EFFECTS OF AUTOMATED PATCH PLACEMENT ON THE MECHANICAL PERFORMANCE OF REFORMED NCF CARBON FIBRE

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Abstract

Whilst there have been efforts into recycling processes for end of life composites, a waste stream that is largely ignored to date is the scrap produced by kit cutting. The few solutions that are available produce a short, randomly aligned reinforcement that cannot be used for structural applications. An approach has been developed that aims to retain the feedstock properties by cutting the scrap into patches and reforming it using the Fibre Patch Placement (F.P.P.) process. F.P.P. utilises binder applied to the fabric to place the patches on a tool. The binder already applied to the fabric is insufficient for the process to work, therefore more must be added. This work investigates the effect of additional thermoplastic polyester resin on the flexural properties and the manufacturing efficiency of the reforming process with varying binder content. Biaxial samples made up of 60mm × 30mm patches were created for three point bend tests. It was found that the addition of binder has little effect on the flexural strength of the material but a large quantity of binder will reduce the stiffness with the possible addition of “pseudo-ductile” behaviour. In terms of manufacturing efficiency, the increased quantity of binder creates a more aligned preform, which is favourable for high performance laminates

1 Introduction

The use of composites is on the rise. In the aerospace sector, large commercial aircraft are now being designed with over 50% by weight composite materials [1, 2], and in the future this technology will eventually trickle down into smaller aircraft with higher production rates [3]. In the automotive sector, the use of composites is starting to be seen in mass produced vehicles, such as the BMW i3 [4]. Whilst there are many options for recycling End-of-Life (E.o.L.) composites in development [5], a more pressing issue is what to do with the offcuts of material produced when cutting preforms [6]. Due to the anisotropic nature of advanced fibre reinforced composites, much of the raw feedstock material is lost during the kit cutting process, in some cases over 40% [7]. Currently this lost material is treated as waste, and usually disposed of in landfill.

The material produced from the limited work on solutions for avoiding the disposal of this scrap can be broadly classified for use in one of three categories of application: Semi or Non – structural; structural; and novel. The non-structural material is usually produced by grinding or shredding the waste material into a particulate or very short fibre state [8], which can then be further processed into a Sheet Moulding Compound (SMC) type material [9]. While it is possible to process waste to recycle material for these applications quickly and relatively inexpensively, the mechanical properties of the original material are lost. Therefore in order to retain the value of the original fibre, the scrap must be reformed into a structural material or used in other high value applications. Several high value applications have been investigated, such as antistatic flooring, industrial paints, cement and road surfacing [10], and in electromagnetic interface shielding [11]. These applications are relatively niche compared with the quantities of scrap that require recycling however, therefore a solution that produces a reformed material that can be used in structural applications would be desirable in both financial and environmental aspects.

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The focus of the work presented here is to discuss a novel technique to reforming scrap fibre reinforcement to produce a material that retains the fibre alignment and the mechanical performance of the virgin feedstock. By cutting the waste material into patches, and then laying them up so that the edges of the patches butt up against each other in the same direction, a ply of aligned fibres with a latticework of discontinuities is created [7]. Plies are offset by a certain distance from the previous ply so that the discontinuities are not stacked directly on top of each other. The dimensions of the coupon remains constant throughout the laminate. An example of plies that can be built up into a laminate is shown in Figure 1.

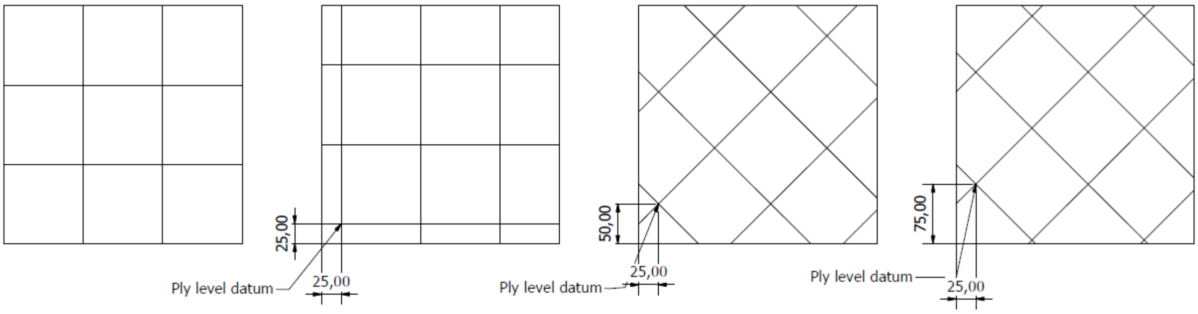

Figure 1. Example of a 4 ply layup scheme using 100mm square coupons to be laid over each other

Previous work has shown this patch reformed composite has beneficial forming and surface quality properties compared with continuous composites [12]. The patchwork material has also shown reasonable property retention.

Whilst the reforming approach shows promise in terms of mechanical properties, in order for it to be commercially successful, there needs to be a rapid, cost effective process to perform the reformation. Automation is therefore required for as much of the process as possible. To place the patches, Fibre Patch Placement (F.P.P.) is a suitable option. A laminate is sequentially build up with patches of pre-defined size. The steps involved in the F.P.P. process are shown in Figure 2.

When using virgin material, continuous spread tape with binder on is fed into the machine (1). This tape is cut into patches of predefined size and shape using a stamping blade (2). The patches are then inspected visually for any quality issues such as wrong size, loose fibres or inadequate cutting (3). After inspection the patches are picked up by a delta robot using a vacuum foam gripper with internal heating. The heating activates the binder on the patch to make sure that it sticks to the tooling. A second vision inspection checks the position of the patch on the gripper and calculates the offset between the patch and the centre of the gripper (4). Based on this a micro adjustment is done to the programmed patch position to make sure that the patch is placement at the right position on the tool. The tool itself is guided by a 6-axis robot to enable direct preforming of three-dimensional geometries (5).

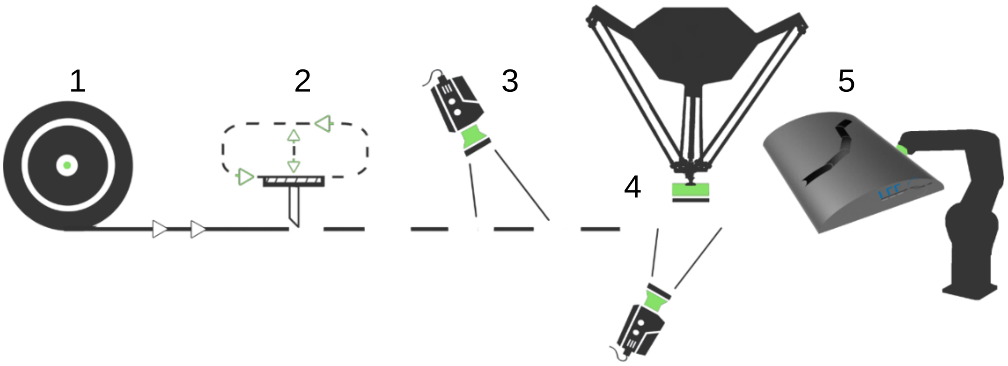

Figure 2. F.P.P. Process steps [13]

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While F.P.P. usually uses continuous unidirectional fibre tape with very low areal weight (80g/m^2), modifications were required to process pre-cut patches made of heavier NCF material. The vision systems use the dark, uniform appearance of the carbon fibre, but since the biaxial patches have cotton stitching, a different method based on contrast and grey value detection is required. Typically a patch is heated through thickness while it is transported from the cutting to the tool. With thin spread tape and a low melting binder this works well even with frequencies of one patch per second. For material with larger areal weight, different heating concepts have to be used to guarantee a high placement rate and proper activating of the binder, and since the quantity of binder on the reclaimed scrap will most likely either be unknown or be unsuitable for the process, additional binder will be required.

The effect of polyester binder content on material performance has been investigated for a variety of constituent material types and infusion methods with conflicting results. Khoun et al.[14] investigated the effects of binder content on both wash out and mechanical performance of quasi isotropic glass fibre reinforced epoxy, finding that in tension the modulus decreases but strength remains reasonably constant with increasing thermoplastic polyester binder content. In flexure, modulus was found to decrease reasonably linearly, and strength remained constant up to 2%wt binder, after which a significant drop was observed. This is attributed to the effect on permeability of the fabric that the binder has. It has been noted that the binder located on the outside of the tow could block the resin from saturating the fabric [15], which would slow infusion times and has the potential to increase void content. On the other hand, the interlaminar toughening effect of adding polyester binder to an epoxy resin was investigated by Daelemans et al. [16]. It was found that the inclusion of polyester resin leads to a large increase in interlaminar fracture toughness without negatively effecting the flexural stiffness or strength of the material.

Tanoglu et al. [17] found that the flexural strength of a glass fibre / polyester composite reduces but flexural modulus increases with increasing polyester binder content, and interlaminar shear strength is not affected. The mode I fracture toughness reduces greatly with the inclusion of binder. This is attributed to the chemical compatibility of the binder with the sizing agent used on the fibres. The binder can effectively act as a barrier between the sizing agent and the matrix, thereby decreasing the effectiveness of the chemical bonding between fibre and resin, in turn reducing the fracture toughness of material. The type of resin used will also have an effect, with the authors stating that an epoxy resin used with the same component materials had a much greater reduction in fracture toughness [18]. In glass fibre/ vinyl ester composites [19], it was found that the type of binder has a great effect on material properties. Thermoplastic polyester binder has a detrimental effect on properties while a catalysed epoxy binder can increase fracture toughness properties. In both cases the interlaminar shear strength was reduced.

It is clear that there is conflicting evidence as to what the effect of interleaving plies with binder on both fracture toughness and flexural performance. Since failure in the reformed material will be a combination of both these the current work presented aims to determine how the binder affects the reforming material, both in terms of manufacturing rate and quality and on flexural performance.

2 Methodology

To investigate the effect of additional binder on the reformed material, the investigation was divided into two sections, manufacturing and performance. Firstly, modifications to the F.P.P. equipment were investigated to find the effect on placement rate and accuracy of adding 14 g/m^2 and 28 g/m^2 binder to the patches. Secondly, the performance was tested by creating samples and testing them in three point bending. Control samples created by hand with no additional binder were also tested. The carbon fibre reinforcement used was Formax 24k FCIM 359-PB biaxial NCF with a total areal weight of 441g/m^2, infused using a Huntsman resin system combining XB6469 epoxy and Aradur 2954 cycloaliphatic polyamine hardener. The binder used was AB-Tec co-polyester ABE-003 binder which has a melting temperature between 110-130 °C in 14g/m^2 veil format. The 28g/m^2 additional binder was made up of two layers of 14 g/m^2 veil. The veils were applied to virgin biaxial fabric, and then placed on a tool plate enclosed in a vacuum bag. The binder and fabric were then heated in an oven under vacuum at 110°C

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for 1 hour so that the binder adhered to the fabric. Once cool, the patches were then cut using a CNC ply cutter.

2.1 Manufacturing modifications

Since the time it takes to activate the binder is important for viable rates of reforming, a pre-study was performed to evaluate four heating concepts to ascertain the most suitable modification to the process for the reforming approach. The first concept consists of heating the tool plate to 160 °C. The patches were then placed onto the tool with the binder facing towards it. The second concept was an evolution of this. Binder veil was placed on the heated tool and once it had melted, patch placement was started with the side of the patch with the binder applied facing away from the tool. The patches stuck to the tool due to the already melted binder. Concept three was to use an infrared heating lamp. The final concept used the internal heating of the gripper as a reference process.

In concept 1, the patch must be pressed onto the surface of the tool to activate the binder. Whilst this takes less than a second, the act of applying pressure generates some residual tack on the gripper side of the patch, which results in the patch adhering to the gripper instead of the tool face or the patches already applied to the tool. Concept 2 rectifies this since there is less pressure applied to the patch, so it sticks to the binder already applied to the tool face and not to the gripper. Once the patch has been applied to the tool, it takes 30 and 35 seconds for the 14g/m^2 or 28g/m^2 binder to melt respectively. For small components there will therefore need to be a gap in between laying up each ply to let the binder melt, however, assuming a patch can be applied at a rate of 1 per second, any components with greater than 35 patches will not require a gap between plies. The infrared heater of concept 3 heats the patches to only 140°C in 8 or 12 seconds for the for the 14g/m^2 and the 28g/m^2 binder respectively. This creates a holding point that reduces the placement rate, and a fast robot is required since the patch starts to cool as soon as it is picked up. Finally, the internal gripper heater was unable to melt the binder due to the thickness of the patch.

Based on this study, concept 2 with a heated tool and a first layer of binder is chosen for the trials as the most effective heating option. 8 samples were made, 4 with 14g/m^2 binder and 4 with 28g/m^2 binder applied to the 60mm × 30mm biaxial ([0°, 90°]) patches. The samples were one patch wide (30mm) and 6 patches long, and were made up of 4 biaxial plies which were offset from each other by half a patch length.

2.2 Flexural performance

As well as the preformed samples, a discontinuous plate was laid up by hand with no additional binder which was then sectioned into control samples. The continuous plies were cut from biaxial feedstock and discontinuities were cut using a sharp modelling knife and a heavy straight edge to minimise fibre direction deviation. As soon as the ply was cut it was moved to the tool plate to minimise how long it was handled. The preformed samples and the control sample plate were then infused with epoxy resin with the infusion direction along the length of the sample using Vacuum Assisted Resin Transfer Moulding (VARTM). Once infusion was complete, the composite was cured under vacuum in an oven according to the cure cycle recommended by the resin manufacturer.

Specimens with a length of 150mm and width 20mm were sectioned from the plates using a diamond edged circular saw so that each sample had a stack of discontinuities close to the centre of the sample. These were tested under three point bend load conditions according to ASTM D790 [20], with fixture geometry as shown in Figure 3. A Zwick 1478 electromechanical test machine with a load limit of 50kN was utilised for these tests, with a 2mm/minute displacement rate applied.

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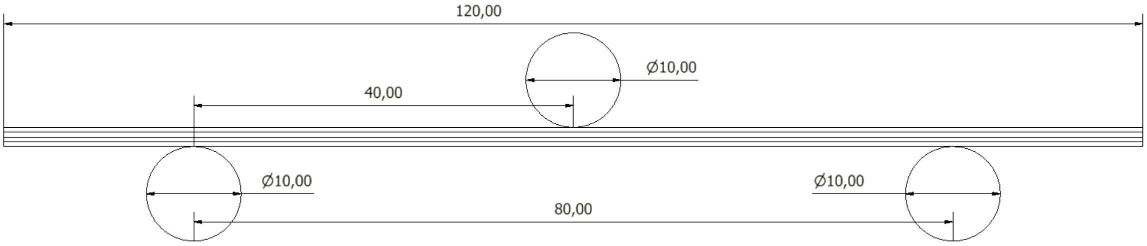

Figure 3. 3 point bend fixture geometry

Since a span to depth ratio of greater than 1:16 was used, flexural stress and flexural modulus was calculated according to equations 1 and 2 respectively.

$$\sigma_f = \left(\frac{3PL}{2bd^2}\right)\left(1 + 6\left(\frac{D}{L}\right)^2 - 4\left(\frac{d}{L}\right)\left(\frac{D}{L}\right)\right) \tag{1}$$

$$E_B = \frac{L^3 m}{4bd^3} \tag{2}$$

Where: P = load at a given point on the load deflection curve (N); L = Support Span (mm); b = width of beam (mm); d = beam thickness (mm); D = deflection of the centreline of the specimen at the middle of the support span (mm); m = slope of the tangent to the initial straight line portion of the load deflection curve.

3 Results and Analysis

The averaged flexural strength and stiffness of the FPP reformed material is compared with control samples laid up by hand in Figure 4. The error bars show one standard deviation. There is little effect on flexural strength depending on binder content, but there is some variation present in the measured modulus. The error bars are also reasonably long, which suggests a large variation in results. In all cases the laminates showed very low voidage levels

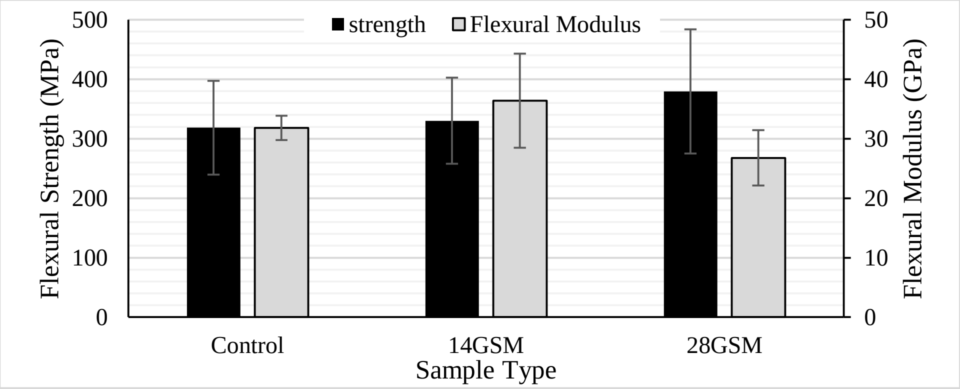

Figure 4. Flexural strength and stiffness of biaxial reformed samples with varying quantities of binder

The majority of the samples failed with brittle failure, as shown by the sudden drop off in stress, shown in Figure 5. The two principal failure mechanisms present in these samples were delamination from a discontinuity, and compressive failure in the top surface. Due to the makeup of the samples, discontinuities in half the plies were present towards the middle of the length of the sample. How close these discontinuities were to the centre depended on the position of the sample in the plate. The ultimate failure mode was invariably compression in the topmost plies. The location of this compressive failure was between the load point and the location of the nearest set of discontinuities.

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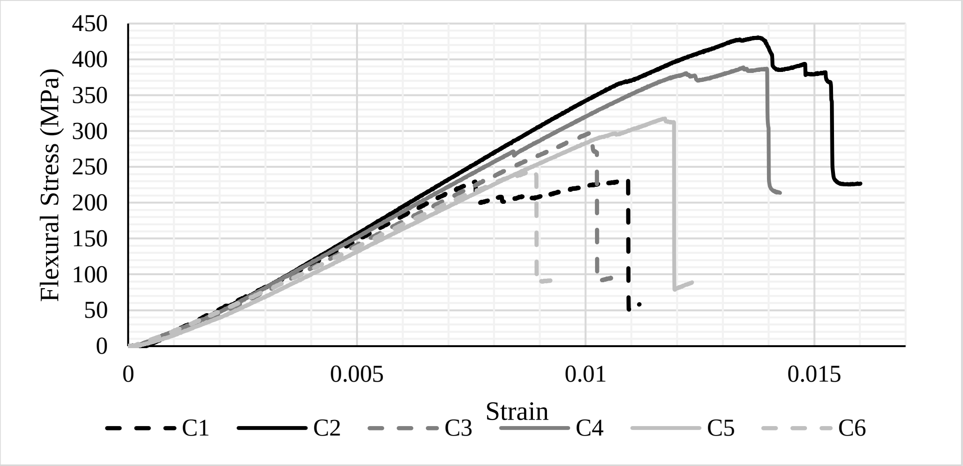

Figure 5. Flexural Response of handmade control samples

All failure started with delamination to a certain extent at the discontinuity nearest the load point either on the top surface in compression or bottom surface in tension. Since the strain is similar on the top and bottom surface, crack initiation occurs at similar displacements for both bottom and top surfaces. The delamination then starts to propagate towards the load point. The cracks in samples C1, C3 and C6 only travel a short distance (~1mm) before compression occurs in the top most surface in C1 and C3, and in the 0° ply below the delaminated interface since the top surface was discontinuous. In C5 and C4 the failure mechanisms are similar, but the delamination propagates further (~3mm) before failure closer to the load point. In C2 the crack propagates ~6mm all the way from the discontinuity to the load point before compressive failure occurs at the load point.

It is clear from the control sample results that in flexure failure is highly localised. Performance will therefore be highly dependent on local defects found in the different samples. By looking at placement angle of the 14g/m^2 and 28g/m^2 samples in Figure 6 and Figure 7 respectively, it is clear that the additional binder reduces the number of defects and localised thinning. The difference between the two can be attributed to the robustness of the patch, i.e. how well the patch holds together whilst being handled. With the additional binder of the 28g/m^2 binder, there are fewer loose fibres which affect the visual inspection algorithms, therefore leading to a higher quantity of rejected or misaligned patches in the 14g/m^2 binder samples.

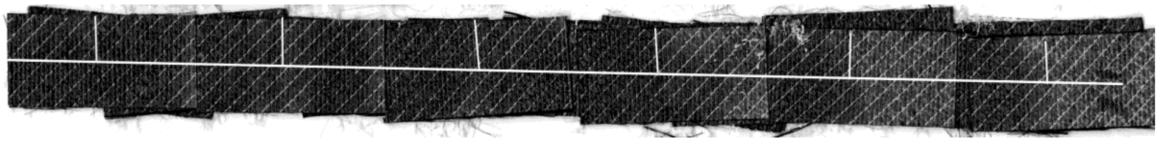

Figure 6. Example of a sample with 14gsm binder applied. White line shows centre of sample and short lines indicate angle of patch

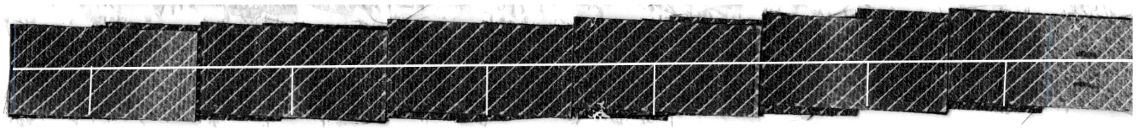

Figure 7. Example of a sample with 28gsm binder applied. White line shows centre of sample and short lines indicate angle of patch

As seen in Figure 6, many of the patches in the surface that can be seen overlap each other. This would suggest that the same occurs in the internal plies. When the patches overlap there will be a localised thickening of the laminate. This will also mean that the other end of the overlapping patch will not butt up against the adjacent patch, creating a localised thinning. As shown by the control samples, ultimate failure in flexure is determined by local defects, and therefore changes in thickness along the length will

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have a great effect on both the stiffness and strength of the sample. This can be seen in the variability of the results in Figure 8. The majority of the samples with 14gsm binder applied are reasonably close in strength and stiffness, but sample 14_3 and 14_5 fail early due to a local thin section of the gauge length. This does not occur in the 28gsm samples due to the more aligned nature of the patches.

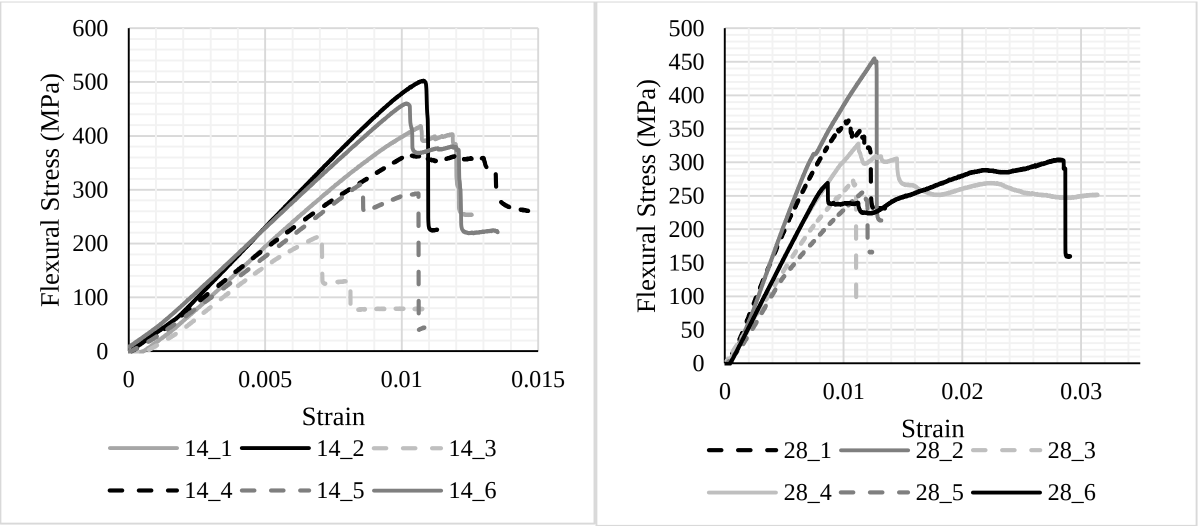

Figure 8: (l) Flexural Response of FPP reformed material with 14gsm binder applied; (r) Flexural Response of FPP reformed material with 28gsm binder applied

The samples made with 28gsm binder applied have a lower modulus than the other sample types. This can be attributed to the plasticising effect of the thermoplastic binder on the resin [16]. Samples 28_4 and 28_6 also show a large region of “pseudo-ductile” failure, where the gradient of the response changes before ultimate failure. This can potentially be attributed to the failure mechanisms present. Compressive failure occurs in the top surface of these two samples at a discontinuity at the loading point. The two ends of the patches that make up this discontinuity then buckle up against each other. The crack then propagates through the thickness gradually and this compressive action occurs through the thickness, absorbing energy. The bottom ply in tension does not fail and therefore acts as a hinge. This compressive action can again be attributed to the plasticising effect of the binder, creating a softer resin which will crush at a lower stress.

4 Conclusions

The current work presented is part of efforts towards creating a highly automated process to reclaim scrap dry fabric that would otherwise be sent to landfill, and reform it for use in high value applications. The Fibre Patch Placement process has been modified to allow thicker NCF material to be used, and as part of these modifications, additional polyester binder has been added to the material. The quantity of binder was varied and the effect on manufacturing efficiency and flexural performance was analysed. It was found that the two quantities of binder tested had little effect on the flexural strength, but the greater quantity of binder reduced the flexural stiffness. The failure modes were similar however, with a combination of compressive failure and a small amount of delamination present. Failure was also localised depending on the location of discontinuities. The quality of the preformed sample also contributed to this localised failure, with the patches with 14g/m^2 binder applied being less robust than those with 28g/m^2 applied, leading to more frayed edges which in turn confused the vision systems of the F.P.P. equipment. This resulted in a less aligned sample and a greater number of rejected patches.

Due to the results discussed, 28g/m^2 polyester binder applied to the scrap would be the more favourable choice to reduce the impact on alignment of plies and reduction in placement rate due to the scrapping of patches despite the loss of stiffness. The next stage of this work is to implement the modified F.P.P. process into a wider method for taking the scrap material produced during kit cutting to create a cost effective, industrially viable route to generating reformed material.

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