Final Report

Controlled Micro Integration of Through Thickness Polymeric Yarns

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1. An executive summary

In this work, a new method of through-thickness reinforcement of composites has been developed which does not have a detrimental effect on the in-plane properties.

An initial study was undertaken to determine the best method for producing the through thickness polymeric reinforcement. This involved placement of molten polymeric strands and room temperature polymeric strands into a dry fabric preform to determine which was the best route. In the preferred method a blunted hypodermic needle was inserted through the dry fabric preform allowing a room temperature polymer coated carbon filament to be inserted through the needle. The needle was then withdrawn leaving the filament in place and the filament was then cut with approximately 5mm of the filament protruding from each side of the preform. This process was repeated for the remainder of the composite plaque to give the required pin density. The dry pinned preform was then pressed in a heated tool to bend the filaments over and press them into the fibres. Thermoset epoxy resin was infused through the tool using the RTM method and cured to form the composite. Several plaques were produced for tensile, bearing and mode 1 tests. These were at a nominal volume fraction of ~47%.

No statistically significant reduction in the in-plane tensile properties was observed between the pinned and unpinned laminate. Mode I delamination testing is ongoing, but preliminary testing has been positive, and it is expected that this method will significantly improve the interlaminar properties. Further work will investigate optimising the procedure, with potential to look at other filaments, pin densities and providing additional benefits such as through-thickness conductivity. Given the repetitive nature of the pinning, the potential for automation may also be investigated. Recently a curved preform was produced using the technique; it offers excellent preform stability with low bulk-factor.

2. A clear indication of whether aims/ objectives/ milestones/ deliverables have been met.

The performance of conventional laminated composites is frequently limited by their poor through thickness mechanical performance. A number of approaches exist to address this but have been limited by material properties of the through thickness fibre, the high levels of yarn flexibility and robustness required, and the need for robust stitching needles resulting in significant levels of fabric damage [1-4]. Also, several methods have caused undesirable defects such as resin pockets, localised fabric compression, breakage of in-plane fibres and tufting loops created within the cured composite [5-7]. With tufting the necessity to use a substrate to grip the yarn, lack of

accurate control and irregular stitching results in low throughput [6]. Z-pinning [8,9] has proven most useful for prepreg but the necessity of having relatively large pins causes disruption [10]. Many of these methods lack control and the resultant fibre preform is stiff and not conducive to complex shapes. The use of 3D woven fabrics is costly and can produce composites with lower in-plane V_f.

Research at Ulster University has focussed on the design and development of through thickness reinforcements (generally 3D woven - recently through EU (ICONIC, MARINCOMP), DSTL, MCM ITTP, NIAECC etc.). A recent project (EPSRC grant EP/L02697X/1) developed tailored through-thickness fibre reinforced extruded/drawn thermoplastic monofilament yarns which were stitched/ tufted into preforms; this work showed improved properties in open-hole tension and toughness [11,12]. This insight has determined however, that in order to achieve high rate deposition and rapid processing, there is a critical need to develop technology which can overcome the drawbacks associated with conventional stitching; therefore, a one sided micro extrusion unit to inject a molten, homogeneous, through thickness reinforcement into dry fibre preforms using a series of sub 500µm hypodermic needles was proposed. A micro extruder will feed an array of needles which will inject the molten thermoplastic reinforcement at regular intervals into the room temperature fabric as the head's needles penetrate the fabric, and inject a fibre of molten thermoplastic whilst the needles are being withdrawn. It was proposed that the molten thermoplastic will solidify rapidly due to its large surface area. Rather than the discrete 'crack stopping' effect that stitching or weaving provides, where the pitch of the through thickness reinforcement is generally between 3 and 10 stitches/cm^2 , the proposed array will have up to 50 reinforcements/cm^2 with a very fine polymer yarn at the sub 400µm diameter. In this work high temperature thermoplastics, polysulfone and polyether sulfone, which possess a glass transition point of >200ºC will be used [13]. The localised through thickness reinforcement will consolidate the dry fabric, improve fabric handling, maintain drape characteristics and improve stability for subsequent infusion. Using an array of fine needles will limit fabric disruption and damage to the preform whilst providing the desired through thickness reinforcement. The approach will be scaled up in subsequent studies and fully automated by using large arrays of needles.

The overall objective of this project was to research the underlying polymer material properties to develop a novel micro injection array system for the direct placement of through thickness polymeric yarns within dry fibre preforms; this will overcome several manufacturing related challenges to improve quality, reduce cost and increase rate. The project developed a laboratory scale micro extrusion injection system and an understanding of the principles required to ensure that the specified polymer is "dosed" into the dry fibre preform throughout its thickness accurately and uniformly. The subsequent dry fibre material was be analysed to determine resultant damage effects and composite performance, and was be benchmarked against other methodologies through literature. To achieve this goal, much research was required regarding the rheology of the molten high temperature yarns, the visco-elastic response during the yarn formation process, and the effect of parameters such as cooling rate (crystallisation if semi-crystalline thermoplastics are investigated). This work helps to address the two over-arching Grand Challenges and could provide a ten-fold increase in rate compared to tufting or stitching; it is especially aligned with the priority area of high rate deposition and rapid processing technologies. Further to this, and enhanced method was developed which allows fibre reinforced thermoplastic to be inserted through-the-thickness of the fibre preform at a micro scale.

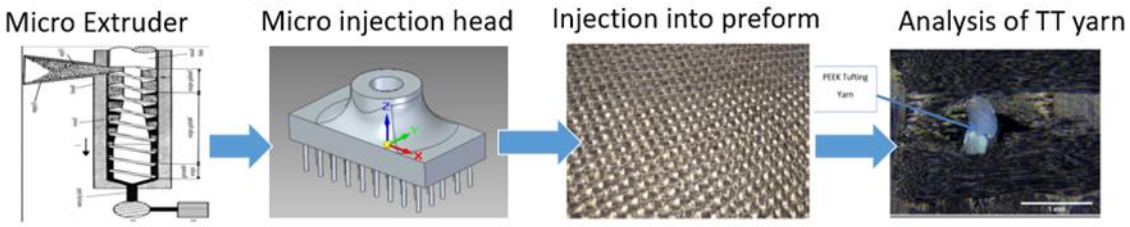

Figure 1. Proposed plan of work.

The aims and deliverables of the project have largely been met and some additional areas of learning have been generated. The following key findings have been concluded:

1. Ability to produce through-thickness reinforced composites with no knock-down on in-plane properties.
2. Test results that validate the tensile properties.
3. Quality micrograph and CT images that can be used by modellers to build representative unit cell.
4. Ability to make a stabilised curved preform using the technique.
5. Ability to make a low bulk-factor preform with +- 45 deg fibres and through thickness reinforcement.

It is important that this work is further funded to increase the TRL. Although the technology is relatively simple, it answers many of the shortcomings of existing preforming technologies and does so in a cost-effective way compared to competing techniques. A full EPSRC standard research grant will follow. Also, an application for further Hub funding will be made to enable Ulster/ NIACE to become involved in future Hub activities. Also, as the technology lends itself to high volume scale up onto a robotic head enabling the reinforcement of complex geometries, we will engage with industrial partners through an EPSRC Network Grant to bring together researchers, industry and other groups such as MTC and NCC to assist with higher TRL work.

3. An overview of the research undertaken in the form of a draft publication – either a conference paper or journal paper.

The following is split into 2 sections. The first deals with the initial trials using molten polymer and the second is for room temperature polymer which was found to be more successful and is the candidate for further mechanical characterisation.

Part 1. Molten polymer:

The aim of this section of the project was to extrude molten thermoplastic to improve the interlaminar properties of fibre reinforced polymer composites.

Initially a handheld extruder was used along with a modified nozzle and hypodermic needle to inject thermoplastic through the layers of a dry preform. Four

polymers were selected (polyamide 6, polypropylene, ABS and PET-G) and were successfully injected through glass fibre which was then infused with resin.

Limitations to the process soon became apparent. A great deal of distortion was found in the fibres after the pinning process. The pinning also seemed to affect the resin flow through the composite and it was found that the pinning also decreased the volume fraction of the composite. There was also a debate raised about whether the thermoplastic pins would be effective as the polymer molecules are not aligned.

Without a significant overhaul to the experimental set up these issued could not be overcome and this was not feasible given the timeframe of the project.

Materials and methods

In order to carry out the extrusion of molten polymers, a handheld extruder was required. A polymer welding set was purchased (Dohle micro) due to its small size and the fact that in addition to the handheld extruder it also had a system to direct hot air towards the tip of the extruder (which would help keep the polymer molten in the needle). Both the extruder and the air system were temperature controlled and could be set to separate temperatures. The downside to this system was that despite being the smallest extruder which could be found, the extruder was still quite heavy which limited the amount of fine control. Although smaller extruders are available (like in 3D printers), these were considered to lack the torque necessary to force the polymer through a needle. Based on the experience gained in this project that assumption was likely correct.

Four polymers were selected, namely polyamide-6, ABS, PET-G and polypropylene. 3mm filaments were sourced from 3DFilaprint. These were chosen as it was easy to obtain consistent filaments; by comparing their performance it should be possible to make predictions over what other polymers may be suitable.

In order to inject the polymer through the fibres, the original nozzle was replaced with a replacement nozzle with a hypodermic needle. Given the fact that the needle had to be robust enough to penetrate several layers of glass or carbon fibre and also had to have an internal diameter large enough to allow the viscous molten polymer to flow through it, the decision was made to use veterinary needles rather than normal medical ones. Several needle sizes were purchased, but preliminary testing was carried with a 13 gauge needle. A brass nozzle was machined and the hypodermic needle was brazed in place. The air flow was directed around the needle to help keep it molten as it flowed up through the needle. This set up proved to be effective and the polymer was able to flow through the needle.

Thermal testing was carried out on the polymers to try and identify the processing window. Differential scanning calorimetry (DSC) was carried out on a TA instruments Q100 from -90 to 250°C at a ramp rate of 10°C per minute under a flowing nitrogen atmosphere. The purpose of the DSC was to identify the glass transition temperature and the melting point of the polymers. Thermogravimetric analysis (TGA) was carried out using a TA instruments SDT Q600 from room temperature to 600°C at a ramp rate of 10°C per minute under a flowing air atmosphere. TGA was used to measure the degradation temperature of the polymers. The processing window was simply the region below which the polymer degraded, but above either its melting or glass transition temperature.

Although the project was initially envisioned to be used on carbon fibre, it was decided to conduct preliminary testing on glass fibre instead. The reasons for this was

because using glass fibre makes analysis much easier (the volume fraction can be measured easily as the epoxy can be burnt off leaving the glass fibres and the difference in density should allow for better resolution should SEM or x-ray imaging be used). Infusion was carried out using the vacuum bagging method. Gurit prime 27 resin was used along with Gurit slow hardener. The bagging technique also allowed the flow of the resin through the part to be tracked.

Results and discussions

The experimental set up can be seen in Figure 1. The extruder was not modified except for the replacement of the nozzle. The air nozzle was redirected around the needle to ensure that it remained hot enough for the polymer to remain molten. The needle extended out far enough to allow full penetration through the fibres. The speed of the extruder was set to the maximum which was found to extrude approximately 55 mm^3/s. One flaw with using an extruder was that it took several seconds between the extruder being turned on and polymer coming out of the needle (as it took a while for the pressure to build up. It was not possible to stop the extruder, insert the needle and start it up and then withdraw the needle and be sure that the polymer was inserted through the fibres (especially as the polymer could solidify in the tip of the needle and block it and given the weight and design of the extruder it was not possible to accurately predict where the end of the needle was). As a result, the extruder was turned on and left running throughout the pinning procedure.

Figure 2. Extruder and the modified nozzle with the needle attached.

To minimise damage to the needle and to ensure that the fibres did not move around during the extrusion process, the glass fibre preforms were put into a frame and clamped in place. 10 layers were used to give a suitable thickness and the points where the needle was to be inserted. Serval plaques were produced, to compare the different polymers as well as seeing the effect of stitch density and the time taken to remove the needle from the fibres.

The DSC of the polymers can be seen in Figure 2. What is interesting is that two of the polymers (ABS and PET-G) do not have a defined melting point. Both PA-6 and polypropylene have a measurable glass transition temperature and a clearly defined melting point. The TGA of the polymers can be seen in Figure 3. The start of the degradation temperatures were recorded and this was the highest temperature the extruder could be set to. These results are summarised in Table 1.

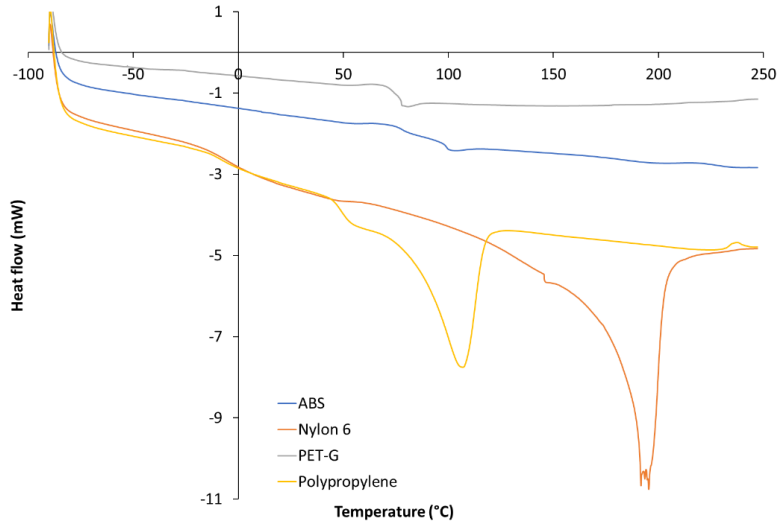

Figure 3. DSC results of polymer used.

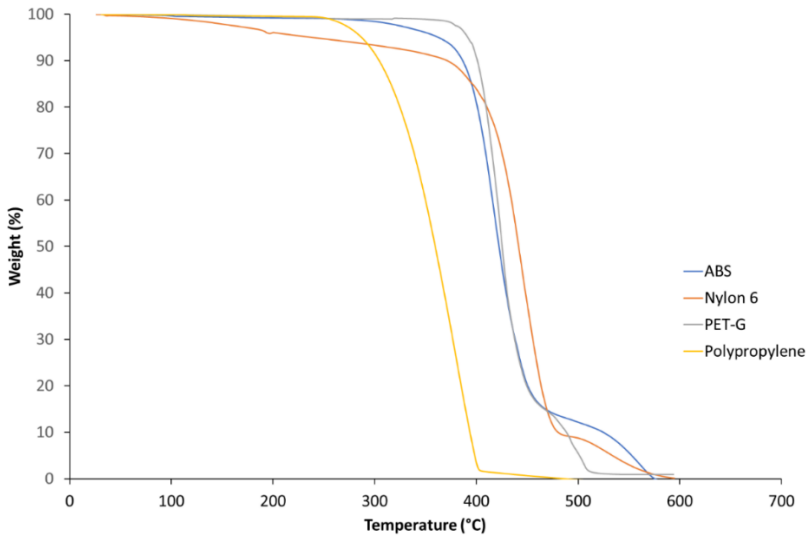

Figure 4. TGA of polymers used.

Table 1: Summary of thermal results			
Polymer	Melting point (°C) (end of transition)	Degradation temperature (start of transition) (°C)	Temperature extruder and air blower set to (°C)
Polyamide 6	215	360	330
Polypropylene	122	235	200
ABS	114 (T_g)	270	240
PET-G	85 (T_g)	360	300

The polymers were extruded through the needle and it was found that they could consistently flow through the needle. It was found that the two polymers without a clear melting point (ABS and PET-G) had high viscosities compared to the other polymers. However, it was possible to extrude all the polymers through the needle so this was not an issue, but could be if a smaller diameter needle was used.

Preliminary plaques were made to see whether the four polymers could be consistently injected. This can be seen in Figure 4. Several things were interesting with this plaque. Every attempt was made to ensure that the process was done consistently, with the withdrawal time for each injections site was 5s. Given this was done by hand it is likely that there was a great deal of variation. The first point to make was that the pinned area was readily apparent as the polymer could be seen sticking up from the fibres. This proved to be an issue when bagging the fibres as the points could penetrate the bag. After infusion and curing, a clear difference could be seen between the areas where the polymer had been injected trough the fibres and areas where it had not. It would appear that the injection of the molten polymer affected the flow of the resin through the fibres. There is evidence of some discolouration due to degradation, but this is due to the hot air nozzle coming into repeated physical contact with the extruded polymer which remained on the top of the fibres. The underside of the fibres were examined and there was no evidence of any degradation.

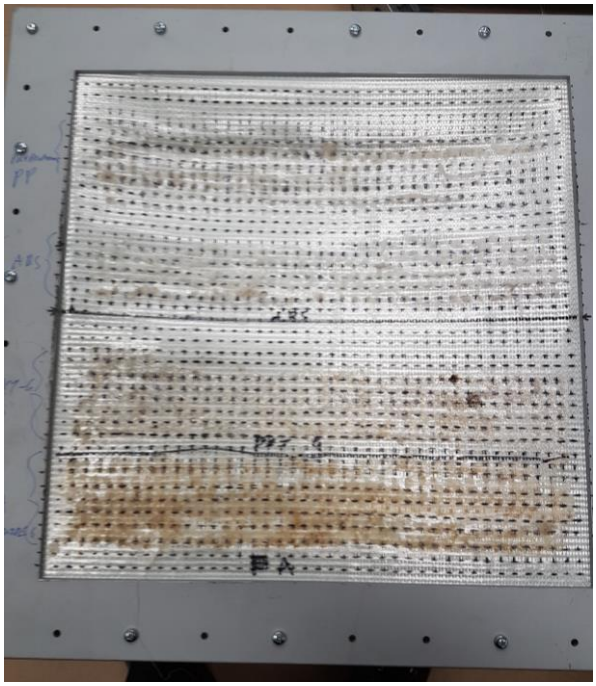

Figure 5. Preliminary plaque with the different polymers injected into it (from top to bottom: Polypropylene, ABS, PET-G and Polyamide 6).

To see what effect the pinning had on the flow of resin, a second plaque was made with different pinning densities and withdrawal times. This will vary the amount of polymer inserted between the layers of the glass fibre and by tracking the flow of the resin through the laminate it will be possible to see whether the presence of the polymer affects the flow of resin. Three insertion densities were chosen (with insertions every centimetre, one every 1.5 centimetres and one every two centimetres (as well as a region with no insertion to see how the resin flows without any pinning. Four

different speeds of withdrawal were used: 5 seconds, 3 seconds, 1 second and inserting and withdrawing the needle as quickly as possible.

The structure of the laminate was studied and found to be unsatisfactory. Although the glass fibres were held in a frame, the weight of the extruder did distort the fabric during the pinning process. It was found also that melted polymer would stick to the top of the nozzle and hot air fixture and this meant that the top layer of the fibres kept sticking to the extruder. It is also speculated that the polymer sticks to the needle in a molten form (which is quite sticky) and as the needle is pulled from the fibres this causes the layers to come apart. As the polymer is extruded into fibres, some of the polymer is injected between the layers and this keeps them apart (and this separation between the layers could help explain why the resin is able to more easily flow through the glass fibre). Another potential reason for the distortion of the layers could also result from the polymer contracting as it cools. This would explain the distortion of the laminate and also explain why it remains deformed even when vacuum bagged and a vacuum applied.

Conclusions

An extruder was successfully modified to allow a thermoplastic polymer to be extruded through a hypodermic needle. Four polymers were selected (polyamide 6, polypropylene, ABS and PET-G.

Thermal analysis was used to determine the processing parameters required to ensure that the polymers flowed through the needle without degradation. Studies with glass fibres found that the needle could be inserted through the fibres and the polymer extruded. Although the polymer did pin the fibre layers together, it was found that the process did cause distortion to the fibres.

Several plaques were produced to try and identify the issues and overcome them. It was found that in addition to distortion of the fibres, the pinning process also seemed to affect the flow of resin through the fibres.

It was found that the pinning process did create several undesirable side effects. The weight of the extruder distorted the fibres during the pinning process (even though they were held in a frame). In addition, it is thought that the cooling polymer contracted and pulled the fibres out of alignment. As the polymer tended to stick to the nozzle, it is also thought that the polymer would stick to the needle and this would pull the fibres apart as the needle was pulled out and the molten polymer would be inserted between layers. This lead a substantial decrease in the volume fraction of the composite.

As a consequence, it was decided that this approach would not work using this technique. Although it is possible that using a different technique might be used to correct the flaws identified in this work, the short timescale of the project did not allow for this to be investigated.

Part 2: room temperature

The aim of this section of the project was to place pre-extruded thermoplastic composite yarns to improve the interlaminar properties of fibre reinforced polymer composites. This was achieved using a manual process involving a blunted hypodermic needle which was inserted through the dry fabric preform allowing a room temperature thermoplastic polymer coated carbon filament to be inserted through the needle. The needle was then withdrawn leaving the filament in place and the filament was then cut with approximately 5mm of the filament protruding from each side of the preform. This process was repeated for the remainder of the composite plaque to give the required pin density. The dry pinned preform was then pressed in a heated tool to bend the filaments over and press them into the fibres. Thermoset epoxy resin was infused through the tool using the RTM method and cured to form the composite. Several plaques were produced for tensile, bearing and mode 1 tests. These were at a nominal volume fraction of ~47%.

Materials and methods

As this is a new technique, a key element of this is the development of methods to consistently insert and process the pins as well as analysing the effectiveness of the process. The process involved the following steps:

1. Assemble dry preform, in this case 11 layers of Tenax 5HS Satin 375GSM fabric arranged in 0-90 configuration. This is chosen as a baseline due to compatibility with previously manufactured 2-D samples. This is aimed at a 4mm plaque with a nominal 47% Vf.
2. Insert pins/staples. In the case of carbon samples these use a 17 Gauge (Birmingham Gauge) needle to aid insertion.
3. Trim pins/staples, this process differs depending on carbon/metallic pins: pins are manually cut off after removal of the needle.
4. Heat/press the pins/staples. The precise method used is detailed in the following sections.

The first experiment used the Nylon coated carbon thread, this was manually inserted through the thickness with the use of a 17 gauge needle. The 11-layer carbon layup was placed on a tool fixture to prevent blunting of the needle/ fouling with underlying supports, the filament was threaded through the needle then the needle forced through the carbon. The press was taken to ~100Bar hydraulic pressure, spacing was achieved by the placement of 2 aluminium blocks of 4mm thickness either side of the specimen. One lesson from these samples is the needles wear out with not much use. It must be noted that the needles used are stainless veterinary needles selected for availability, and that if this process were to be used on a larger scale it would be necessary to select more robust materials for the needle. Future samples will be manufactured using a fresh needle, it is also noted that using the clamping jig may help as this will provide a greater gap on the through side of the material. To achieve the stitch pattern, it was initially planned to use a mask with a multitude of holes to allow precise positioning, however due to the extreme manufacturing time it was

instead chosen to continue using the weave pattern of the carbon as a basis for pin locations. The pinning process took some considerable time, with the process going from start to infusion taking 4 days (not including time for tool prep). The bulk of this time was spent pinning, and during this process several small developments were made in the pinning process primarily based around controlling the spool in such a way as to prevent unwinding that would require a halt to work in order to re-wind the filament. It was necessary once pinning had been completed to trim the back side of the plaque, this was done manually to approximately 5mm to mirror the top side. There was therefore significant wastage of material from this process as the pin ends could not easily be used to pin another plaque.

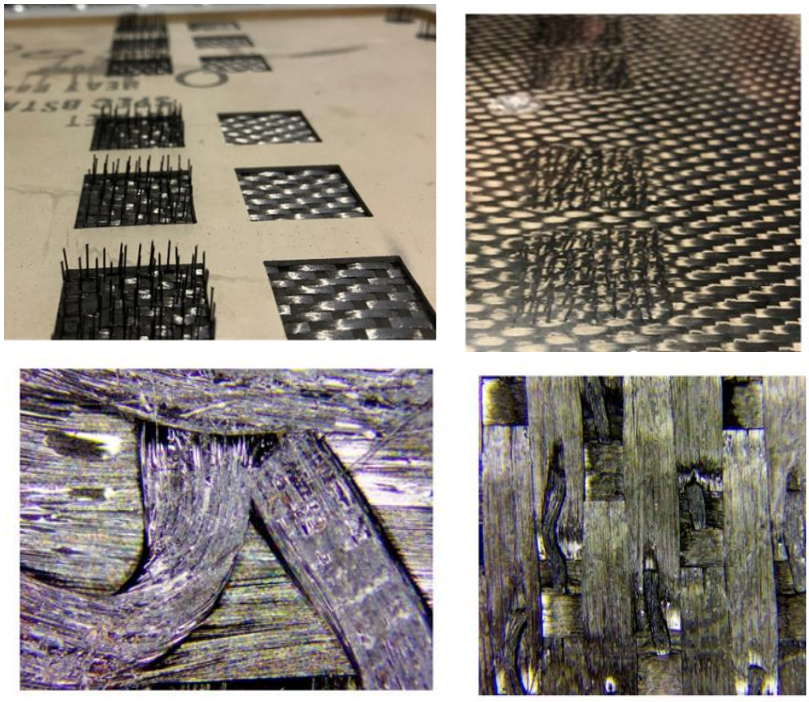

Figure 6. Images of carbon run, note the consistent flattening of the pins.

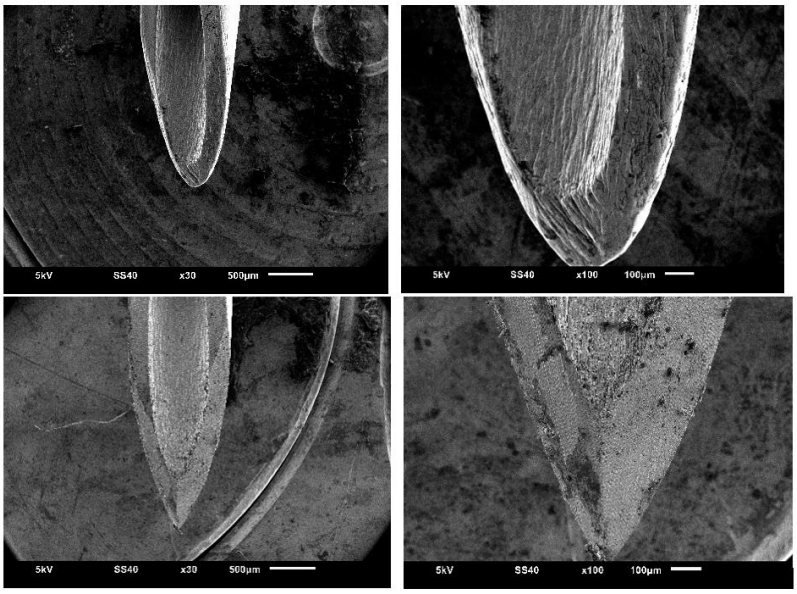

Figure 7.Top: images of blunted needle at 30x (left) and 100x (right), Bottom: corresponding images of a brand-new undamaged needle, note the significant erosion of the tip.

The next phase of the process is pressing. The tool was placed in the oven pre-prepped and heated to 150°C, after several hours the tool was removed from the oven, and the fibre was placed in it and clamped up as normal save for the requirement for gloves and extreme care handling the hot tool. The original intention of this method was to allow immediate infusion of the part once the tool had cooled, however this was not done due to a desire to inspect the success of the pinning process.

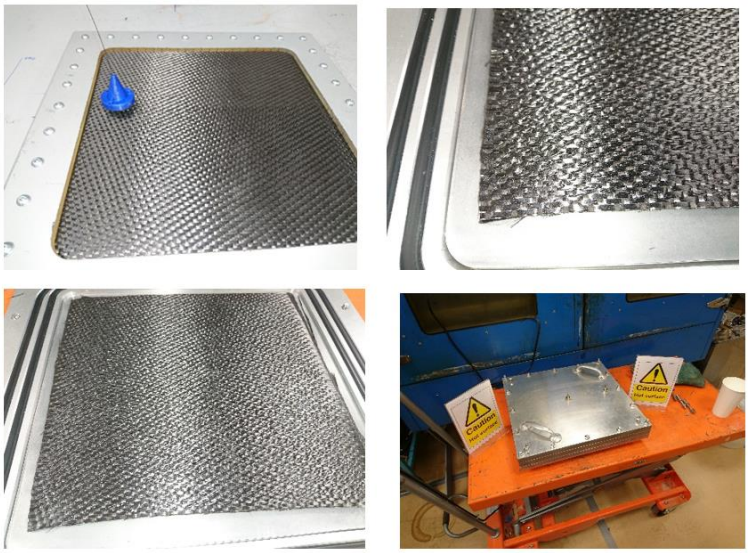

Figure 8. Top left- Mid-pinning of plaque, note the underside of the jig is resting on the ends of the bolts against the table. Top right-RTM tool after being heated and clamped. Bottom left- dry fibre after tool had been allowed to cool to ambient. Bottom right detail of fibre and RTM tool.

After the inspection the tool was re-clamped, and an infusion performed as normal. In this case Prime 27 resin/Prime Slow hardener was used to match prior samples made without pins.

Figure 9. Image of intermediate preform, inset close-up of part corner.

The conclusion of the pinning process shows that a nominal method of using either a hot press or preheated RTM tool at ~150˚C is suitable. It is envisaged that this process would scale well with automation, particularly the pinning process contains many inconsistencies and repetitive actions when performed as a manual process which could be improved significantly by automation. Additionally, on a larger scale at the fibre manufacture stage the use of hot rolling could prove beneficial for a continuous process as opposed to the single batch methods used on the experimental scale.

Material Evaluation/Testing

The next stage is to conduct analysis and characterisation of this material to compare to literature and other methods used. The first mechanical test selected was ASTM D3039 Tensile testing. This utilised a Zwick Z100 Universal test machine with the program and method being followed taken from an established library of standardised tests. The first samples taken were from a 2-D plaque manufactured from nominally the same material and resin system as the Pinned plaque. These results were then compared with the pinned composite.

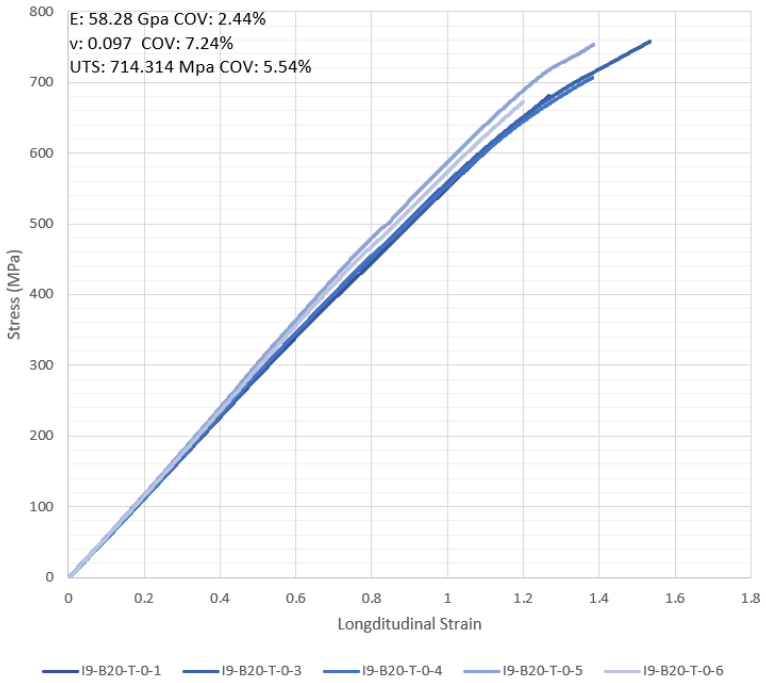

Figure 10. Tensile curves for 2-D specimens, these were manufactured using the same tooling and heat press process as the pinned samples.

This test shows a curious result, the 2d sample shows a 2.34% lower modulus than the pinned sample and a corresponding 0.93% lower ultimate tensile strength. The issue here is that these values are within the COV for either test, in the case of the 2-D the modulus COV was 2.44% and the UTS COV was 5.54%, therefore such a small change in modulus/UTS is regarded as statistically insignificant.

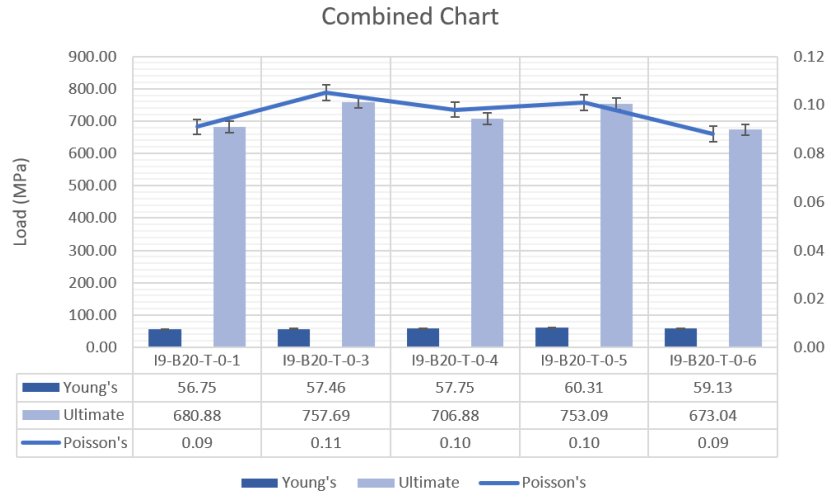

Figure 11. Chart of properties for 2D samples.

One theory for the change in UTS spread between the 2-D and Pinned samples is the introduction of crack initiation sites by the pins. In the 2-D laminate the fracture is random, based on which fibres fail first under tension, whereas in the pinned laminate

the introduction of crimp/waviness results in fibres more likely to fracture in the same conditions. It could also be the case that a reduction in tensile properties caused by the pins has been offset by the increase in volume fraction provided by the extra material added, particularly the ends of the pins which form a layer across both outer faces of the laminate.

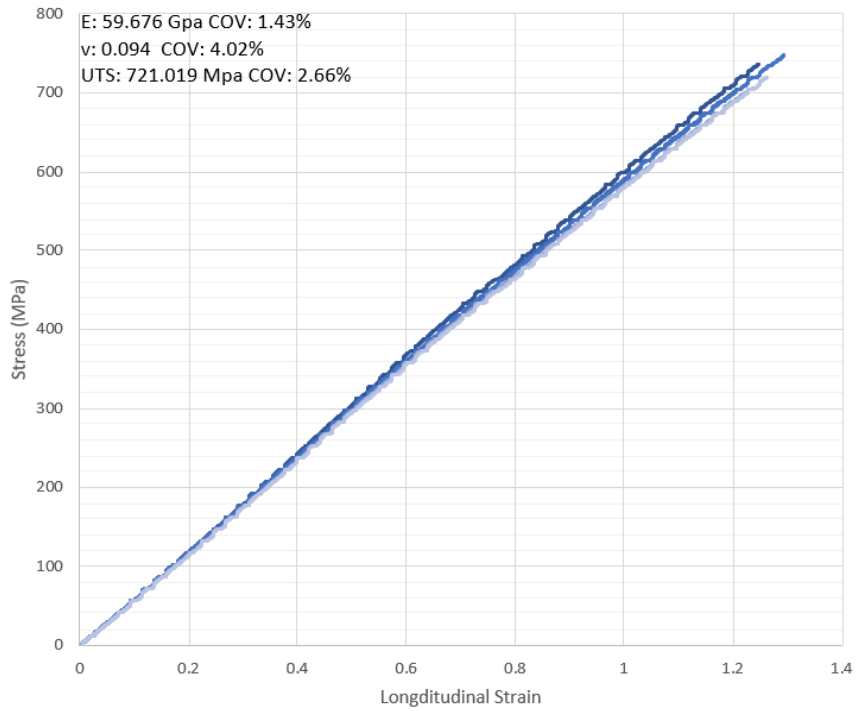

Figure 11. Tensile curves for pinned specimens, note the significant reduction in spread as evidenced by the reduced coefficient of variation (COV).

For the pinned specimens the actual failure type was different. The 2-D samples suffered very clean fractures with minimal fraying/delamination. However, the pinned samples exhibited rougher edges with delamination being held by individual fibres. In most cases one end of the specimen was fractured but remained attached with the remaining unfractured fibre holding the end onto the specimen. One possibility, which has yet to be investigated, is that the pins are acting as crack initiation sites which causes the change of spread. As shown in the crimp/waviness section the pins do not proceed perpendicularly through the part which could explain the change in material failure.

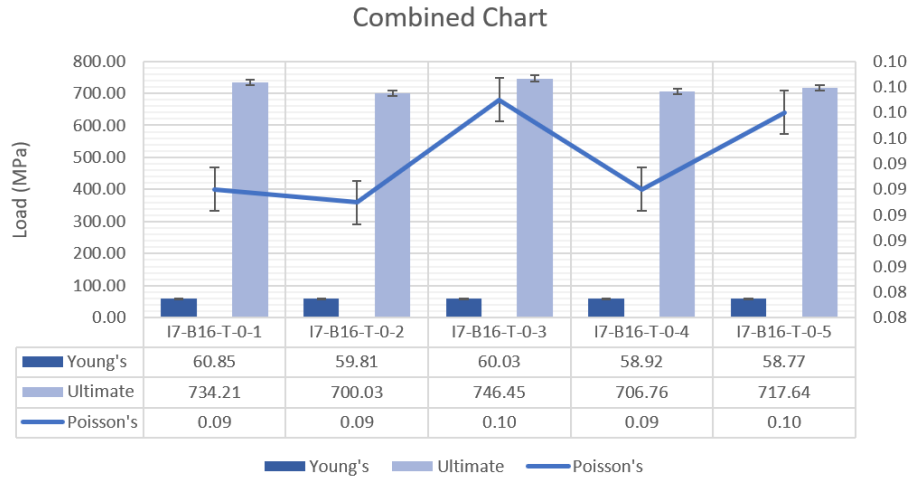

Figure 12. Chart of young's modulus, ultimate tensile strength and Poisson's ratio, error bars indicate standard error for pinned sample.

One more observation that was noted between the failures was that there was reduced instances of delamination in the pinned samples. Whilst it can be seen with the naked eye in the 2-D samples that there is splitting between the layers after failure, this was markedly reduced in the pinned samples which suggests that the through thickness properties have been enhanced by the pins.

Crimp/Waviness

It was decided to section a sample to attempt to quantify the amount of crimp and waviness present, as well as any fibre damage created by the process:

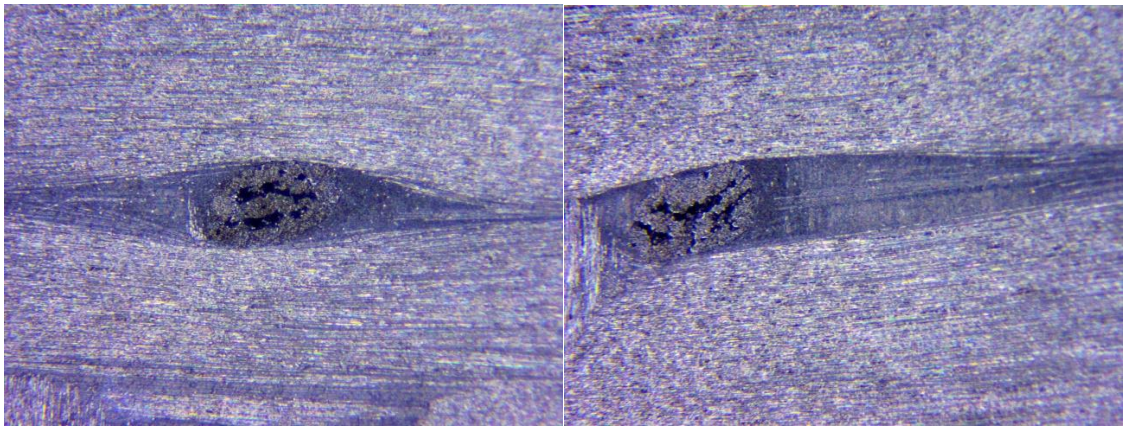

Figure 13. Images showing in-plane waviness caused by pinning, this shows the end-on view of the pin.

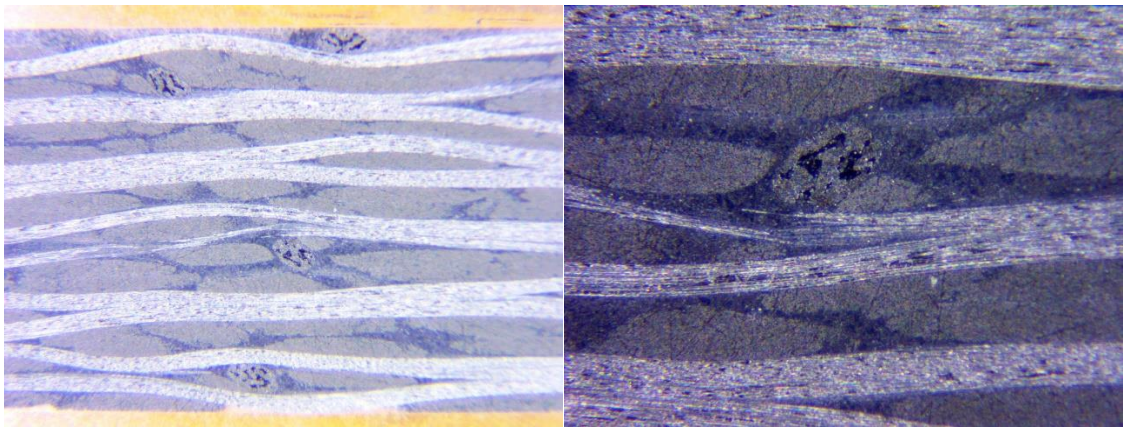

Figure 14. Side-on images of pins, note the pins are at an angle which makes identifying the pin from the fibre weave difficult.

Whilst the angle of the pins makes it difficult to analyse any crimp present, there are some points of interest from this analysis. Firstly, is the angled nature of the pins, this can be attributed to a combination of the manual pinning process with the needle causing a bias in the angle of insertion, there is also the fact that there is little control over the lay-up during the compression phase. This has been noted as a shift in the layers after compression in the hot press. Secondly is the apparent presence of a void contained within the pin. However, this could simply be the colour of the black nylon material (presumed) to be used to bind the filament together. As the right-hand images above represent the best magnification available for the Olympus microscope used further magnification was required. Therefore, further images were taken using a more conventional optical microscope:

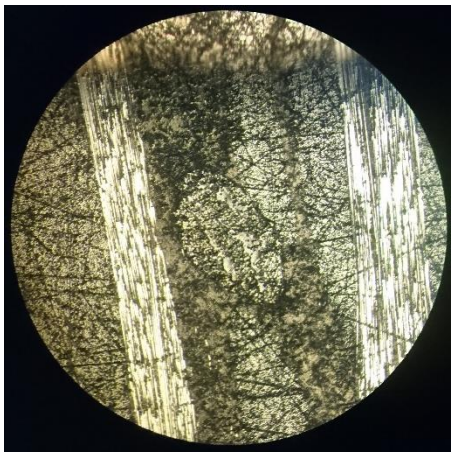

Figure 15. Image of pin at greater magnification.

Therefore, to answer these question conclusively it was decided to further analyse these samples with SEM imagery, with the greater depth of field allowing a conclusive answer to the question of void presence: These issues aside, it is notable that there remains a distinct change in the region around the pin, showing that through the infusion process there is minimal diffusion of the polymer in the pin with the resin system. This could be regarded as either an advantage or a disadvantage depending

on the desired effect, further investigations aim to include mode 1 evaluation to quantify the delamination improvement offered by this method.

CT Analysis

One question that proved difficult to answer with the microscopy analysis is the precise angle of the pin through the part. whilst the pins are placed by hand perpendicular to the fibre during the subsequent removal and pressing process, where there is no fixture to hold the fibre layers from sliding, the pin can change angle and flatten. As this is happening in 3-D space it is very difficult to section through the part to find a cross section of the pin, therefore it was decided to attempt to use MicroCT analysis to see if the pin may be resolved. Due to the nature of CT relying on differences in material density to resolve images, and the material being composed of materials of similar density (i.e. the carbon, nylon and resin components) it was difficult to isolate the pins from the sample. However it was possible to resolve an image showing the shape of the final pin:

Figure 16. 3-D image of the pins, in this case the image is of the nylon polymer rather than the carbon component as this would have been masked by the main carbon lay-up. The straight edges are artefacts from beam hardening of the CT.

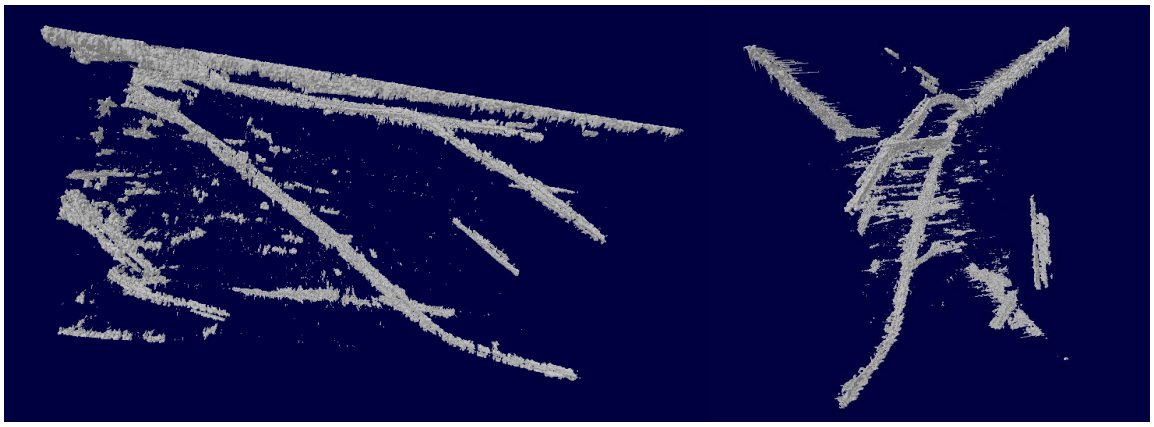

Figure 17. Side (left) and end (right) views of the pins.

From this analysis it can clearly be seen that the pins adopt a very shallow angle in the final part. it is suspected that one possible reason for this is the method of pressing, with the free fibre being compressed in the heated RTM tool. This encourages the pins to bend flat as the compression is applied faster than the effect of the heat transferring to the pin ends and softening them. One possible solution to this issue is to retain the fibre in the clamping jig during the press process, thus resisting the effect of sliding of the layers. However as it is only the fibre holding the pins perpendicular there may likely still be issues of the pins attempting to flatten rather than bend at the ends, especially with thinner laminates.

Mode 1

Another commonly reported evaluation for through thickness re-enforcement is Mode 1, the most common method being the double cantilever beam test for which ASTM have a standard under D5528. In the general case Z-pins and Tufts tend to pull-out, whereas stitched and 3-D woven materials tend to fracture. It is therefore of interest to see if the flattening of the polymer pins provides any benefit over a conventional z pin or a tuft. Additionally, this will quantify the through thickness benefits of the pins over a conventional 2-D laminate.

(Note. This work is still ongoing and complete results for mode 1 will be presented in the journal publication). Samples were cut from the plaque and assembled. A set of hinges were obtained with a 25mm width and 30mm length to the contact patch. These were glued to the ends of the specimens using the same methods and adhesive used for the tensile specimen tabs. As-per the ASTM D5961 standard the samples were marked on the sides with white paint marker and markings added for the end of the film insert, 1mm increments for the first 10mm and 5mm increments for the remainder of the sample. These markings were left intentionally short of centre on the part to facilitate ease of following the crack on the recorded footage.

Figure 17. Image of pre-test samples, note the markings for distance have yet to be added.

The insert marking was added by means of marking the top of the specimen at the insert end prior to applying the white marking, this was then transferred to the side of the part. The test was conducted on an Instron 5500R machine with a 5Kn load cell and wedge grips.

It was observed during the testing that there were significant issues with crack "jumping", this was anticipated for the pinned samples as a product of each row of pins failing in sequence, however this was also observed for the 2D samples.

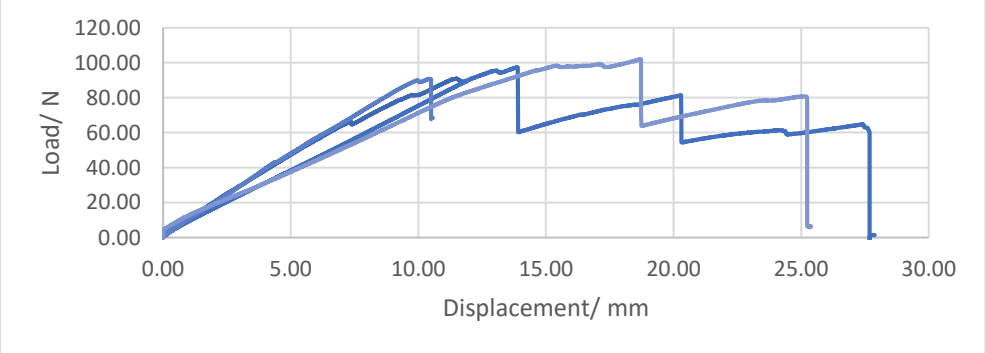

Figure 18. Chart of 2-D tests note load drops that correspond to crack jumps.

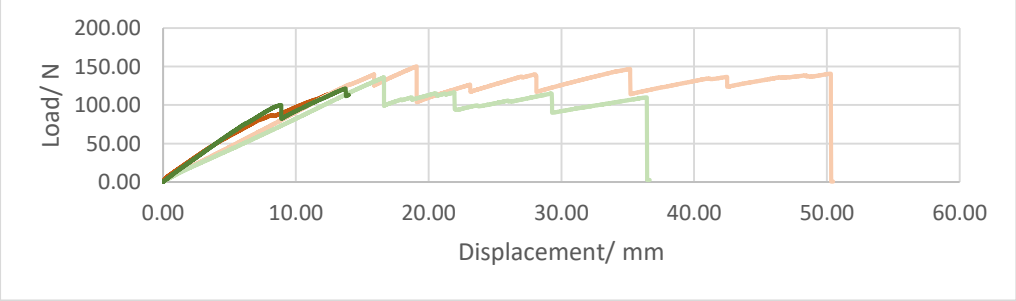

Figure 19. Chart of pinned tests, note saw-tooth pattern corresponding to pin failure.

Whilst not strictly an evaluation of Gi, it is interesting to note the noticeable increase in loading for the pinned samples, with the average peak load observed for all tests (initiation and propagation) being ~33% higher for the pinned samples. In order to translate this load into values for tensile opening it is necessary to track the movement of the crack in the parts. It was decided to improve upon the standard by attempting to use DIC methods. – More results to follow in Journal publication.

Conclusions:

This work has demonstrated a very promising technology which overcomes many of the shortcomings associated with existing methods. No statistically significant reduction in the in-plane tensile properties was observed between the pinned and unpinned laminate. Mode I delamination testing is ongoing, but preliminary testing has been positive, and it is expected that this method will significantly improve the interlaminar properties. Further work will investigate optimising the procedure, with potential to look at other filaments, pin densities and providing additional benefits such as through-thickness conductivity. Given the repetitive nature of the pinning, the potential for automation may also be investigated. 2 Conference papers have been accepted and several journal publications will follow. This work is being continued under an Ulster University funded PhD, but requires greater funding for collaborative research to develop the TRL.

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