Novel stitching yarn for improved delamination performance of carbon fibre composites

Dooher, Thomas; McGarrigle, Cormac; Dixon, Dorian; McIlhagger, Alistair; Harkin-Jones, Eileen; *Archer, Edward

Engineering Research Institute (ERI), Ulster University, Jordanstown campus, Shore road, Newtownabbey, Northern Ireland, BT37 0QB.

* Corresponding author - email: e.archer@ulster.ac.uk

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Abstract

Carbon fibre reinforced polymer composites are replacing metal where weight saving is required. Due to their laminate structure, one issue which is of concern is delamination. Sewing is seen as a simple method of improving the delamination performance, but as yet a suitable yarn does not seem to been identified.

In this work, 4 thermoplastic yarns were created using polysulfone, polyethersulfone, polyphenylsulfone, polyetheretherketone and the mechanical properties (as a straight fibre, knotted fibre and looped fibres) compared to a commercial yarn from schappe.

It was found that the commercial yarn had much better mechanical properties as a straight fibre compared to the thermoplastic yarns in both terms of stiffness and strength. It was found that the ultimate tensile strength of the commercial fibre was reduced by approximately 90% when knotted and by approximately 60% when looped compared to the straight fibre. The thermoplastic yarns did not show any significant change in performance. As a consequence, despite not having the same mechanical properties, the thermoplastic yarns may prove to be better suited to stitching.

Introduction

In recent years, carbon fibre reinforced polymer (CFRP) composites have been used more and more in industries such as the aeronautical industry where their high strength and stiffness are being used to replace conventional metal components in order to save weight and boost fuel efficiency and performance. CFRP have anisotropic mechanical performance as the composite consists of a large number of fibres which only have mechanical properties along the lengths of the fibre. Typically components are made by taking thin sheets of carbon fibre and arranging the orientation of the different layers so that the component will have the necessary mechanical properties in the desired directions[1]. On the one hand, this approach can save weight as if the component will not be subjected to a load from a particular direction there is no need to add layers to reinforce the component in that direction. On the other hand, not only does the component need to be carefully designed but the loading that it is subjected to has to be predicted otherwise it may fail. In addition, the bonding between the different layers is primarily just resin which means that the interlaminar properties tend to be weak meaning that delamination is a concern[2]. Once the composite delaminates it has essentially failed. It has been found that with CFRP composites a low energy impact (such as a dropped tool) is enough to initiate delamination[3]. Several methods have been proposed to combat this such as designing a 3-dimensional weave which does away with the need for thin layers and means that that the composite is held together by strands of carbon fibre which are woven through the composite in the z-direction. However, despite the promise of this technique,

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the properties of a 3D weave are hard to predict with small changes to the weave resulting in significant changes to the mechanical properties of the composite[4]. Another method which is used are z-pins, which are small metal pins inserted into the composite before curing. The advantage of these is that the size of the pins can be varied, along with the density and location of the pins so they only need to be placed where reinforcement is required. The disadvantages are that the pins cause damage as they are forced through the composite and either break or cause the carbon fibres to bend round them and this weaken the properties of the composite; and the composite is only reinforced at the sites were the pins are inserted; and the reinforcement is dependent on the bonding between the pins and the resin[5]. One other method which is attracting research is the idea of stitching the composite layers together. Although this would damage the carbon fibres in the same manner as z-pins, stitching would have several advantages over z-pins. For example, as the sewing thread is stretched across the top and bottom of the composite it not only provides reinforcement at the stitching sites but also along the line of the stitching[6]. This means that potentially a lower density is required compared to z-pinning (and thus less damage to the carbon fibres) and that the reinforcement of the yarn is not dependent on the interaction between the yarn and the resin. Despite a great deal of work being carried out, a suitable stitching yarn has not been identified[7]. Most researchers have looked at commercial fibres such as Kevlar which have excellent mechanical properties as a straight fibre, but this does not appear to translate into a suitable stitching yarn possibly because the knotting and twisting of the yarn during stitching damages the fibres and significantly reduces their mechanical properties[8]. In this work, the opposite approach will be used. Rather than look at existing commercial yarns, a selection criteria was drawn up and a range of thermoplastic polymers were reviewed and promising polymers selected. The criteria used was low water absorption (so that the yarns would not degrade in the presence of moisture), chemical resistance (as the yarn could be subjected to fuel and solvents), high temperature performance (as the yarns would be subjected to temperatures of approximately 180°C for around 12 hours during the curing process)[9] and scratch resistance (as if bits of the yarn flake off during the sewing process, then it will reduce the properties of the yarn and potentially jam up the sewing machine). Despite an extensive literature review, the mechanical properties which make a good sewing yarn were not found and so part of this work will be to try and establish the mechanical properties which affect the properties of a sewing yarn. As it is likely that the mechanical properties that make a good yarn are a compromise between flexibility and stiffness, it was decided not to use mechanical properties as part of the selection criteria for polymers. However, after applying the selection criteria, the polymers which met the selection criteria were the high temperature polymers such as the polysulfones (polysulfone (PSU), polyethersulfone (PES) and polyphenylsulfone (PPSU)) and polyetheretherketone (PEEK) which are characterised by impressive mechanical properties. Polysulfone has a tensile strength of 70.3MPa, a Young's modulus of 2.48 GPa [10]and a glass transition temperature of 190°C. Polyethersulfone has a tensile strength of 83MPa, a Young's modulus of 2.6GPa[10] and a glass transition temperature of 242°C[11]. Polyphenylsulfone has a tensile strength of 70Mpa, a Young's modulus of 2.3GPa [10]and a glass transition of 209°C[12]. PEEK has a tensile strength of 98, a Young's modulus of 4GPa[13] and a glass transition of 309°C[14].

Method and materials

The sulfone polymers (PSU grade: P-1800-NT-11, PES grade: A-100-PNT and PPSU grade: R-5500-NT) used were donated by Solvay chemicals and the PEEK (grade 450P) was purchased from Victrex polymers. All polymers were dried at 150°C for 2 hours to remove any moisture prior to use. A commercial yarn was obtained from Schappe (Product number: 408146, product type: FAC Carbone 1K*2 2*67 TEX, fibre type: Tenax-J HTA 40 F15 1K 67 TEX 155) and used as a control. To create the yarns, the polymers were extruded using a twin screw extruder (Thermoscientific Haake Rheomix OS PTW16) with a 2mm die and to draw the fibre out, the attached pelletiser (thermoscientific type L-002-0061) was used with the blade removed (as this drew the fibre out at a constant and controlled

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rate. The speed was set to 8 as preliminary work had shown that this produced the most consistent diameter. The yarn was then wound by hand onto a bobbin. The temperature of the barrel was kept as low as possible and the screw speed was set at 5rpm to draw the yarn out as much as possible. For the PSU and PES, the barrel and die temperature was set to 360°C and for the PPSU and PEEK the barrel temperature was 385°C and the die temperature was 380°C.

To measure the tex of the yarns, 10m of each yarn was weighed out. This was weighed on a set of scales and the value multipled by 100 to give the tex (the weight in grams per 1000m). A length of 10m was chosen as it was a balance between getting a sufficient length to average out variations in thickness and wasting too much material.

To test the mechanical properties of the yarns, resin tabs were stuck onto the ends of the yarns to improve the grip on the yarn and to try and limit the yarns breaking at the grip. Three different types of measurements were taken. Mechanical testing on the straight fibres was carried out in accordance with ASTM D-3822-07. In addition, mechanical testing was also carried out using loop and knot configurations in accordance to ASTM D 3217-07. This was done to try and replicate the effects of sewing where the yarn would be twisted, knotted and looped around itself. The points of interest from these results will be the Young's modulus of the material, the yield strength (when the material moves from elastic deformation to plastic deformation) and in the case of the knotted samples, whether the sample broke at the knot or not. It is thought the elastic part of the material would be the most relevant to stitching as at this region of the material as after stitching the yarn would return to its original length and not be brittle. The ultimate tensile strength of the yarn (just prior to the yarn breaking) would in theory have greater strength as the polymer chains would be aligned along the length of the fibre, but stretching the yarn to this point was not feasible using the set-up available. There were also concerns over the brittleness and whether the yarn would break during sewing. It is possible however that in future work this research could be carried out. All measurements were taken at a cross speed of 20 mm/min with a grip distance of 25.4 mm. As at least five samples are needed for conclusions to be drawn, 12 of each sample was made initially and any sample which failed at the grip, because the yarn was pulled from the resin or due to an obvious flaw was discarded. Further samples were made if there were a large number of defects, which were mainly due to the resin either not bonding adequately, or sticking to the part of the yarn which was to be tested. In order to calculate the uncertainty in the measurements, the standard error (the standard deviation divided by the square root of the number of samples) was used.

To calculate the mechanical properties of the yarns, it was decided to use the method laid out in the ASTM standards. The strain of the yarns were calculated as usual, but the stress was calculated by dividing the force (in cN) by the weight (in tex) of the material. Normally, the stress is calculated by dividing the load by the cross-sectional area, but using this approach means these results can be compared against other yarns (for which calculating the cross sectional area may be problematic due to variations in thickness, fibre shape and for multi-filament yarns which comprise more than one fibre).

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Results and discussion

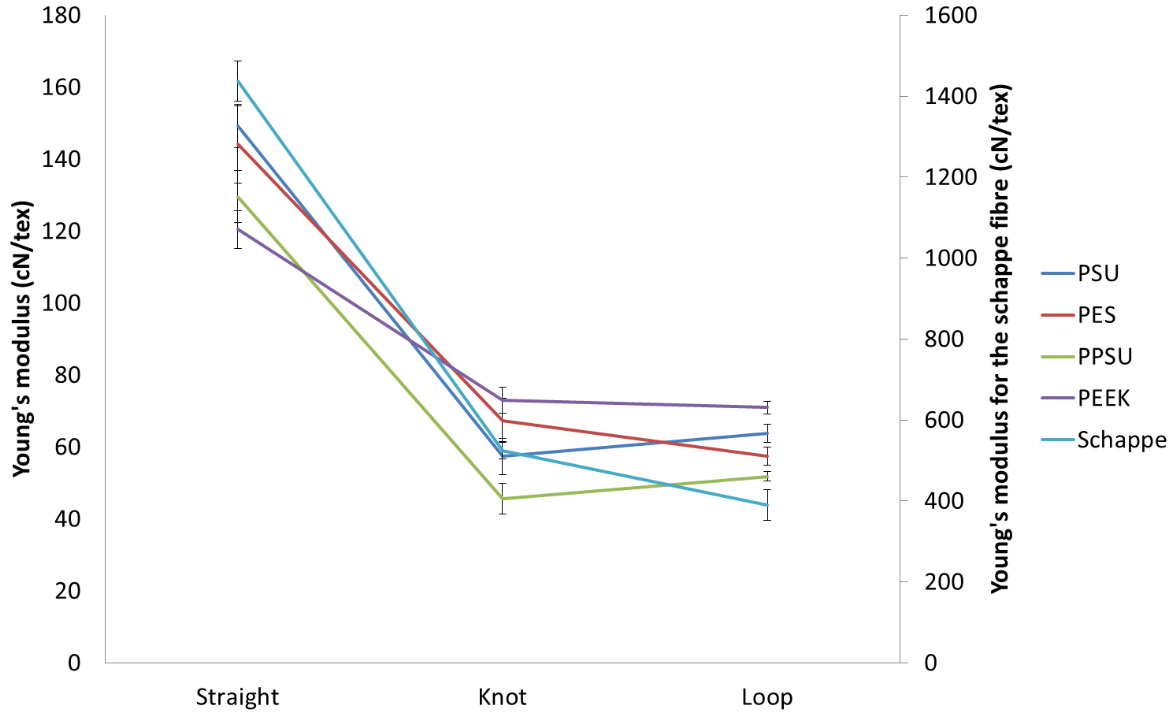
The Tex values of the yarns can be seen in Table 21.

Table 1: Weight of the yarns in Tex (g/1000m) (measured using 10m of material)	
Polysulfone (PSU)	171.92
Polyethesulfone (PES)	154.04
Polyphenylsulfone (PPSU)	175.88
Polyetheretherketone (PEEK)	103.25
Schappe	141.87

It was decided that rather than rely on the linear density measurements from Schappe for their fibre, the weight would be measured using the same method as the yarns which were made. This will mean that comparisons between the results are more valid since the measurements were made in the same manner. It is interesting to note that the weight of the sulfone polymers are similar while the weight of the PEEK is much lower implying that a thinner yarn was created.

The tensile testing results can be seen in Figure 1 and Figure 2. The Young's modulus of the yarns was compared first and it was found that the commercial fibre from Schappe was a great deal stiffer than the thermoplastic yarns produced (which is why the values were plotted on a secondary axis). It is also clear that all the yarns seemed to have a drop in stiffness when they were knotted or looped. It is not clear whether this is because the properties of the yarns were significantly altered when they were knotted or looped; or whether the reduction in stiffness is a result of the test conditions. It is likely that in the case of the knot test that when a load was applied to the yarns, the specimen could either stretch as normal or the knot could tighten and the reduced stiffness is a result of these two effects acting in tandem. When a graph of the raw data was reviewed, it was clear that in the case of the thermoplastic yarns there was not a clearly defined transition between elastic and plastic deformation which further supports this theory. In the case of the loop test, the test conditions would also suggest the difference between the straight fibre test and the loop test are more likely to be the result of the testing conditions than a change in the material. Firstly the total length of the yarns were longer than the distance between the grips (since there were two yarns looped through one another) which would make them seem less stiff. Secondly, although ideally both yarns would extend in the same manner, the yarns are sharing the load so often one would extend while the other would remain the same length. What is interesting looking at this data is that the thermoplastic yarns created and the commercial Schappe fibre both show the same basic trends despite their differences.

Figure 1. Effect of knotting and looping the yarns on the Young's modulus



From looking at the ultimate tensile strength of the materials in Figure 2, a different trend emerges. The four thermoplastic yarns do not show any real change between the straight fibres and the knotted samples, while the Schappe fibre shows a significant reduction in the ultimate tensile strength, with the knotted sample having approximately 12% of the strength of the straight fibre. This would indicate that the tight twisting of the fibres during knotting does lead to damage of the fibres, while for thermoplastic yarns this does not seem to affect their mechanical properties. If we compared the looped samples, it is clear that in the case of the thermoplastic yarns there is a significant increase (which is attributed to the test conditions rather than any change in the yarns). However in the case of the Schappe yarn, rather than see an increase in the ultimate tensile strength

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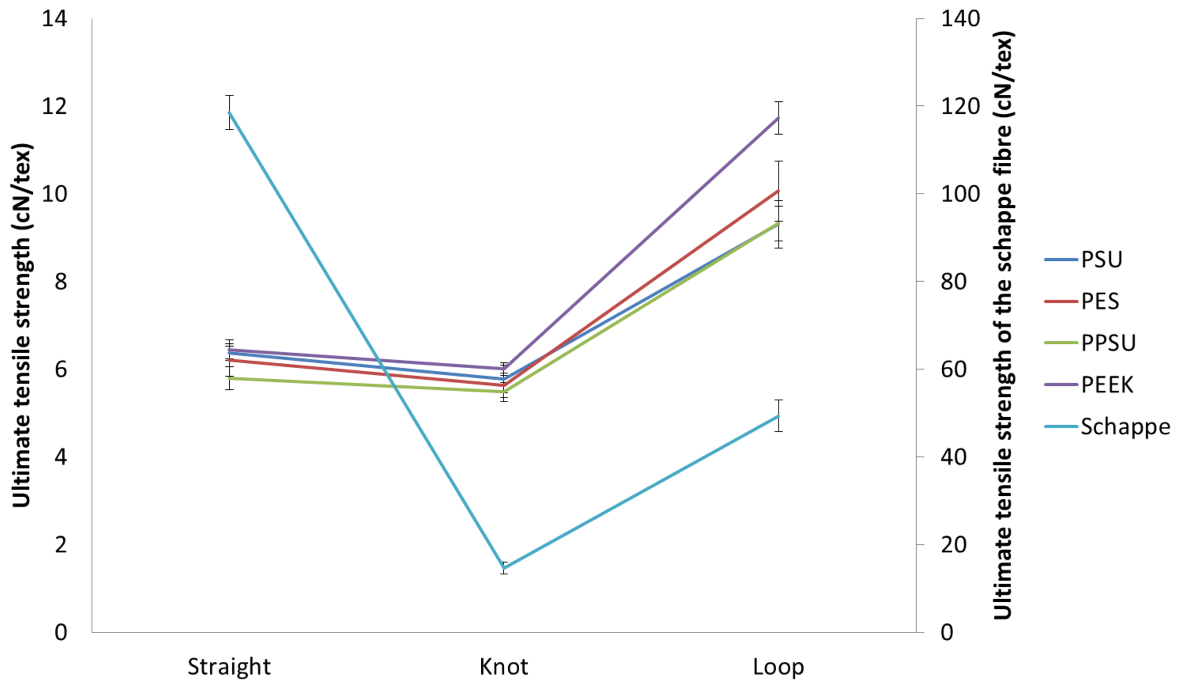
there is a decrease of around 60% compared to the results for the straight fibre, which would suggest that even looping the yarn significantly reduces it mechanical properties. As a consequence, it can be argued that although straight fibre performance is often the main consideration in choosing a sewing yarn, this does not necessarily mean the yarn will be a good sewing yarn.

Figure 2. Effect of knotting and looping the yarns on the ultimate tensile strength



These results would correspond with what other researchers have reported with other commercial fibres such as Kevlar. However, despite an extensive literature review no papers were uncovered where the yarns were subjected to tensile testing using methods similar to those carried out in this work so this is speculation. The final test will be to sew the yarns into a carbon fibre laminate and see how well the yarns actually sew and how the interlaminar properties of the laminate are affected. Although the sewing machine available was described as “heavy duty”, it was found that it was not capable of penetrating carbon fibre laminates thick enough to allow for delamination tests. As a result, tests are being carried out to see whether another sewing machine is capable of sewing carbon fibre laminates.

Conclusions

Based on the tensile testing results it is clear that as a straight fibre, the commercial Schappe fibre is superior to the thermoplastic yarns produced in terms of stiffness and ultimate tensile strength. There was a drop in stiffness in the yarns when they were knotted and looped, but this is attributed to test technique rather than any change in the properties of the yarns. However, when the ultimate tensile strength is compared, it is clear that while the thermoplastic polymers showed no significant change between the straight fibres and the knotted fibre, and a slight improvement with the loop test (which is attributed to the test conditions); the commercial Schappe fibres showed approximately a 90% decrease in ultimate tensile strength for the knotted sample compared to the straight sample and a decrease of around 60% for the looped sample compared to the straight fibre. This would indicate that the tight twisting has damaged the fibres in the yarn and lead to early failure. Further work is required to assess how well the different yarns can be sewn into a carbon fibre laminate and how well they reinforce the laminate.

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Future work

The main focus of work is to get access to a high torque sewing machine and carry out sewing trials using the yarns created and the commercial Schappe yarn to try and determine the ease of sewing and their ability to improve the delamination performance. Another potential avenue for experimentation is to add a filler material to the yarn to better tailor the properties of the yarn. A further test protocol which is also being considered is the use of an environmental chamber to artificially age the yarns as from literature it would appear that all the testing has been carried out on pristine yarns and of course one important consideration is whether the yarns have the same properties throughout the likely lifespan of the component.

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