.74	7.68
6C	AR	1599	3099	170			
	S	1662	1995	148	3.94	-35.65	-12.56

These changes in properties, when using spread fibre bundles in composites, have not been reported previously. There is currently very little work reported in the literature

regarding use of spread bundles in composites. Czél *et al* (2012) and Czél & Wisnom (2013) reported using thin spread carbon bundles. However, these were positioned between layers of as-received E-glass; therefore they were hybrid not mono-fibre composites. In addition, these composites were not solely composed of spread fibre bundles, and, furthermore, no comparison of the mechanical properties was made with mono-fibre or hybrid as-received composites.

The reduction in failure stress, observed in spread composites, is not believed to be a result of the spreading process itself. The reason for the failure stress decrease, across all of the spread composites, is thought to be related to flaw sensitivity. The tensile specimens of spread composites contained far fewer filaments, in comparison to as-received composites. In addition, the spread composites, as mentioned earlier, were significantly thinner. These factors are believed to have increased the sensitivity of the spread composites to flaws.

4.5.2.2 Influence of Hybridisation

In the current study, analysis of the initial failure and final failure strains was conducted, to determine the presence of the hybrid effect. Comparisons were made between the initial and final failure strains of the hybrid composites compared to the mono-fibre composites.

Table 4.11 presents the average initial failure strains of the as-received and spread mono-fibre carbon and hybrid composites. The first failure strain for each hybrid composite was compared to the corresponding as-received or spread, mono-fibre carbon composite.

From Table 4.11, it can be seen that there was an increase in the average initial failure strain for as-received and spread, three-layer [GCG] and [CGC] hybrid composites, when compared to three-layer mono-fibre carbon composites. The greatest increase of 43% was observed in the [GCG] hybrid composites (as-received and spread). This was expected as there was a lower carbon fibre volume fraction in these composites compared to the [CGC] hybrids.

In the case of spread six-layer hybrids, an increase in initial failure strain was also observed, when compared to six-layer mono-fibre carbon composites. Conversely, a decrease in initial failure strain was observed for the as-received six-layer [GCG]₂ and [CGC]₂ hybrid composites.

It is interesting to note that the initial failure strains, for the three-layer and six-layer spread hybrids composites, were greater than the corresponding as-received composites.

Table 4.11 Average initial failure strain for as-received and spread mono-fibre carbon and hybrid composites.

Fibre/Lay-up	State	Initial Failure Strain	% Change
3C	AR	0.85	
	S	1.00	
[GCG]	AR	1.22	43
	S	1.43	43
[CGC]	AR	1.07	25
	S	1.30	31
6C	AR	0.95	
	S	1.14	
[GCG] ₂	AR	0.84	-12
	S	1.41	23
[CGC] ₂	AR	0.67	-30
	S	1.31	15

Presented in Table 4.12 are the final failure strains for the as-received and spread mono-fibre carbon and hybrid composites. It was seen that in each case, as-received and spread, there was an increase in the final failure strain for hybrid composites. The smallest increase in final failure strain was observed in the [CGC2]₂ as-received hybrid composites. The largest failure strain was observed in the [GCG]_{2s} spread hybrid composite.

The ultimate failure strain increased for each of the hybrid composites, compared to the three- and six-layer mono-fibre carbon composites. The increase for the as-received [CGC]_{2s} hybrid of 1% was not a significant increase. The greatest increases in average ultimate failure strain was observed in the spread [GCG]_{2s} and [CGC]₂ hybrid composites; 34% and 34% respectively.

This is interesting, as the spread [GCG]_{2s} hybrid had the largest difference in V_f between the two fibre types; average volume fractions of 8.28% and 50.65% for the carbon and E-glass respectively were measured. Whereas, the difference in volume fraction of the two fibre types in the spread [CGC]_{2s} hybrid was much smaller. In this case the fibre volume fractions were 19.18% and 31.81% respectively. According to the rule of mixtures approach, the failure strain should have been higher in the [GCG]_{2s} spread hybrid composite, in comparison to the [CGC]_{2s} hybrid composite. This is because the ratio of the two fibre types was much greater in the [GCG]_{2s} hybrid composite. The as-received composites showed this relationship. This could mean that by spreading the fibre bundles, the ratio of the two fibre types can be reduced, as the crack arresting potential of the E-glass component is enhanced.

The lowest increase of 8% on the other hand was observed in the [CGC] as-received hybrid average volume fractions of 18% and 36% for the carbon fibre and E-glass fibre respectively. This data fits with findings in the literature that the hybrid effect or synergistic effect of adding E-glass to carbon composites is greater when the carbon fibre is at lower volume fractions.

Table 4.12 Average final failure strain for as-received and spread mono-fibre carbon and hybrid composites.

Fibre/Lay-up	State	Final Failure Strain	% Change
3C	AR	1.84	
	S	1.35	
[GCG]	AR	2.04	11
	S	1.52	13
[CGC]	AR	1.99	8
	S	1.59	17
6C	AR	1.80	
	S	1.34	
[GCG] ₂	AR	2.09	16
	S	1.80	34
[CGC] ₂	AR	1.83	1
	S	1.82	35

The findings with regards to as-received hybrid composites are not new. Inter-ply hybrids have been studied previously (Bunsell & Harris, 1974), and have shown the apparent improvement in failure strain. The apparent improvements in initial and final failure strain, in spread hybrid composites, are new findings with respect to the existing literature.

A number of factors led to the improvements reported here. Firstly, tremendous effort was expended in obtaining spread fibre preforms that fulfilled the original acceptance criteria which were; minimum segmentation, minimum fibre damage (as assessed visually) and a near uniform spatial architecture. Secondly, a large volume of work was

undertaken to retain the fibre architecture prior to impregnation. Ultimately this involved the “pinning” of the extreme ends of the preforms with fast curable adhesive. Thirdly, the sequential improvement in the method of impregnation was developed to ensure minimum filament movement and maximum V_f . Due to the extremely thin, in some case mono-layer, architecture of the spread bundles, impregnation was almost instantaneous. Another improvement was the apparent lack of voids in most of the spread composites. This reduction in void content, and improved impregnation, will have reduced the occurrence weaker failure initiation sites such as entrapped air and resin rich regions. Fourthly, the edges of the composite were polished using a fine-grit adhesive paper on a belt grinder. Fifthly, due care and attention was paid to ensure that the reinforcing fibres were uniaxial where practically possible. Finally, the sample was loaded to ensure that axial loading of the filaments was predominant. The intimate nature of the E-glass and carbon filaments meant that the crack arresting potential of the E-glass filaments in a hybrid composite was enacted as stated by Zweben (1977), Czél & Wisnom (2013) and Diao *et al* (2014)

The data suggests that greater improvements, in initial and final failure strain, can be achieved when using hybrid composites manufactured using spread reinforcing fibre bundles. The use of individually spread and impregnated hybrid fibre bundles has been reported once in the literature, by Diao *et al.* (2014). The quality of that hybrid fibre composite was shown in Figure 4.89. The spread hybrid composites manufactured in the current study represent the closest example of a hybrid composite in which the two reinforcing fibre types are dispersed as intimately and uniformly as practically possible. However, it is accepted that the quality of the composite can be improved even further using the procedures developed by the author. With reference to the idealised hybrid

composite proposed by Swolfs *et al.* (2015) the recommendation was for individually spread mono-filament layers to be laminated in an alternating pattern – this current programme made this possible and demonstrated that such a stacking sequence, in a hybrid composite, does lead to an apparent increase in the initial and final failure strains when compared to a mono-fibre carbon composite.

4.5.3 AE Analysis: As-received, Spread and Hybrid Composites

In the current literature, there is not one universally agreed upon method for analysing AE data from composite materials. The different failure mechanisms exhibited by composite materials, such as fibre fracture and matrix cracking, should have different AE characteristics.

The parameters most commonly analysed include: amplitude, energy and frequency. When trying to distinguish between failure modes, amplitude is the most widely considered factor. Previous work has aimed to determine the amplitude ranges for different failure mechanisms. However, there are differing reports with regards to which amplitude range represents a specific failure mode.

For example, Barré & Benzeggah (1994) reported ranges of amplitude, for four different failure modes; these ranges are presented in Table 4.13. The authors stated that the ranges presented were not firm, and may differ in each material. Proof of this is provided by Zheng *et al.* (2000), who recorded an amplitude signal, during a failure event, of 72.7 dB. According to Barré & Benzeggah (1994) this would represent a fibre pull-out failure. This was however impossible, as the specimen from which this amplitude was recorded, was purely composite of matrix material. Zheng *et al.* (2000) also recorded a fibre pull-out failure with an amplitude of 62.3 dB. This falls outside of

the range, proposed by Barré & Benzeggah (1994), for this failure type. This information makes it clear that determining failure mechanisms using amplitude alone can be inaccurate.

Table 4.13 The amplitude ranges and associated failure modes proposed by Barré & Benzeggah (1994).

Amplitude Range (dB)	Failure Mode
40-55	Matrix Cracking
60-65	Interface Failure
65-85	Fibre Pull-out
85-95	Fibre Fracture

In a more recent study, Fotouhi *et al.* (2016) studied the failure mechanisms of a uni-directional hybrid composite. The hybrid composite used was the same that was used by Czél *et al.* (2012) and Czél & Wisnom (2013). Using amplitude and energy, the authors split the AE data into specific ranges, each relating to a specific failure mode. Presented in Figure 4.92 is a schematic example of the regions associated with each failure mode.

Three distinct regions were defined:

1. Noise (amplitude 40-65 dB; 0-30 aJ)
2. Delamination and matrix cracking (60-85 dB; 30-800 aJ)
3. Fragmentation (75-100 dB; 800-65000 aJ)

It can be seen in Figure 4.92, that even with using energy as a further defining parameter, the amplitude ranges are not completely separate from one another. Whilst this is not a perfect method, it provides useful information and can be used as a guide.

Using the ranges defined by Fotouhi *et al.* (2016), comparisons were made between failure in as-received and spread, and mono-fibre and hybrid composites from the current study.

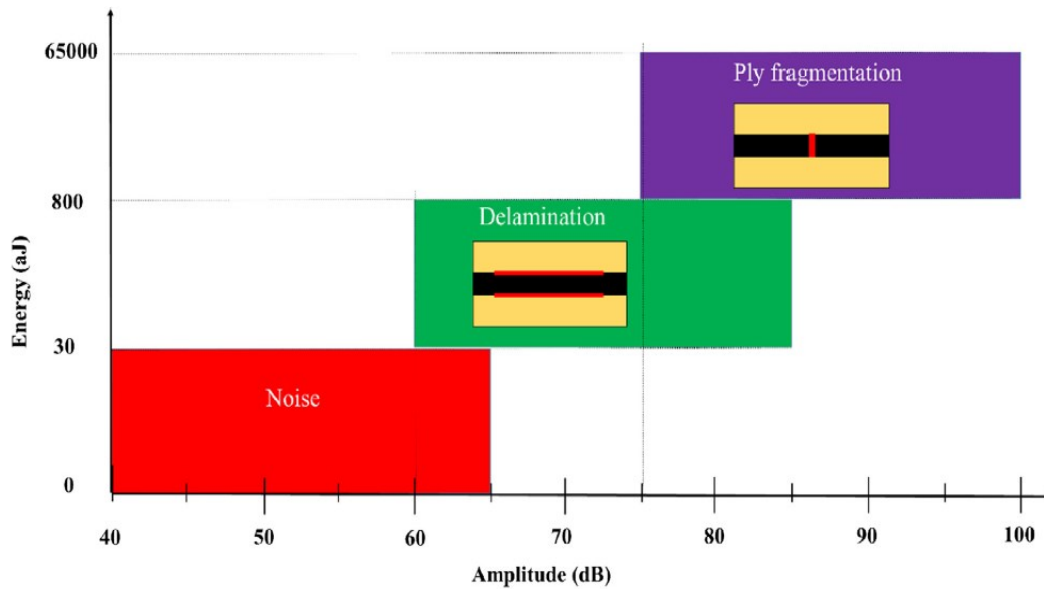


Figure 4.92 A schematic illustration of the amplitude and energy ranges associated with failure in a hybrid composite; Fotouhi *et al.* (2016).

Presented in Figure 4.93 and Figure 4.94, are representative examples of three-layer, as-received and spread, mono-fibre carbon composites respectively.

The first observation was that there were significantly more AE events recorded in the as-received sample. In the spread sample, the AE events recorded up to peak load were predominantly noise (40-64 dB). At final failure, a band of AE events was observed that exhibited amplitudes in the ranges of delamination/matrix cracking and fibre fracture. The sudden death of the spread composite at the first indication of damage provides evidence for the sensitivity of the spread composites to flaws.

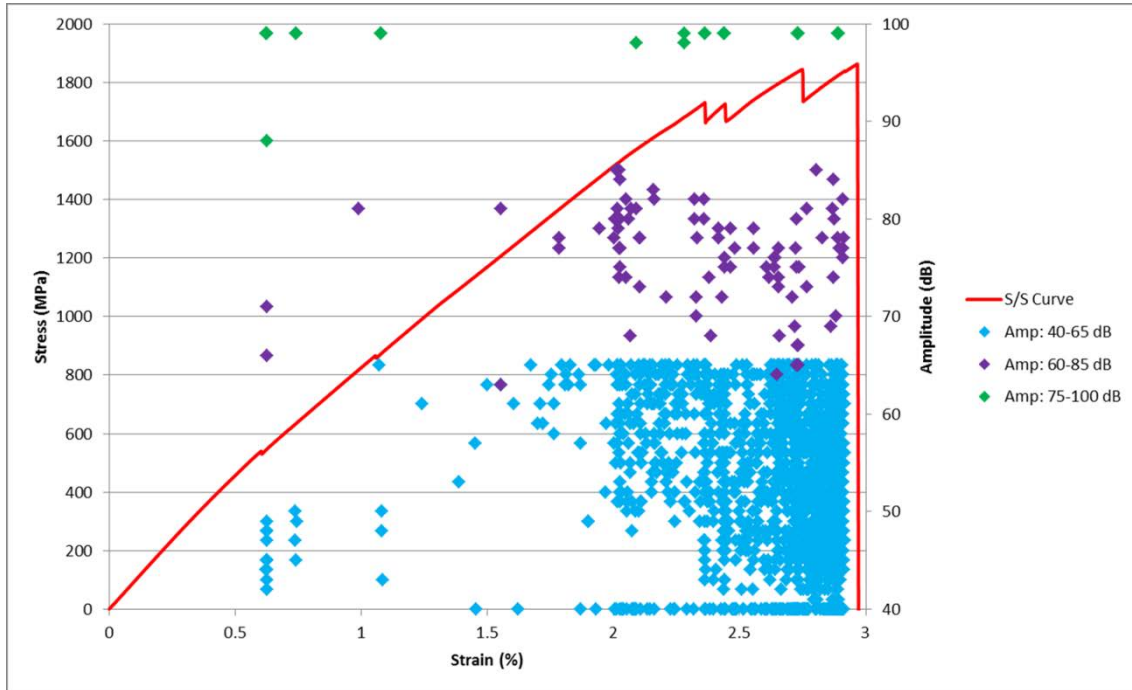


Figure 4.93 A representative example of the AE distributions recorded in a three-layer as-received mono-fibre carbon composite.

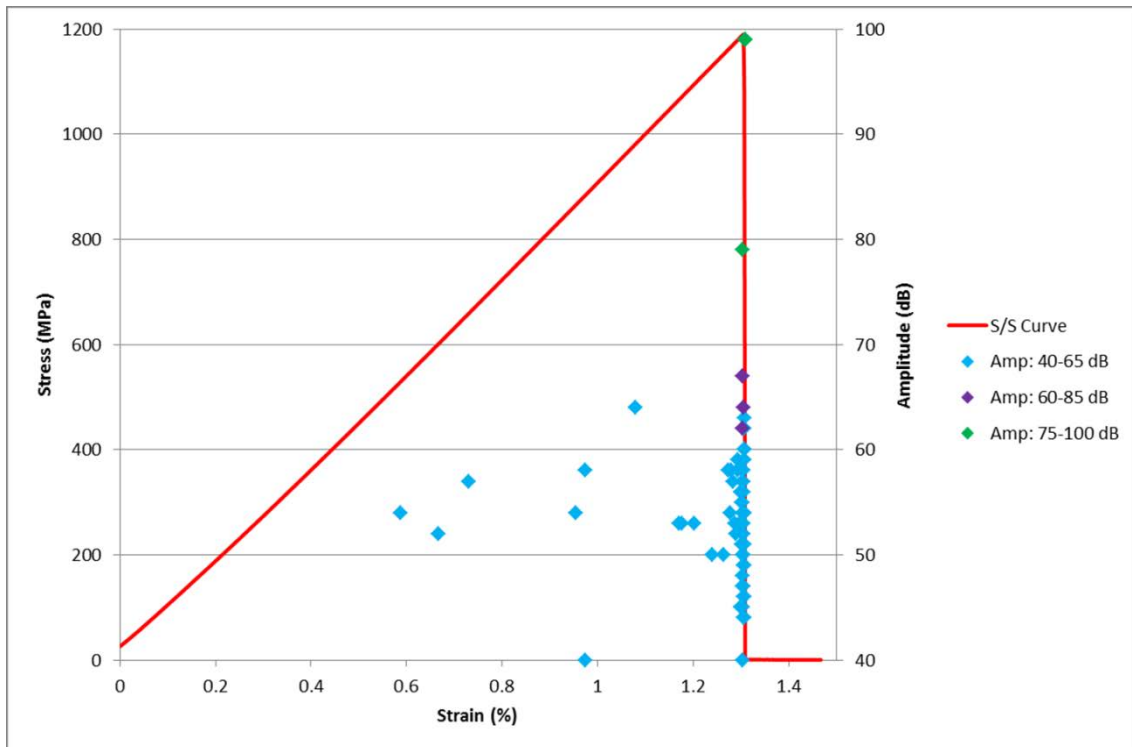


Figure 4.94 A representative example of the AE distributions recorded in a three-layer spread mono-fibre carbon composite.

Presented in Figure 4.95 and Figure 4.96 are examples of as-received and spread, three-layer, mono-fibre E-glass specimens. With reference to Figure 4.95, there are significantly more AE events in the lower amplitude region (40-65 dB), in comparison to the as-received carbon composite. Fotouhi *et al.* (2016) defined this region as noise with no further explanation. Whilst the energy data was also used to determine failure modes, it was observed that, as with amplitude, the regions had some overlap. A large proportion of the events were at the higher end of the amplitude range (>50 dB). Taking the amplitude ranges defined in Table 4.13 (Barré & Benzeggah, 1994), it is possible that some of the low amplitude AE events were associated with matrix cracking and low energy delamination events.

With regards to the spread sample, fewer overall AE events were recorded; this suggests the material withstood a smaller amount of damage before final failure. As with the as-received sample, a large number of low amplitude AE events were at the higher end of the noise range. In addition, at each significant load drop in the stress/strain curve, it was observed that bands of AE events were recorded. Using the initial failure as an example, just above 1% strain, there were a number of AE events recorded in each amplitude range. The predominant failure mode was characterised visually, during testing, to be longitudinal splitting. This would fit with the AE data as a number of AE sources would be present in this kind of failure. For example, there was friction between the two newly formed fracture surfaces, matrix cracking in the longitudinal direction, and filament failure at the end of the split. These events would fall into the low, medium and high amplitude ranges respectively. This banding of AE events was observed in the as-received and spread mono-fibre E-glass composites.

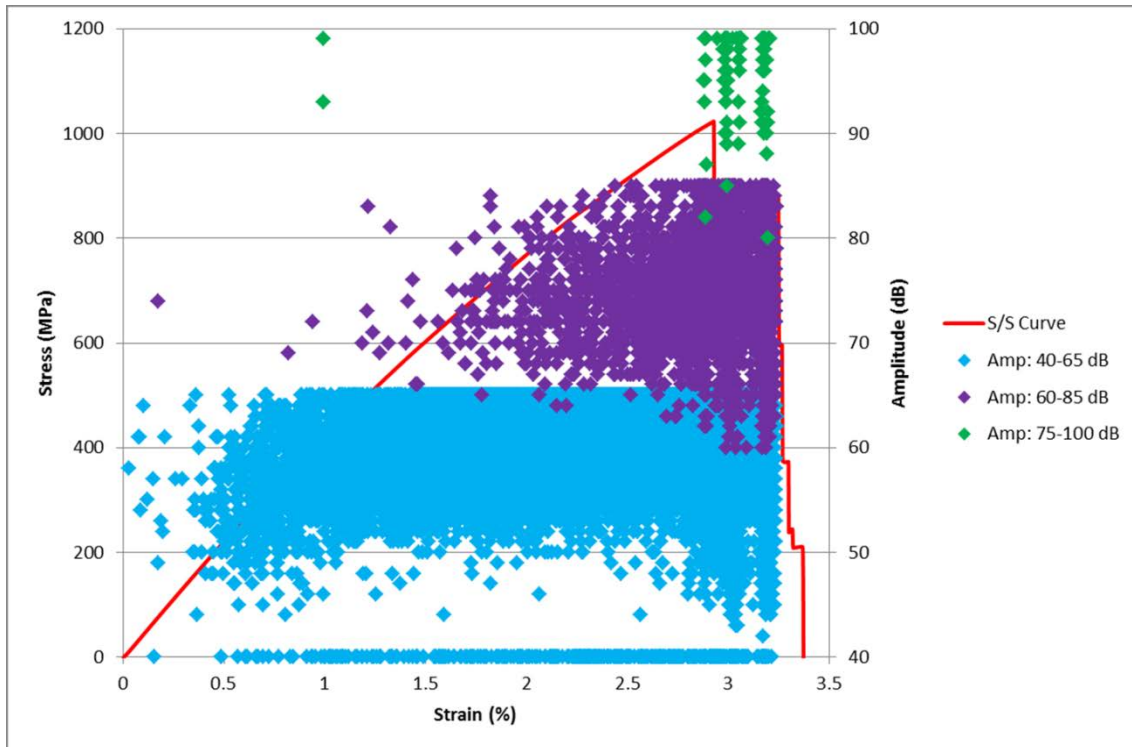


Figure 4.95 A representative example of the AE distributions recorded in a three-layer as-received mono-fibre E-glass composite.

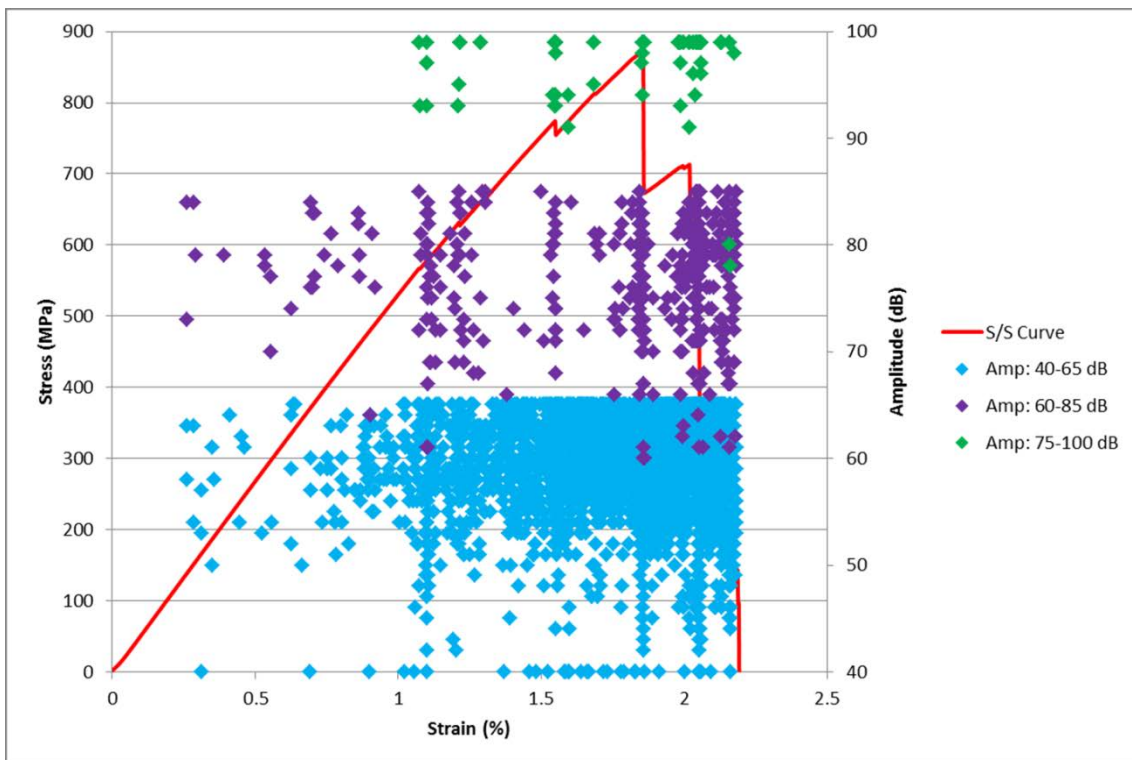


Figure 4.96 A representative example of the AE distributions recorded in a three-layer spread mono-fibre E-glass composite.

The AE events for hybrid composites were analysed, in order to determine whether there was any discernible difference in the failure behaviour. Only examples of spread hybrid composites will be presented here.

Presented in Figure 4.97, Figure 4.98, Figure 4.99 and Figure 4.100, are representative examples of AE events recorded, during tensile testing of three-layer [GCG] and [CGC] hybrids, and six-layer [GCG]₂ and [CGC]₂ hybrids respectively. Comparisons with the mono-fibre spread carbon and E-glass composites were made. With regards to as-received hybrid composites, similar trends in AE events were observed; i.e. spread composites exhibited fewer AE hits overall.

The [GCG] (Figure 4.98) and [GCG]₂ (Figure 4.99) exhibited more AE events than the other hybrid composites. However, most of these events were recorded in the lower amplitude range. One possible explanation, assuming some of the noise is related to failure, is that there was matrix cracking and some low energy delamination around the carbon filaments. Czél & Wisnom (2013) suggested that having a spread carbon bundle, surrounded by E-glass layers, led to multiple regions of fragmentation and delamination in the carbon layer; a similar finding was reported by Manders & Bader (1981). This would enable the composite to reach a higher failure strain and stress as the carbon fibre component contributed to the load bearing for longer. The large degree of AE events observed in the current study, in the ranges proposed as being matrix cracking and delamination, suggest that this was the case here.

The failure was mainly characterised by longitudinal splitting, the dominant failure observed in mono-fibre E-glass samples. This was the case for all hybrid configurations.

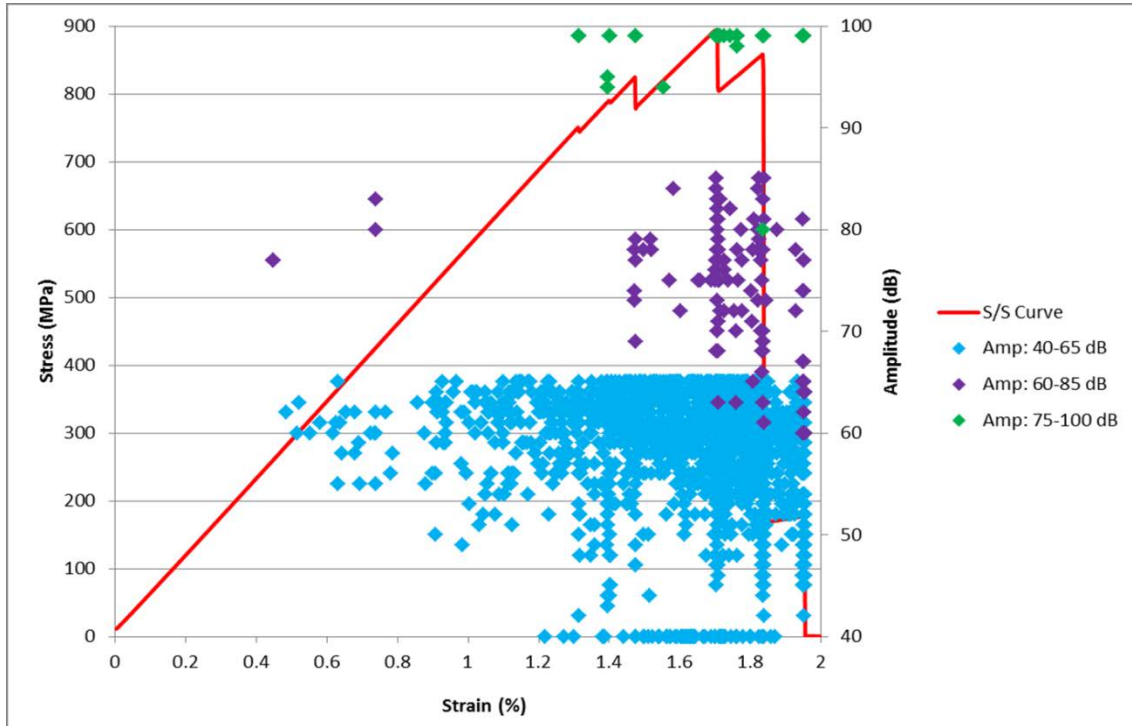


Figure 4.97 A representative example of the AE distributions recorded in a three-layer spread hybrid [GCG]_s composite.

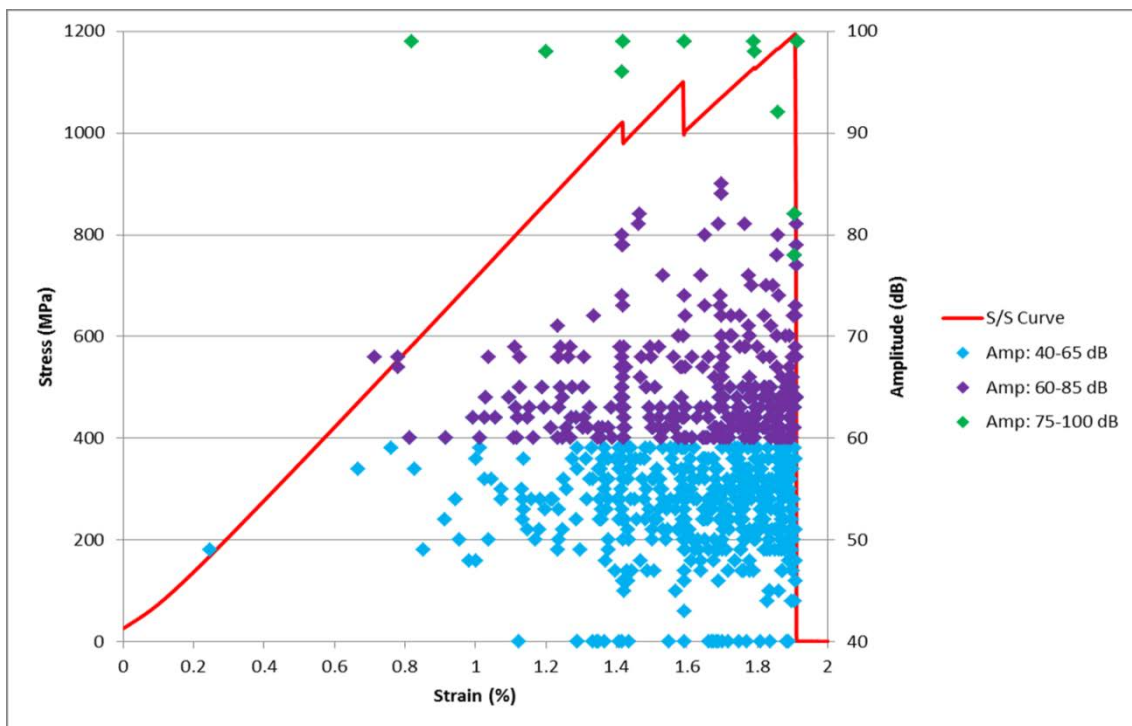


Figure 4.98 A representative example of the AE distributions recorded in a three-layer spread hybrid [CGC]_s composite.

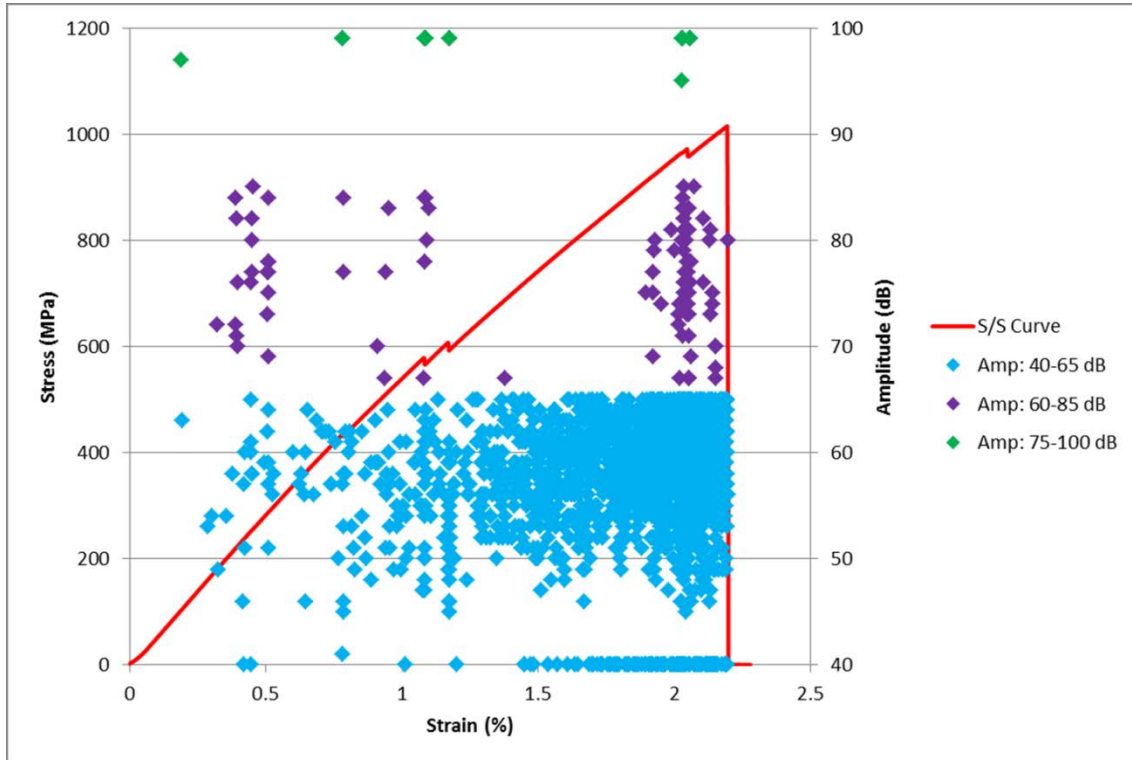


Figure 4.99 A representative example of the AE distributions recorded in a three-layer spread hybrid [GCG]2 composite.

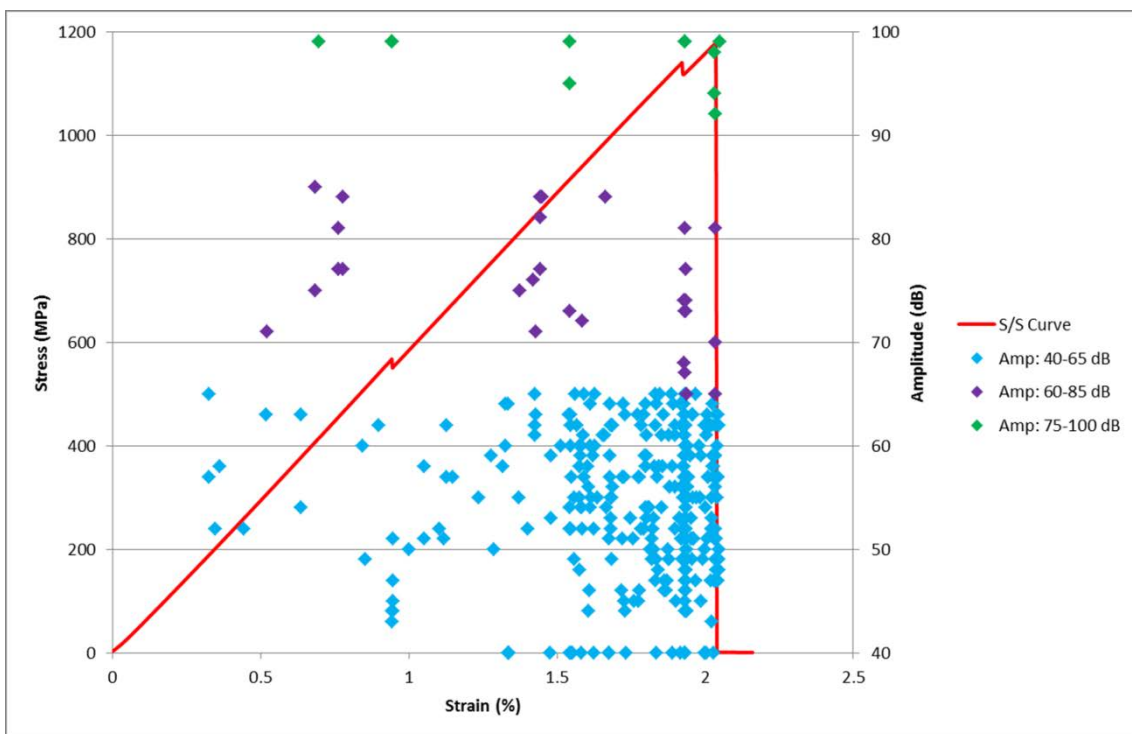


Figure 4.100 A representative example of the AE distributions recorded in a three-layer spread hybrid [CGC]2 composite.

In the current literature, two predominant modes of failure in hybrid composites have been discussed. Firstly is the more common, classic hybrid failure as presented in Bunsell & Harris (1974) and Manders & Bader (1981) for their inter-ply composites. This is characterised by linear loading up to initial failure. At this point a large load drop is observed, which is believed to indicate that the carbon has failed. The E-glass component then carries the re-distributed load as the strain increases until failure.

The second reported failure mode is pseudo-ductility (Czél *et al.*, 2012; Czél & Wisnom, 2013). In this case, the hybrid reaches an initial failure stress and strain, at which point there is no characteristic load drop. Instead a series of small load drops are observed. The failure is defined as more stable failure.

With regards to the current study, neither of these failure behaviours was observed. In some cases, hybrid composites loaded linearly and failed catastrophically with no occurrence of initial failure. Referring to the examples presented here, multiple failures were observed up to peak load. However, there was no characteristic load drop associated with carbon failure. The load traces, in addition to the increases in measured initial and final failure strain, suggest that the failure of carbon was more stable. The carbon filaments were able to contribute for a longer period than more conventional hybrid composites presented in the literature.

In order to determine whether the carbon filaments were failing prior to the E-glass filaments in the hybrid composites, waveforms of AE events were analysed from different regions of the stress/strain curves. It has been suggested in the literature that the carbon elements will completely fail before the E-glass (Pandya, Veerajau & Naik, 2011).

Presented in Figure 4.101 is a representative load/displacement trace for a [GCG] hybrid. This trace is from the AE system, and is made up of each recorded AE event hence why the trace is not a continuous line. With reference to the Figure the black boxes, numbered one to three, indicate the regions from which waveforms were selected for analysis. Region one is the first failure, region two is the first large drop in load and region three is the peak load. Figure 4.102 presents representative waveforms of filament failures from each of the three regions in Figure 4.102. Each of the waveforms had very similar characteristics the only difference between them being the point at which they were recorded and their amplitudes. The amplitudes recorded for these three waveforms were 69, 66 and 71 dB for region 1, 2 and 3 respectively.

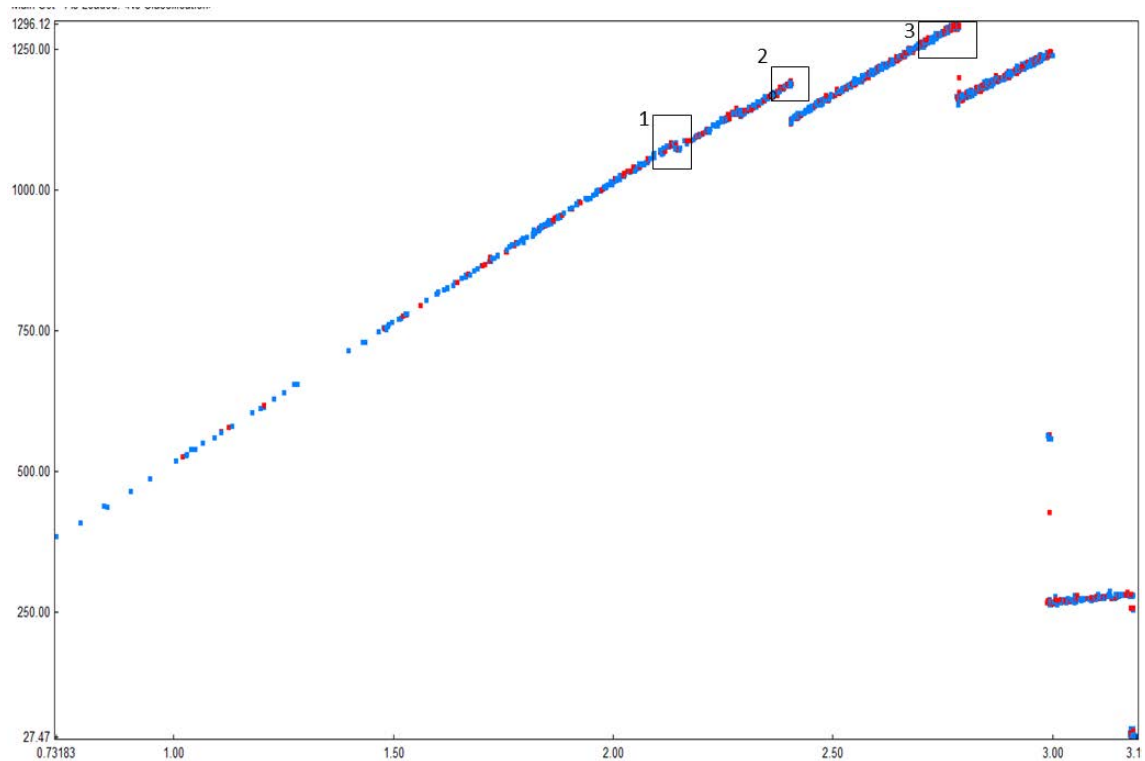


Figure 4.101 A representative AE load/displacement trace for a [GCG] hybrid composite.

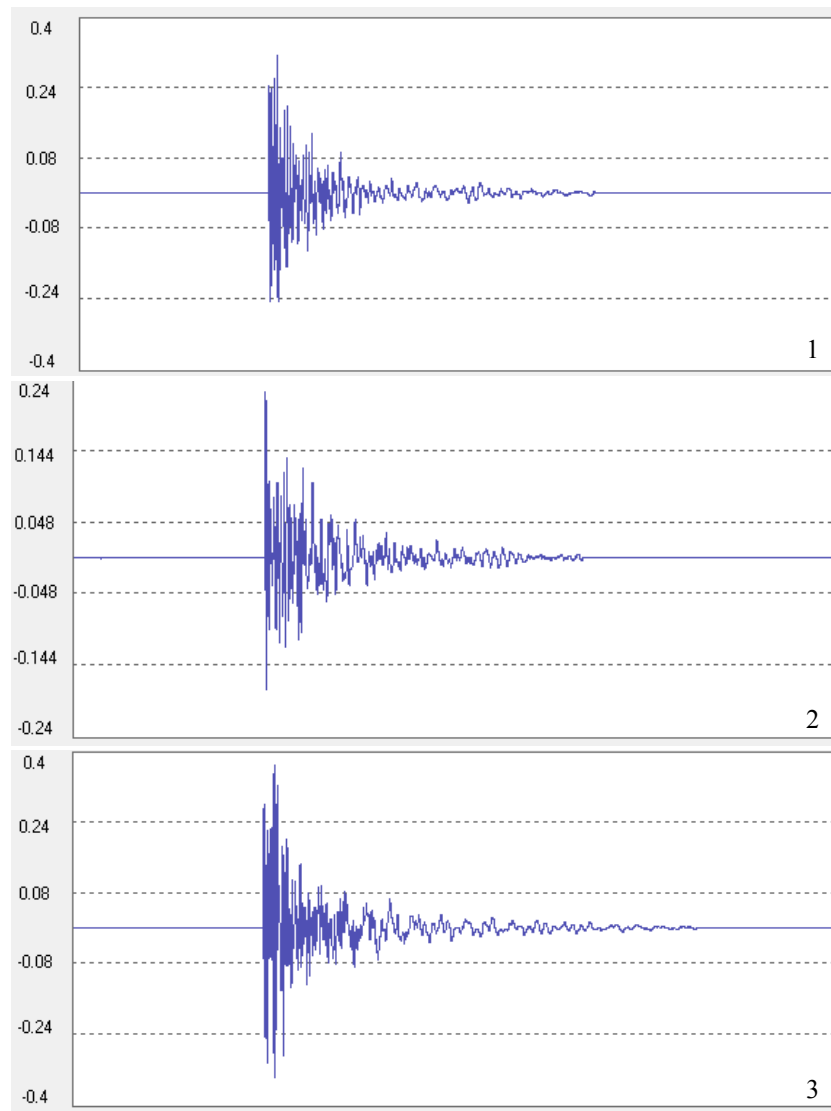


Figure 4.102 Representative waveforms recorded during tensile loading, in a [GCG] hybrid composite.

If the models are correct in assuming that all carbon elements will fail before the E-glass then it could be suggested that waveform one is a carbon filament failing and waveform three is an E-glass filament failing. However, as each of the waveforms studied were relatively similar, and of very similar amplitudes, it would be difficult to determine which was a carbon filament failing and which was an E-glass filament failing.

Presented in Figure 4.103 is representative stress/strain curve from the AE system recorded during a tensile test of a [CGC] hybrid composite. With reference to the Figure the boxes numbered one to three relate to the regions from which example waveforms were selected.

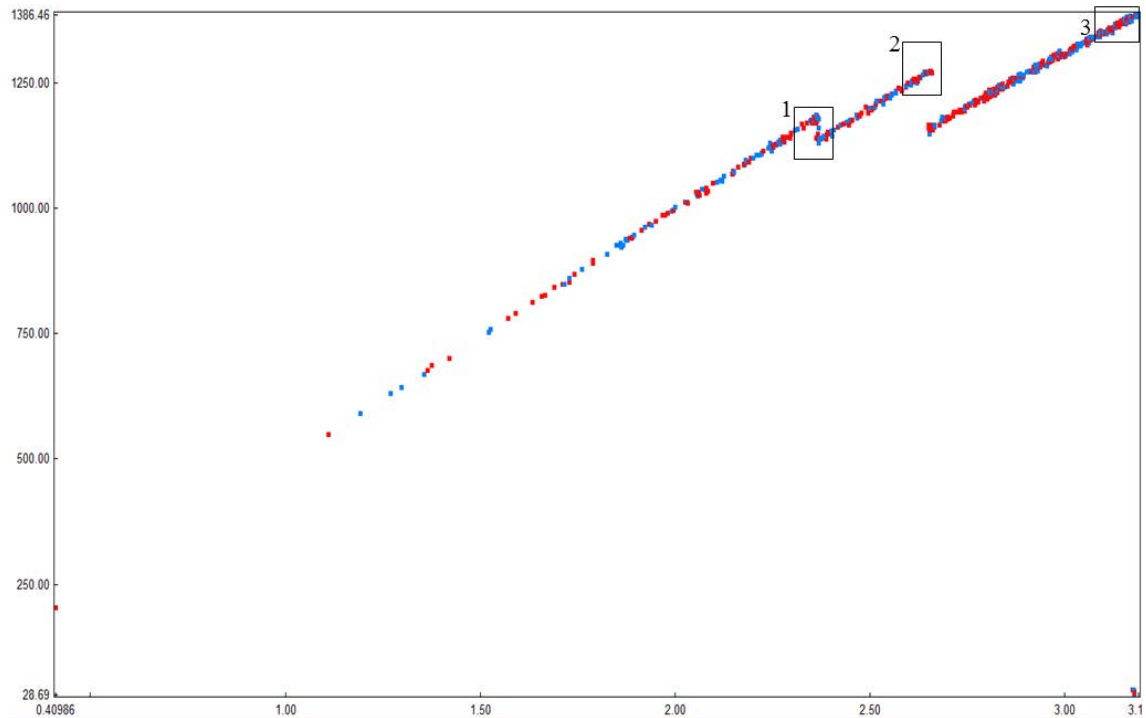


Figure 4.103 A representative AE load/displacement trace for a CGC hybrid composite.

Region one relates to the first failure, region two relates to the first large load drop and region three relates to the UTS at which point catastrophic failure occurred. Relating to the models there should be more carbon failures around region one and more E-glass failures at region three. Figure 4.104 presents representative waveforms from regions one, two and three. With reference to the Figure it can be seen that each of the three waveforms were very similar to each other, and also to those observed in the [GCG] hybrid. The amplitude of the waveforms presented were 69 dB, 70 dB and 70 dB for

region one, two and three respectively. As with the [GCG] hybrid composite waveforms, it appears that distinguishing between a carbon or E-glass filament failure is extremely difficult.

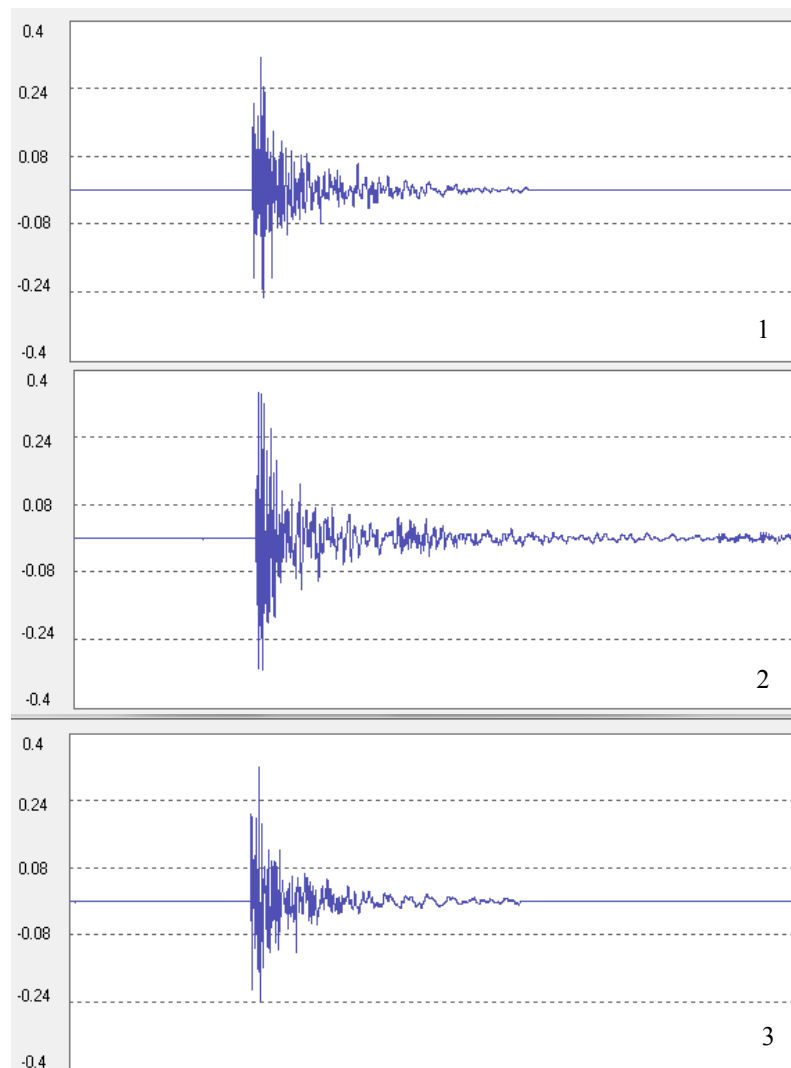


Figure 4.104 Representative waveforms recorded during tensile loading, in a [CGC] hybrid composite.

5. Conclusions and Recommendations for Further Research

5.1 Conclusions

The following conclusions have been drawn from the research presented and discussed in the previous chapters.

- (i) **Fibre Spreading:** A primary aim of this research was to develop a technique for spreading carbon and E-glass fibre bundles to an idealised state defined by the author. Two unique and distinct methods for spreading as-received 12K carbon and 2400 Tex E-glass fibre bundles were developed and analysed. These were based on a vacuum-assisted rig and a mechanically-assisted spreading method using tension-release and micro-fibre fabric. Patent applications have been made for both of these processes. The percentage increases in the width achieved for the as-received type-II carbon and type-II E-glass fibre bundles were 1121% and 956% respectively. These values for increase in fibre bundle width via spreading surpass any reported in the literature.
- (ii) **Fibre Bundle Tensile Testing:** The influence of spreading on the tensile behaviour of the fibre bundles was investigated. In the case of type-II E-glass fibre bundles there was a statistically significant decrease, of 18.04%, in the average tensile failure stress at a gauge length of 100 mm. However, at a gauge length of 50 mm this was not significant (15.02%). The spread carbon fibre bundles had a greater average tensile failure stress at both gauge lengths; this was statistically significant at 100 mm (5.77%) but not for 50 mm (1.44%).

- (iii) Tensile Testing of Composites: The initial failure strain for hybrid composites was seen to be greater when compared to mono-fibre carbon composites. The largest hybrid effect (defined by the apparent improvement in the initial failure strain) of approximately 35% was observed in the spread hybrid $[GCG]_{2s}$ and $[CGC]_{2s}$ composites.

5.2 Further Research

- (i) The applicability of the two proposed techniques for fibre spreading should be trialled with a wider range of E-glass and carbon fibres as well as other fibre types.
- (ii) A post-processing method to create a mono-layer of carbon filaments should be designed and developed.
- (iii) A method of automatically spreading E-glass and carbon fibre bundles to a mono-layer should be investigated.
- (iv) The influence of lubrication on the tensile properties of as-received and spread E-glass fibre bundles should be measured and the resulting influence on survival probability, acoustic emission and failure behaviour should be investigated.
- (v) Interrupted composite tests should be conducted to gain deeper insight into the failure mechanisms associated with hybrid composites using spread fibre bundles.
- (vi) A detailed programme of SEM analysis should be undertaken to define further the failure mechanisms during tensile failure in mono-fibre and hybrid, as-received and spread composites.

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