MECHANICAL PERFORMANCE OF NEEDLE-PUNCHED CARBON FIBER REINFORCED PHENOLIC COMPOSITES

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ABSTRACT

Traditional composite laminates that are highly used in the aerospace and automotive industry have reinforcing fibers that lie in the X and Y orientation of the laminate or ply stack. The resulting composite product is one with anisotropic properties, being weaker in the Z orientation of the laminate. Composite failure will occur between the reinforcing layers at the resin rich interlayer. To improve the composite's resistance to delamination, a needle-punching process is utilized to re-orient parent carbon fibers thru the thickness of the dry fiber ply stack. The needle-punching equipment consists of a needle-board carrying rows of barbed needles. The needle-board drives the needles through the preform, and the barbs re-orienting the fibers in the Z direction. Rayon based 8-harness satin carbon fiber is needle-punched and infused with a phenolic resin using Vacuum Assisted Resin Transfer Molding (VARTM). Varying degrees of needle-punch density are evaluated for their respective inter-laminar shear strengths. A correlation model of needle-density to mechanical behavior was developed and fiber re-orientation was analyzed by microscopic imaging.

1. INTRODUCTION

Composite material applications continue to grow and expand in several industries such as the aerospace, automotive, construction and wind energy to name a few. Traditional manufacturing processes and materials have evolved since their performance has met the demands of engineered materials early on requiring high strength to weight ratios. Along with the evolution of traditional systems, new composite materials and complex processing equipment have been developed. These advancements have given engineers increased design flexibility where they are able to precisely design the laminate structure, down to controlling the fiber orientation and direction, of composite parts to produce the highest strength required for the given application. These technological advancements do come at a price, and there is still the requirement of producing parts at a reasonable cost. For example, there is much effort put into producing high quality parts by out-of-autoclave (OOA) alternative manufacturing processes.

Focusing on the fiber reinforcement, these can be chopped or supplied as a yarn which is produced as a large bundle of filaments called a tow. The tows are then laid unidirectionally, braided as a sleeve, or woven to produce a 2D fabric that is supplied in many different weave styles. The 2D fabrics can be supplied dry or pre-impregnated with a resin that has been b-staged. With more complex braiding and weaving machines, the tows can be inter-woven into complex and highly dense 3D fiber preforms that maintain their rigid shape when handled. Traditionally, composite parts are built by stacking the 2D fabric layers on top of one another until the desired geometry and part thickness is achieved. This layer-by-layer building process lacks reinforcement thru the thickness of the laminate ply stack. This results in a part with anisotropic properties, being weaker in the thru thickness or out of plane direction. Delamination, or a separation of the plies, is a typical failure mode in composites which results in a great loss of mechanical properties. Some processes, such as stitching and z-pinning, have been developed to improve the thru thickness mechanical performance which will in turn improve the laminates resistance to delamination. Similarly, needle-punching has also been considered for composite processing to reinforce a dry fiber laminate stack thru the thickness or in the z-axis using the parent fibers of the 2D fabric. This research investigates the advantages and disadvantages of the needle-punching process for composites and reviews the variable parameters seen in this process.

Needle punching is a process where layers of reinforcing fabric are joined together by re-orienting fibers through the thickness of the dry ply stack by using barbed needles. As the needles mechanically punch thru the thickness of the ply stack, the barbs on the needle catch the fibers and re-orient them in the z-axis. The series of needles are held by a needle board. The needle board containing rows of equally spaced barbed needles repeatedly punches the laminate. A Feltcraft industrial needle-punching machine is shown in Figure 1.

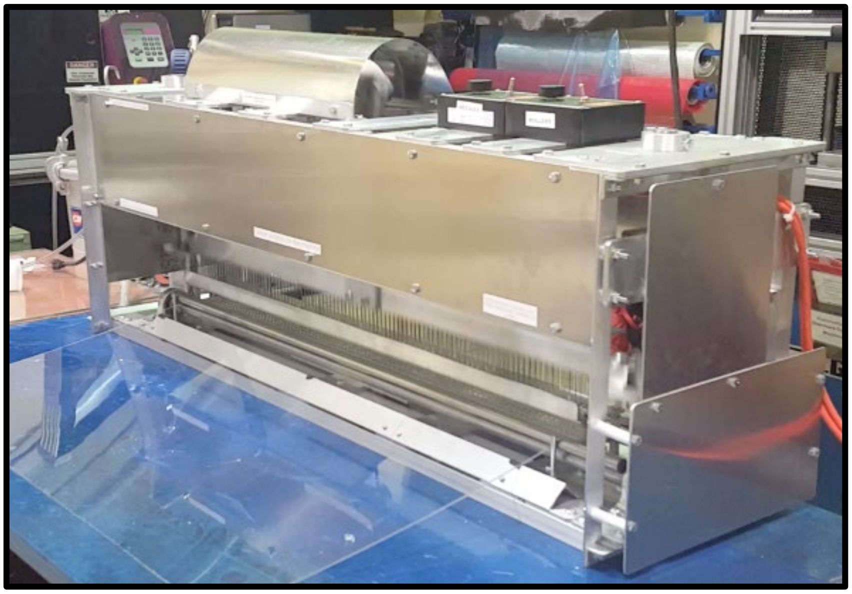


Figure 1. Feltcraft Industrial Needle-Punching Machine.

The needle-board is driven by a motor to repeatedly punch the needles thru the stacked layers of dry fabric plies. The barbed needles transfer the fibers in the z-plane which become entangled with the layers below it and remain in place by frictional forces. This results in a uniformly dense preform. Figure 2, obtained by Chen et al., 2016 represents the post needle-punched laminate, illustrating the fibers displaced through the thickness of the laminate stack.

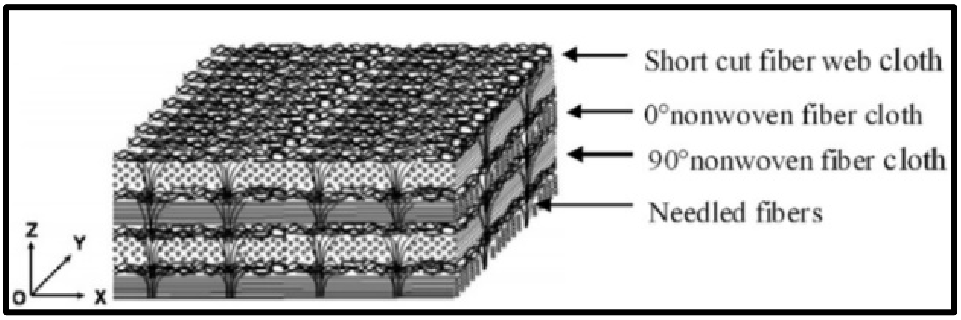


Figure 2. Needle-Punched Laminate Preform [4]

2. MATERIAL SYSTEM

Durite SC1008 liquid Phenolic resin supplied by Hexion Co. is used to manufacture composite panels. Durite SC1008's low viscosity of 180 – 300 cps makes it ideal for the Vacuum Assisted Resin Transfer Molding (VARTM) process. The liquid resin is a one-step thermally cured thermosetting resin with an operational temperature of up to 500°C. The thermal stability makes it ideal for high temperature applications. In liquid state, the resin contains 15% - 30% of solvent (IPA) by weight which reduces the viscosity significantly. When the phenolic resin is placed under full vacuum, the solvent content will begin to vaporize. If allowed to vaporize during the VARTM process, it will cause the resin to become foamy. In addition, the viscosity will greatly increase as the solvent content is removed from the liquid resin and the parts by weight is reduced.

Due to its drapability and tow count, an 8-harness satin weave of rayon based carbon fiber fabric was chosen as the reinforcing material. The fabric was obtained from Cytec Engineered Materials Inc and has a dry fabric thickness of 0.48mm with a fiber aerial weight of 261g/m^2.

3. MANUFACTURING PROCESS

Manufacturing starts with the cleaning and application of mold release to a two-piece flat panel mold. The mold pieces are square 18 inch x 18 inch steel plates with a thickness of 0.25 inches. The size of the mold plates match the size of the GENESIS heated compression press platens. The mold release application allows the composite panel to release freely from the mold. Cleaning and mold release application is performed per manufacturer instructions in between cure cycles. Ten layers of carbon fabric were cut 13 inch x 13 inch in size. The layers were stacked on one another and two opposite edges were stitched. The stich was needed to prevent the individual layers from shifting or sliding out of position as it was fed through the needle-punching process. The needle machine has variable speeds for the punch frequency and the material feed rate as it passes thru the needle punch zone. The needle punch frequency was set to 135 punches per minute and material feed rate of 9.75 inches per minute. The ply stack was processed through the needling machine three times to obtain the desired preform consolidation.

The preform is then infused with the liquid phenolic resin by the VARTM manufacturing process as shown in Figure 3. The resin was pre-heated to 65.5C (150F) in an oven prior to infusion. The mold and preform setup were also heated to the same temperature prior to infusion by a thermal blanket placed underneath the mold plate. The resin inlet source is clamped off and vacuum is pulled on the mold/preform. The vacuum level is maintained at a maximum of 20in/mg during the infusion process. This vacuum level prevents the resin foaming that would occur due to the vaporization of the IPA within the resin. Once the target vacuum level is reached, the resin inlet line is opened and the change in pressure draws the resin into the mold toward the vacuum source.

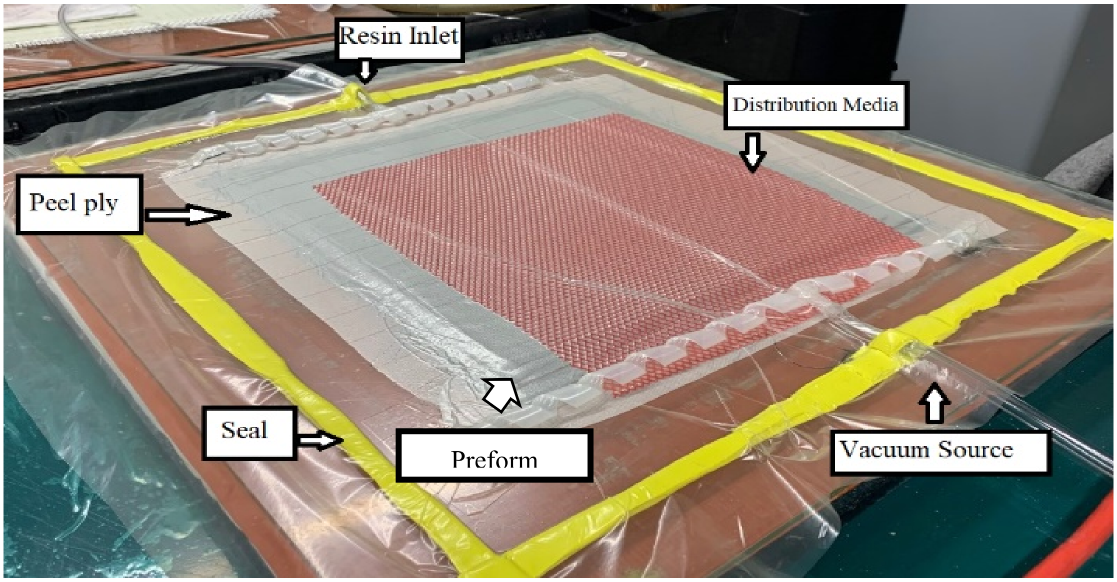


Figure 3 – VARTM Set-up for Needle-Punched Preform Infusion

After the fabric preform is fully infused with resin, the vacuum bagging and infusion materials are removed from the mold leaving only the preform. The second half of the mold plate is carefully placed on top of the preform. The assembly is then placed in the GENESIS heated press for the cure process. A pressure of 5 tons is applied to the mold and the temperature is set to 350 F with a ramp rate of 10 degrees per minute. The cure temp of 350 F is held for 2.5 hours to fully cure the composite laminate. The pressure is released and the panel is allowed to air cool to room temperature. The test specimens are then CNC cut by an abrasive waterjet machine. The waterjet cutting process minimizes heat generation during the cutting process and can maintain tight tolerances. Machined edges are visually inspected with 10x for delamination and porosity.

4. EXPERIMENTATION

Initial needle-punch experiments were performed with various fabrics including polyester felt, glass, silica and carbon plain woven fabrics to observe how different materials would join into a preform after needle-punching. An overlap region of several plies was needle-punched and then tested by manually pulling the plies apart from the preform while measuring the force required to break free from the preform using a handheld force gauge as shown in **Figure 4**. This testing demonstrated that as the needle-punch density is increased, a greater force is required to separate the needle-punched zone. This is due to an increase in the number of z-axis fibers that are being reoriented by the barbed needles used in the needle-punching process.

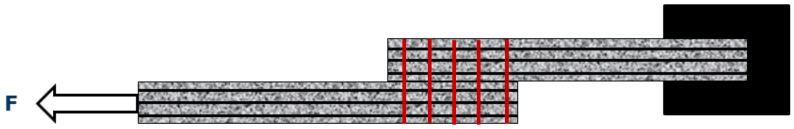
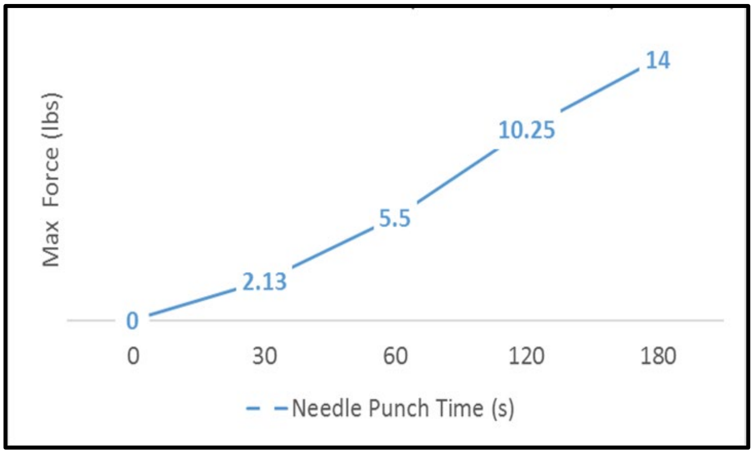


Figure 4. Experimental Set-up of Dry Fabric Lap Shear Test

For the composite needle-punched panels, short-beam strength was determined per ASTM D2344 – Short Beam Strength of Polymer Matrix Composites Materials and Their Laminates. The mechanical testing was performed on a control panel and needle-punched panel on five test specimens with an MTS 810 Servo Hydraulic Test System.

5. RESULTS AND DISCUSSION

Needle-punching of polyester fiber felts showed a linear correlation in the max force required to separate the needle-punched layers to the needle-punch density. **Graph 1** shows the correlation of the dry fabric interlayer pull strength with regards to the needle punch time. This shows that the higher the needle-punch density – which refers to the number of punches per area – of the preform, there is an increase in the amount of reinforcing fibers re-oriented thru the thickness of the laminate in the z-plane. Therefore, the needle punch time and the number of passes has to be such that the z-plane is reinforced uniformly along the fabric and through the layers without breaking the fibers already reoriented.



Graph 1. PE Felt Needle-Punch Trials

The machined edges were observed with a digital microscope. **Figure 5** shows a 200x view of a cross-section of the laminate. Z-axis fibers are shown and confirms that the fibers are being reoriented through the thickness of the ply stack by the barbed needles while needle-punching. The zero degree tows are shown as continuous fibers, while the 90 degree tows from the woven fabric are shown as a series of dots. Fiber damage and broken fibers was also observed because of the needle-punching and is shown in **Figure 6.** Depending on the severity of damage to the in-plane (x-y plane) continuous fibers, the in-plane mechanical properties could be weakened.

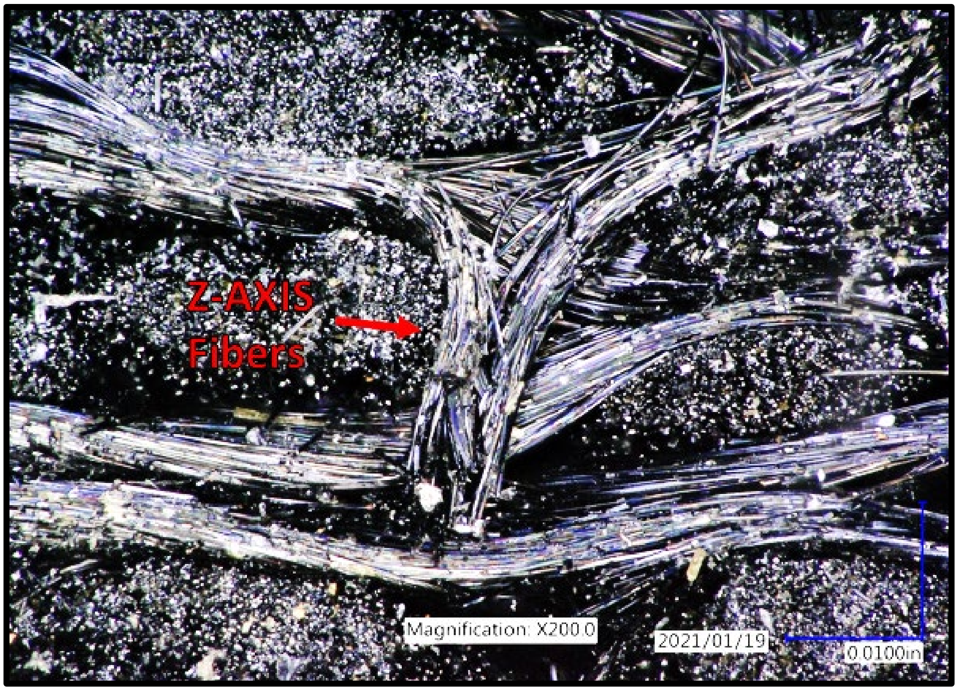


Figure 5 – Optical Image of Z-axis fibers in Needle-Punched Laminate

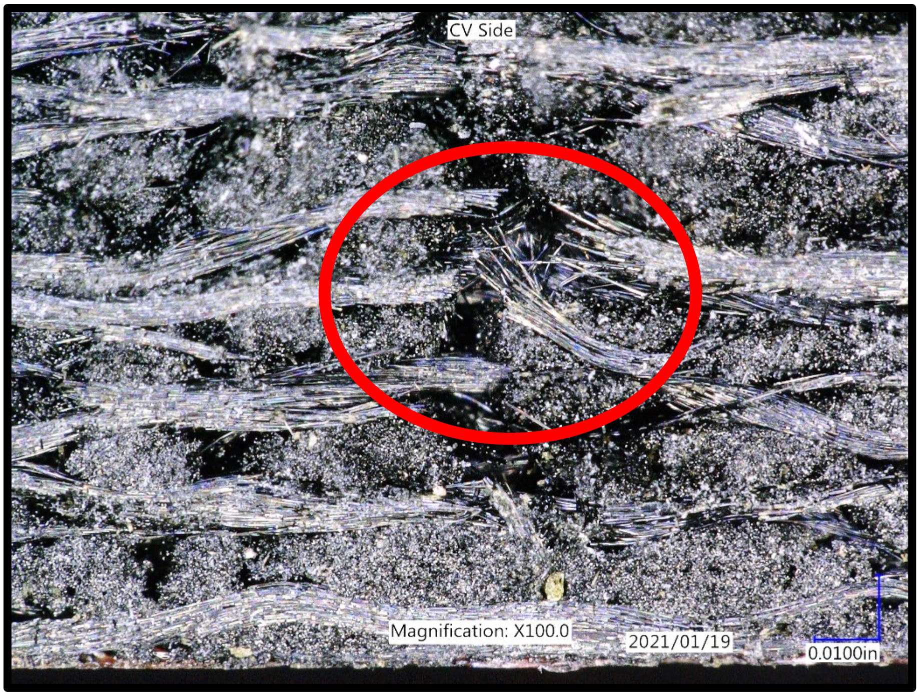
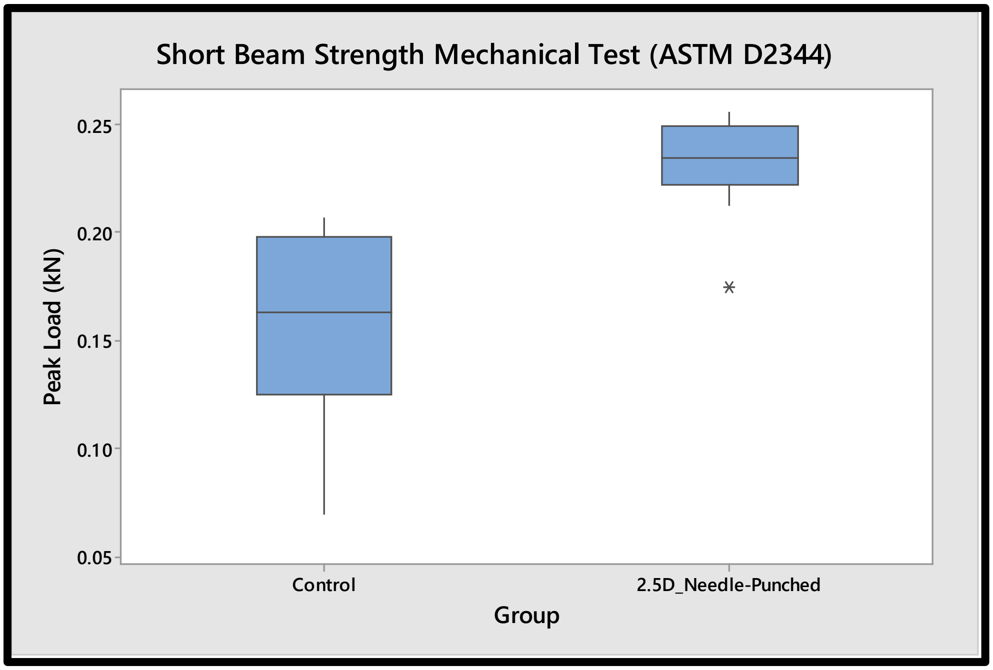
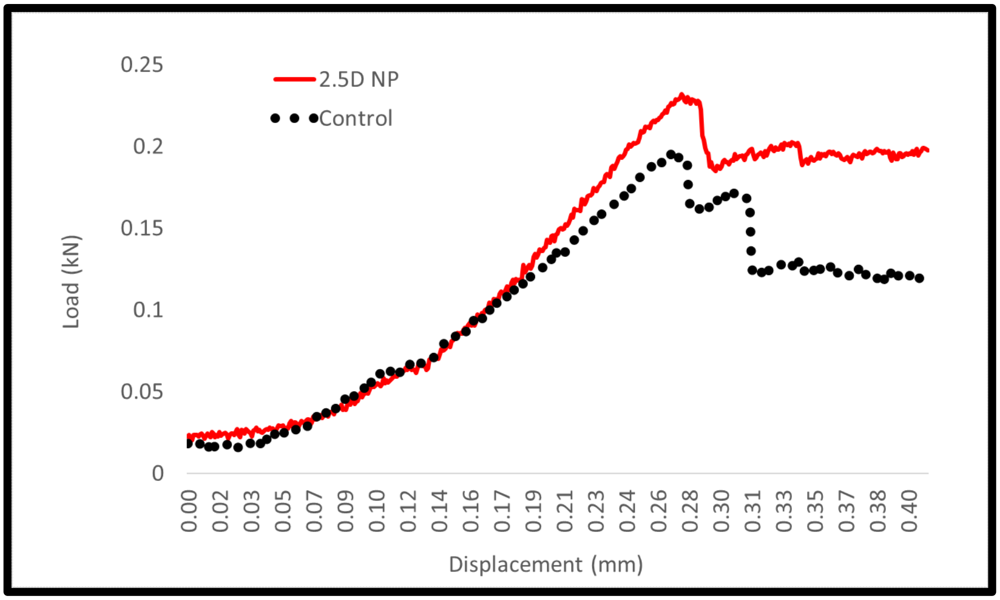


Figure 6 – Optical Image of Broken Fibers in Needle-Punched Laminate

Results from the short beam shear strength testing of a control specimen vs needle-punched specimen is shown in **Graph 2**. An increase of 46.8% for the short beam strength was seen for the 2.5D needle-punched test specimens on average when compared to a control specimen that did not have any needle-punching process performed. The results indicate improved interfacial adhesion between the matrix and the fibers. Additionally, the fibers oriented through the thickness are contributing to the load transfer, delaying delamination. The control group had visual delaminations with visual failure modes being a mix of interlaminar shear and flexure failure. It was observed that the 2.5D NP specimens did not delaminate and had an inelastic deformation failure mode with some minor cracking seen in the matrix. Representative force curve is displayed in **Graph 3**.



Graph 2 – Inter-laminar Shear Strength (ILSS) Test Results



Graph 3 – Short Beam Shear Force vs Displacement Curve

6. CONCLUSIONS

2.5D composites were successfully manufactured by three step process including needle-punching, VARTM and thermal cure under pressure. Needle-punching is a low-cost and high-volume production process for manufacturing 2.5D composites. Individual layers of 8-harness satin weave were successfully joined with z-axis fibers and transformed into a uniformly dense 2.5D preform ready for resin infusion. Heating the resin and mold prior to infusion reduced the viscosity which allowed the resin to penetrate the dense dry fiber preform and fully impregnate the fibers.

The interlaminar shear strength was increased for needle-punched composite panels when compared to traditional 2D composite laminates and displayed a greater resistance to delamination when out-of-plane forces are applied as seen during short beam shear testing per ASTM standards. Fiber damage of in-plane continuous tows was witnessed with use of optical microscope. This could result to weakening in-plane mechanical properties such as ultimate tensile strength. Further mechanical testing of in-plane properties will be performed. Increasing needle-punch density, or the number of needle penetrations per square area, results in higher number of displaced thru-thickness fibers. Based on the application, the needle-punching process will need to be optimized for density to balance the of out-of-plane mechanical property improvement to degradation of in-plane properties.

8. REFERENCES

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