Reinforcement of Cellulose Nonwovens with Thermoplastic Lattices

WEAV3D®

VOLKSWAGEN GROUP OF AMERICA

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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Glossary and Abbreviations

Certain non-standard terms will be used in this report and a quick reference is provided here.

Cover Factor	Used to describe the density of WEAV3D lattice materials, this is calculated by diving tape width by the center-to-center spacing of the tapes in a given direction, resulting in a % covered area. Cover factor for a whole lattice is commonly reported in XX/YY format, where XX is the warp spacing and YY is the weft spacing. A cover factor of 100% is fully dense (tapes are touching edge to edge)
NFPP	Natural fiber polypropylene. This term can either be used to refer to a nonwoven mat, in which case the fibers are most commonly hemp, jute and kenaf, or unidirectional tapes, where the fiber is flax.
Paper Composite	Alternative name for cellulose polypropylene nonwoven material
Warp Spacing	Relative spacing between warp tapes (tapes that run in the machine direction), expressed as a center-to-center distance or cover factor
Weft Spacing	Relative spacing between weft tapes (tapes that run in the cross-machine direction), expressed as a center-to-center distance or cover factor

Executive Summary

WEAV3D, Volkswagen Group of America (VW), and the University of Tennessee Knoxville (UTK) partnered on this project to solve formability issues previously identified by VW and UTK that limited the types of geometries that could be formed using their novel paper composite wet-laid nonwoven. WEAV3D's composite lattice materials, produced from thermoplastic unidirectional tapes, have been previously validated in compression molding processes and were selected to control elongation and stresses within the paper composite during forming.

Task 2 demonstrated that lattice reinforcement has a positive effect on the flexural strength and stiffness of paper composite flat panels, and either has no impact on water uptake or reduced water uptake, the magnitude of both effects depending on the type and ratio of UD tape used in the panels' construction.

Task 3 validated the hypothesis that lattice reinforcements can reduce tearing of the cellulose/PP paper composite during forming, while also exploring the effects of lattice density and positioning. This work was conducted on lab-scale surrogate geometry that provided a springboard for refinements in lattice design needed for the full-scale part forming trial.

Task 4 involved demonstrating the lattice reinforcement method on production-representative tooling and equipment (TRL 7). The part selected for this trial had been previously shown to cause through tearing in the paper composite due to deep draw and complex features. With the addition of the lattice reinforcement, through tearing was eliminated. Post-trial activities involved characterization of consolidation density, water uptake, and flexural testing of specimens cut from the full-scale parts.

The results have shown that adding a lattice reinforcement can have significant advantages to the mechanical performance and drapability of the substrate materials. Further testing is necessary to optimize these effects, along with mitigating issues discovered during result analysis, such as uneven consolidation of the part.

Project Scope

The natural fiber composites on the market today possess either poor performance characteristics, low fiber content, or poor formability in complex shapes. Also, they suffer from a poor ability to recycle. The University of Tennessee (UT) and Volkswagen (VW) developed a new wet-laid thermoplastic and natural fiber composite forming technology. The process enables the formation of complex shapes. In addition, we have demonstrated the ability to mechanically recycle composites and incorporate the material back into the molded structure. However, the wet, nonwoven mat's strength limits handling and continuous processing when high shear stresses are present.

We propose reinforcing wet-laid cellulose and WEAV3D's novel fiber tape reinforcement technology produced from polypropylene and unidirectional natural fibers. We hypothesize that WEAV3D's reinforcing tape can be incorporated directly into the composite molding process. We have two main objectives: improving mechanical performance and improving formability, particularly regarding handling, tear strength, and overall processing and mechanical performance of molded complex part geometries. Panel samples will be formed to validate the integration of the WEAV3D lattice with the cellulose-PP nonwoven preforms and to characterize their mechanical performance (Task 2). Lab-scale forming trials will evaluate handling and tear strength improvements (Task 3). VW will mold a full-scale demonstrator at one of their Tier 1 suppliers to validate formability and mechanical performance on the component level (Task 4). Task 1 was a catch-all for project management activities and will not be reported in detail.

Task 2: Panel Forming and Characterization

Task Objectives

WEAV3D produced a variety of lattice patterns using both glass fiber reinforced polypropylene and natural fiber reinforced polypropylene unidirectional tape materials. These lattices were supplied to UTK, where UTK will experiment with techniques to integrate the lattice with their wet laid cellulose/thermoplastic nonwoven materials.

Once a reliable technique is developed, UTK fabricated a selection of lattice reinforced flat panels to characterize flexural performance, water uptake, lattice read-through, and panel consolidation density relative to the unreinforced baseline. Panel testing evaluated the weight and performance benefits of different tape reinforcement and panel construction (single side vs. double side lattice reinforcement).

Methods

Materials

Continuously formed flat preforms made of 60 wt. % softwood kraft market pulp (Canfor) and 40 wt. % polypropylene fibers (Minifibers) were manufactured by Endeavor Composites, Knoxville, TN. The natural and glass fiber polypropylene lattices with warp and weft spacing of 50%/25% and 25%/66% were supplied by WEAV3D.

Composite Manufacturing

Sheets and tapes with dimensions of 203.2 x 279.4 mm were produced from the preforms. The sheets and tapes were compression molded using a 30-ton, electrically heated and water-cooled Carver Laboratory hydraulic press (model: 3895.4PR1A00), in a ratio of 10:1 with the tape on top of the 10 sheets, for 5 minutes at 190 °C under a pressure of 78.291 kN and cooled to 80 °C under pressure. One flexural and three water absorption samples were manually cut from each composite panel. A control (no tape reinforcement), and 2 orientations of each tape and warp/weft were produced.

Flexural Testing

Flexural samples with dimensions 152.4 x 165.1 mm were cut from each composite. Flexural testing was performed per ASTM D790, with the tape side being tested in tension. Additionally, samples were organized into Fx and Fy to better compare the different warp and wefts as shown in Figure 1. Before testing, samples were conditioned at 25 °C and 65 % RH for a minimum of 48 h. Flexural testing was performed using a dual-column Instron 5567 using a 3-point bend apparatus with a 500 N load cell. The span and rate were set to 140 mm and 9.6 mm/s, respectively. A linear variable differential transducer (LVDT) was used to measure strain up to a displacement of 20 mm, and testing continued up to 40 mm.

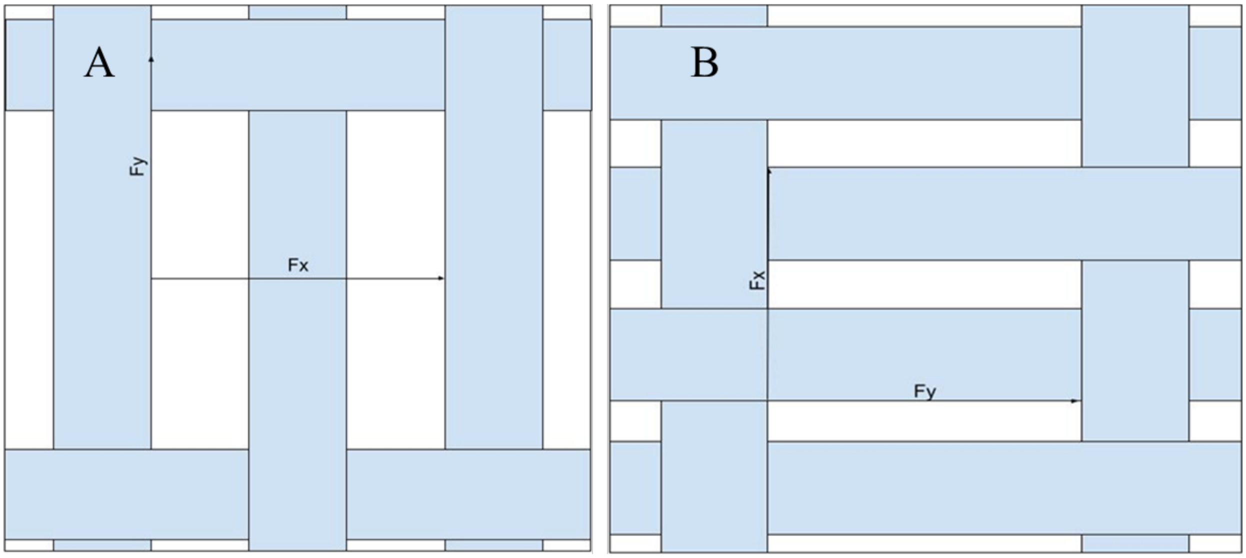

Figure 1: Fx and Fy load directions of warp/weft of A) 50/25 and B) 25/66.

Water Absorption Testing

Three water absorption samples with dimensions 25.4 x 76.2 mm were cut from each composite panel. The water absorption samples consist of all tape, no tape, 2/3's tape, and all tape with an overlap of tape in the center of the specimen as shown in Figure 2. Water absorption measurements were done following ASTM D570. Samples were conditioned by vacuum drying at 80 °C overnight. After conditioning, the dimensions and weight were recorded. The samples were then placed into a temperature-controlled bath at 23 °C for 24 hours where the dimensions and weight were measured again.

Figure 2: W1 is 2/3's tape 1/3 no tape. W2 is all tape with overlap of 2 tapes in the center. W3 is all tape.

Results and Discussion

Flexural Results and Discussion

The addition of the tape significantly improved the mechanical properties of the composites. Figures 3 - 6 depict the Young's modulus, specific modulus, maximum flexure stress, and specific strength, respectively. The addition of the glass fiber polypropylene tape yielded the best mechanical improvements with a 31 – 47 % increase in the Young's modulus, 34 – 44 % increase in the specific modulus, 3 – 34 % increase in the maximum flexure stress, and 10 - 32 % increase in the specific strength. The natural fiber polypropylene tape offered some increase in mechanical properties; however, it behaved more similarly to the control. It is important to note that the control and reinforced composites all exceed the current state of the art natural fiber and filled plastic parts currently in production. The addition of the natural fiber polypropylene tape yielded a 0 – 25 % increase in the Young's modulus, 8 - 30 % increase in the specific modulus, 0 - 6 % increase in the maximum flexure strength, and 0 – 9 % increase in the specific strength. Overall, the addition of a reinforcing agent improved the mechanical properties of the market pulp and polypropylene composite. Natural fiber tapes do not offer a significant advantage in mechanical performance over control. The continuous glass fibers represent an increase in performance that may be of distinct advantage in some applications where strategic reinforcement of certain parts is needed while adding little to the weight of the part. However, glass fibers add more complexity to the recycling of the parts.

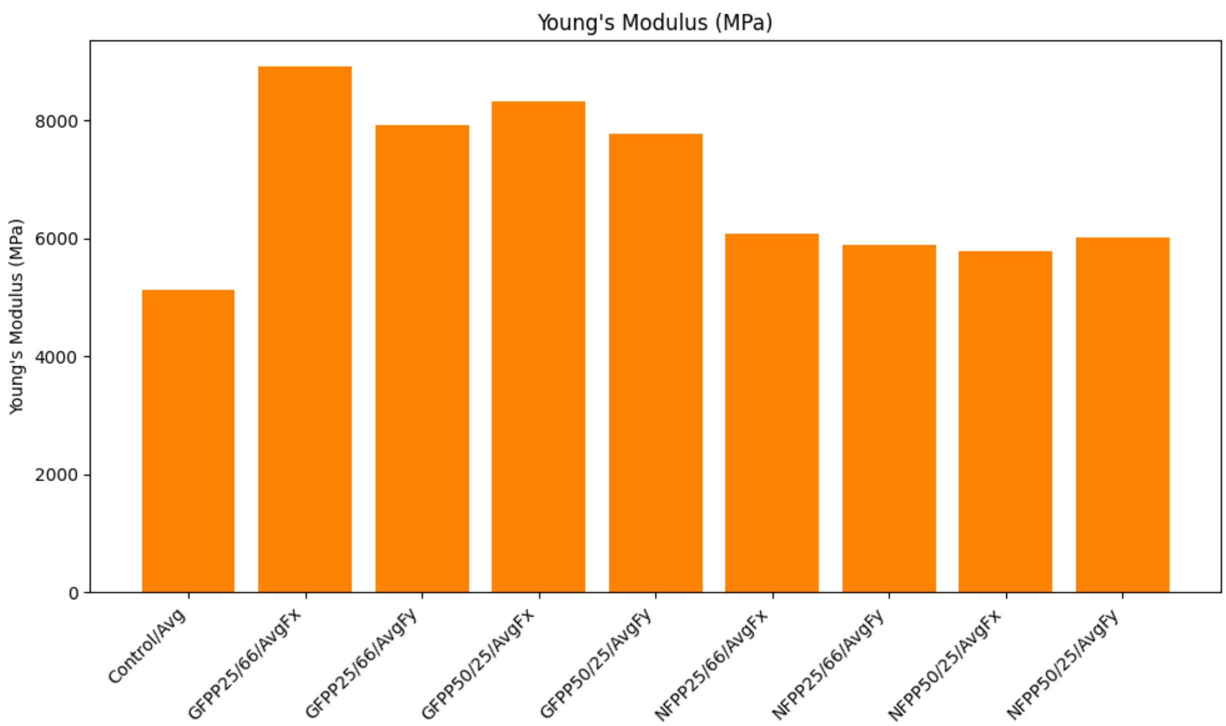

Figure 3: Average Young's modulus.

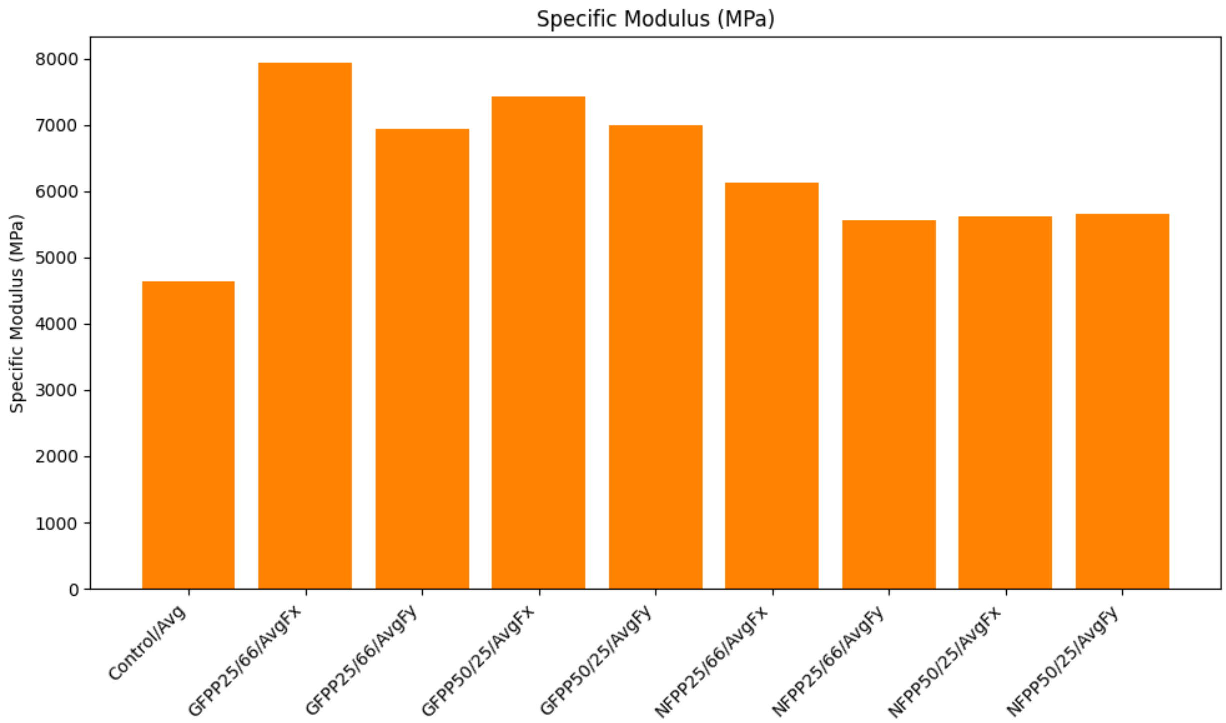

Figure 4: Average specific modulus.

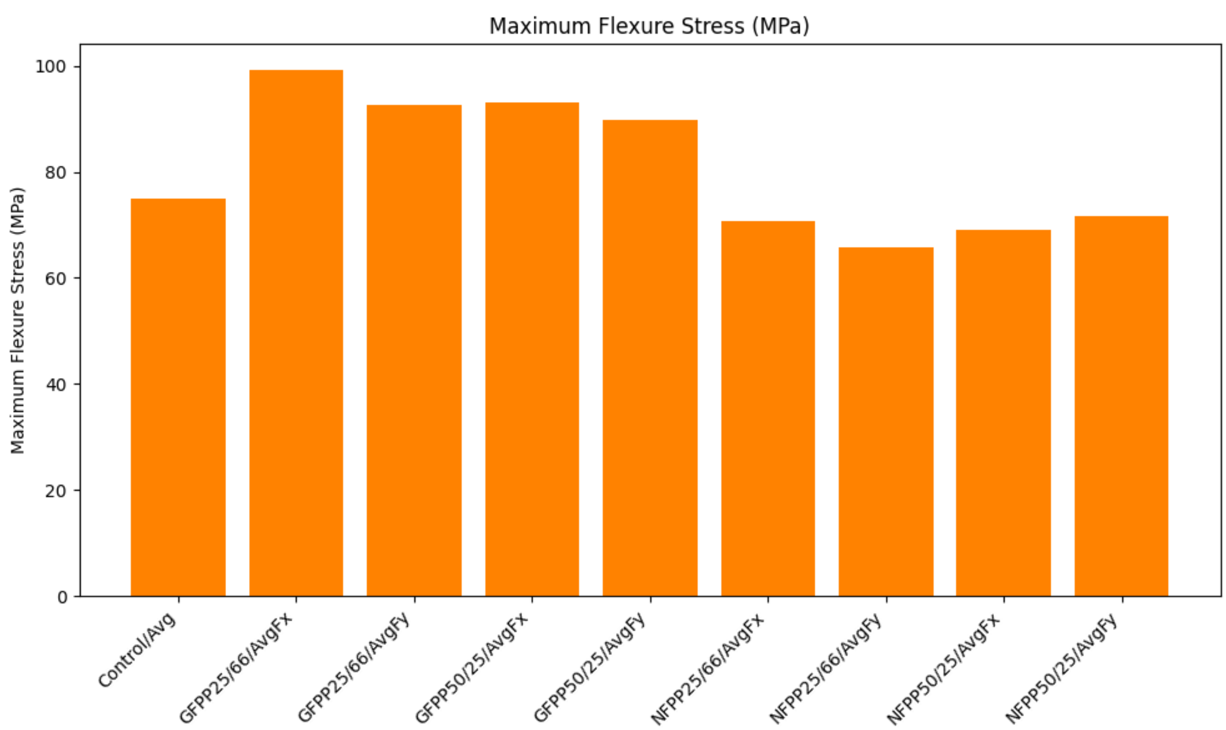

Figure 5: Average maximum flexure stress.

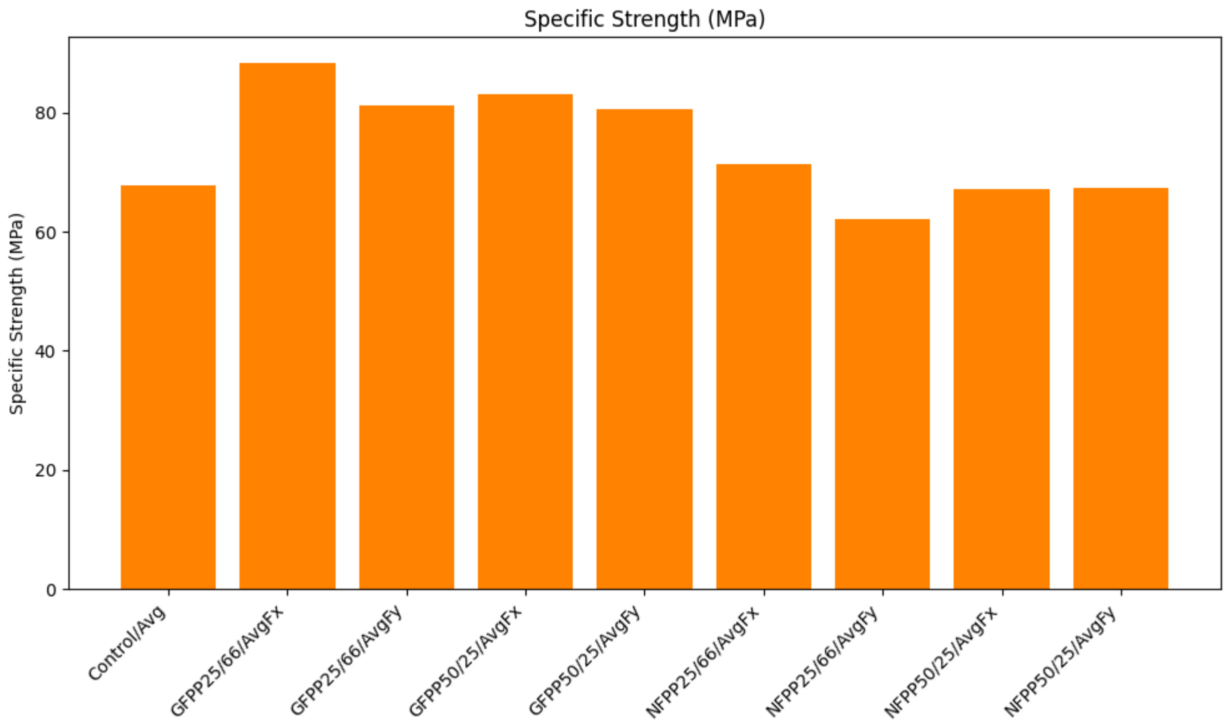

Figure 6: Average specific strength.

Water Absorption Results and Discussion

Figure 7 depicts the normalized water uptake after 24 hours of submersion at 23 °C.

The addition of the glass fiber polypropylene tape significantly hindered water absorption by reducing the water absorption (measured as a percentage of dry mass) of the control from approximately 20% to an average of 19%, 13%, and 14% for samples W1, W2, and W3, respectively. In the case of natural fiber polypropylene tapes, water absorption increased for the W1 samples to 22% while for samples W2 and W3, water absorption decreased to 16% and 17%, respectively. The addition of a fiber reinforcement tape ultimately hindered water absorption. This is likely a result of the increase in local density with the addition of the reinforcing tapes. Previous water uptake results were lower as the composite edges were sealed during laser cutting (Grubb et. al., Composites Part A., 2024). In this study, composites for water sorption were carefully cut using a band saw with unsealed edges. This enabled us to carefully consider tape geometry in the results but allowed for water penetration via the cut edges. A consideration for future work is to find methods to limit water absorption in cut and damaged parts without sealing.

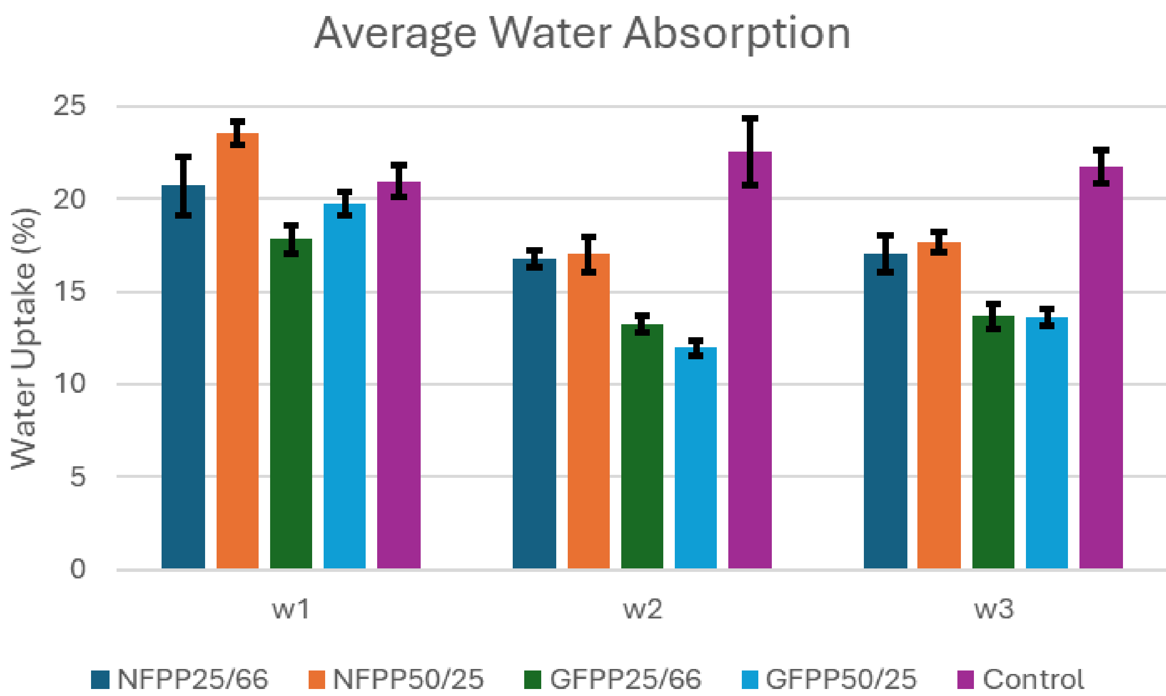

Figure 7: Water uptake of W1, W2, and W3 sample sets.

Panel Consolidation and Read-Through

Analysis of flexural panel specimens for consolidation reveals that the control specimens are consistently within the range of 1.06 to 1.12 g/cc. While it is difficult to separate the differences in material density from consolidation density in the GFPP samples, the NFPP tapes are similar in density to the cellulose/PP nonwoven, and it therefore appears that the lattice reinforced materials are slightly (<5%) less consolidated than the control specimens. In the areas where tape is present, the consolidation density may be as good or greater than the control; however, the opening between the tapes is less consolidated as the tapes prevent consolidation of the panel beyond a minimum thickness. This appears to be supported by the density data of the flexural samples, which show that the NFPP lattice panels with higher lattice densities exhibit a panel density that is statistically equivalent to the control (within overlapping error bars), while the GFPP lattice panels with lower lattice densities are less dense than the control despite having a higher density tape.

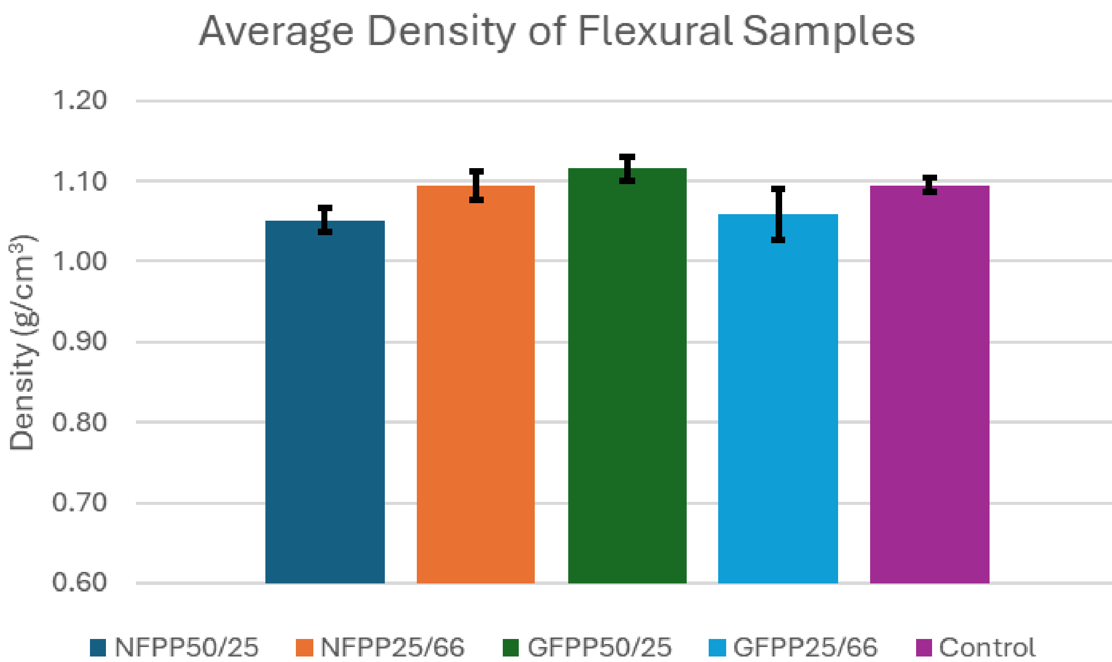

Figure 8: Comparison of densities of flexural panels. Note that the y-axis starts at 0.6 g/cc to improve visibility of the error bars

While the lattice reinforcement did not lead to apparent read-through on the samples, this will always be a factor of substrate material thickness, molding pressure, and resulting consolidation quality. Depending on the application, and for customer-facing parts in particular read-throughs might present a surface defect prompting quality rejection. Its mitigation will have to be investigated in future studies. Another potential solution is hiding such surface defects through covering the A-surface of the affected part with textiles, films, or other materials.

Task 3: Lab-Scale Forming Trials

Task Objectives

WEAV3D will conduct lab-scale forming trials using surrogate part geometry. This will develop preliminary data on handleability and forming behavior, specifically allowing the team to determine whether the lattice reinforcement materially reduces tearing of the cellulose nonwoven and if the lattice introduces any new forming defects (wrinkles, shear distortion, etc.) that need to be accounted for.

VW provided feedback to UTK and WEAV3D regarding the flat panel performance data from Task 2 and lab-scale forming trials. WEAV3D also assisted VW in developing a preliminary material and processing cost model for the impact of lattice integration.

Methods

WEAV3D conducted lab-scale forming trials using a small complex geometry tool (cavity of 6”x6”x2”), 25-ton Carver press, and contact oven with manual shuttle. This tool consists of a combination of features, including a 2” vertical corner, double curvature “bullet nose”, and ½” step downs at the remaining corners, which induce a mixture of biaxial and large uniaxial stresses during forming (Figure 9).

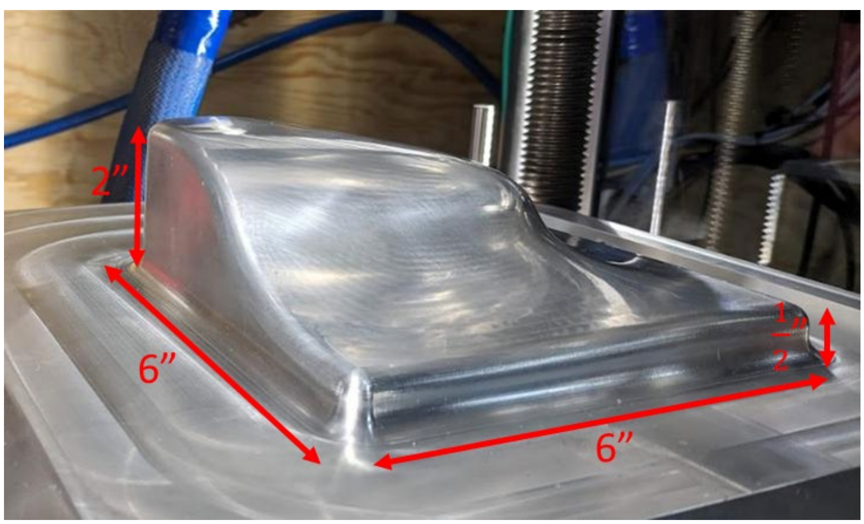

Figure 9: Complex geometry tool with major step-downs dimensioned.

UTK supplied WEAV3D with cellulose nonwoven hand sheets, sized at 9.5” by 11”. WEAV3D produced natural and glass fiber polypropylene lattices with cover factors of 50%/50% and 25%/25%. Sheet stacks were assembled by hand and ultrasonically tack welded to stabilize the lattice position through the remaining steps. Each stack was loaded into a manual shuttle and consolidated in a contact oven at 200-210 degrees C for 1.5 to 2 minutes, before transfer into the forming tool (Figure 10). The forming press is programmed for 2-stage closing, starting with a fast close that switches to pressure mode (applying 20 tons of force) when the tool gap reaches 5mm.

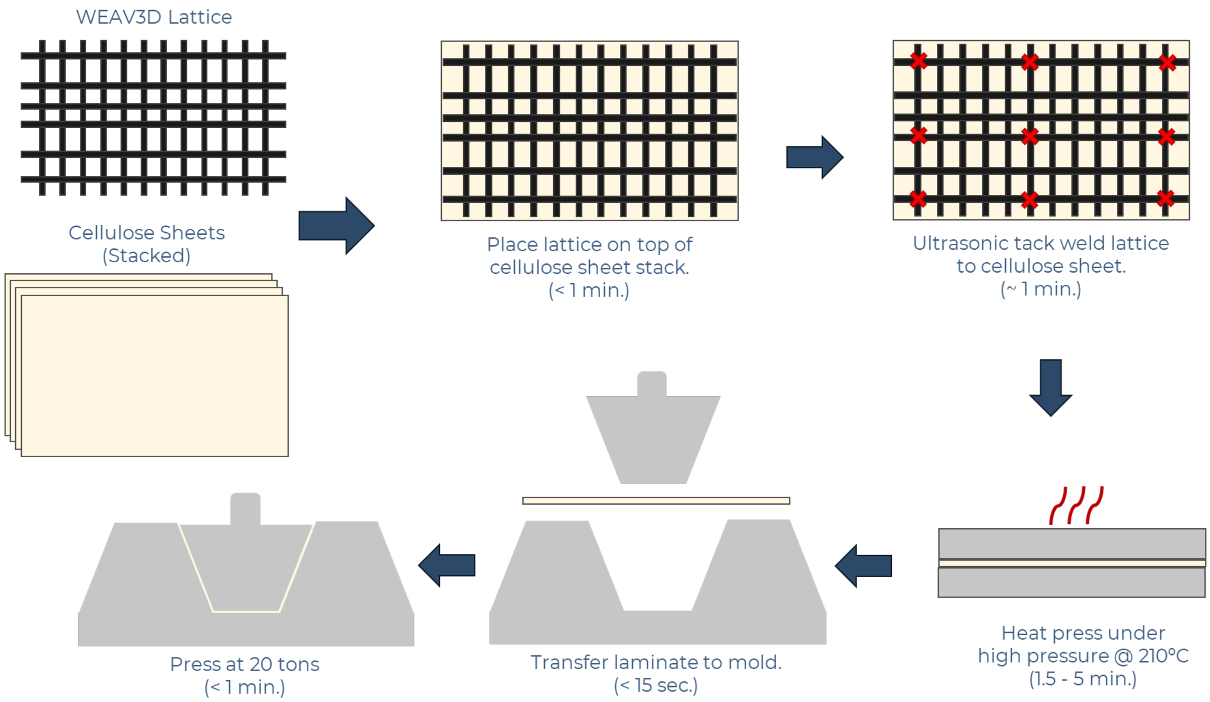

Figure 10: Overview of forming process for lattice-reinforced cellulose nonwovens.

Results and Discussion

Similar to the full-scale part VW selected for Task 4, this tool and work cell were originally designed to mold needle-punched NFPP nonwoven mats. We started the lab-scale trial by identifying the maximum number of cellulose nonwoven sheets needed to fill the tool cavity of 2mm. At 4-layers, we observed minor tearing in the cellulose nonwoven and major tearing at 5-layers (Figure 11). As the cellulose nonwoven sheets are in discrete increments of 250 gsm, we opted to mold 5-sheets thick, even though this occasionally resulted in a stuck tool due to lack of power open on the press.

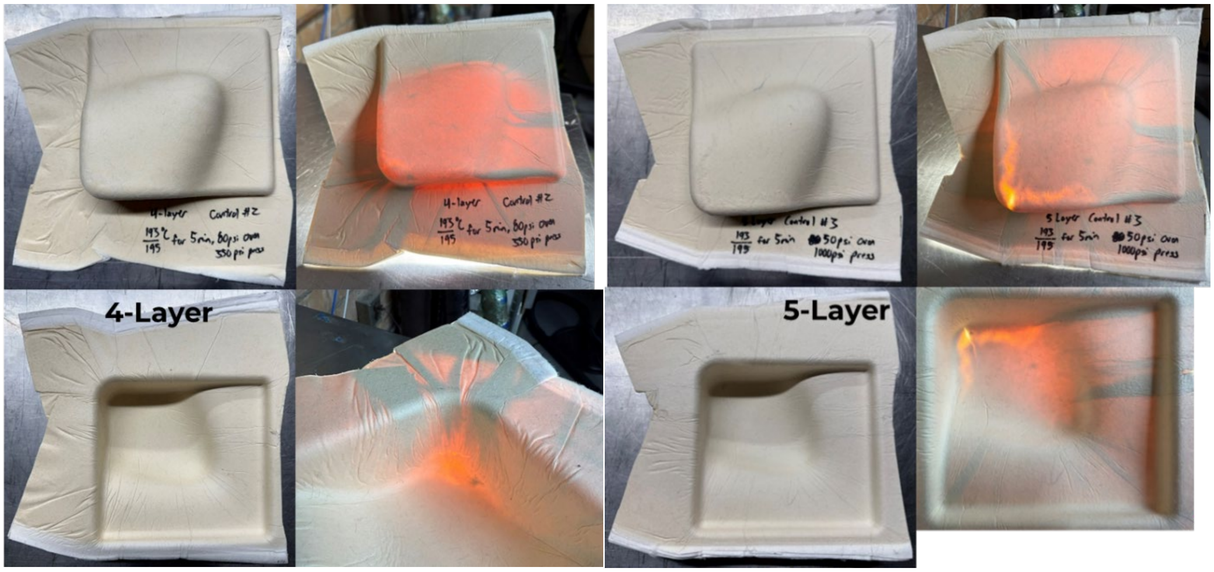

Figure 11: Comparison of 4-layer and 5-layer cellulose nonwoven controls.
Images with backlight shown to illustrate thinning/tearing (lighter), and wrinkling (darker).

From the control images of the 5-layer panels, the top edges around the 2” vertical corner exhibit a mix of partial and full tearing. Adding an NFPP lattice with a 50%/50% cover factor to the outside of the panel eliminated the tearing observed at the corner (Figure 12). Experimenting with a single layer of paper composite on top of the lattice and 4 layers beneath shows that the lattice arrests the propagation of tearing beyond the top layer (Figure 13). Further experimentation with lower density lattices (25%/25%) identified that the position of the tape relative to the stress concentration has a strong effect on whether the lattice can prevent tearing (Figure 14). If the lattice is located properly, lower-density lattices can still achieve the same forming improvement as the higher-density lattice (Figure 15). One surprising effect of the lattice is that it can redistribute biaxial stresses to other regions of the part, so care must be taken to avoid creating tears where none previously occurred (Figure 14).

Figure 12: 5-layer cellulose nonwoven formed with NFPP lattice (50/50), backlight shows no tearing.

Figure 13: 5-layer cellulose nonwoven, 4 layers below lattice and 1 above, with GFPP lattice (50/50) backlight shows no tearing, but small surface tears are visible in the top cellulose layer.

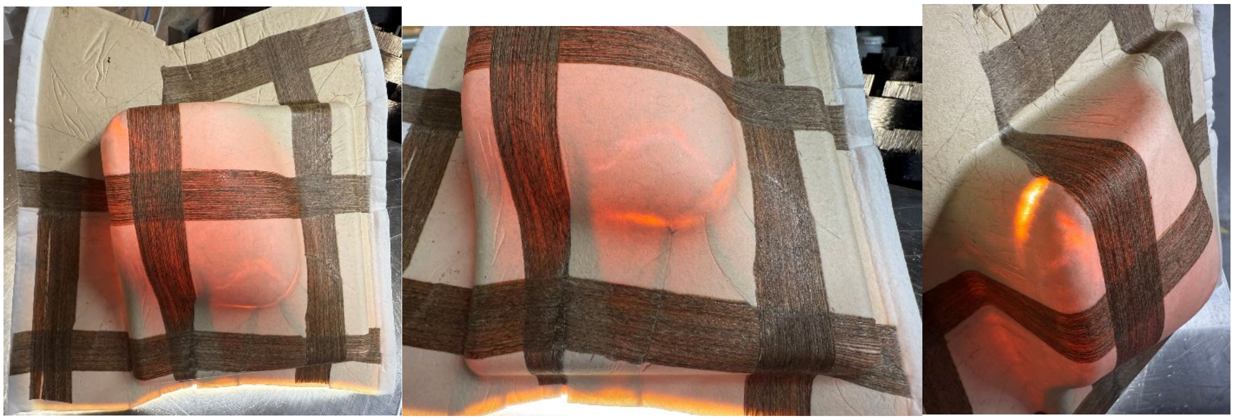

Figure 14: 5-layer cellulose nonwoven formed with NFPP lattice (25/25),
backlight shows no tearing in high stress areas that lack tape reinforcement.

Figure 15: 5-layer cellulose nonwoven, 4 layers below lattice and 1 above, with GFPP lattice (25/25)
backlight shows no tearing, as tapes are properly located on the stressed areas.

One important observation during this trial is that the lattice does not materially increase the frequency or intensity of wrinkles that form in the cellulose nonwoven. The approximate location where wrinkles form is consistent with or without the lattice (Figure 16).

Figure 16: Comparison of overall wrinkling behavior. (Top Left) Close up of region with greatest wrinkling, note the discontinuity of the glass tape as it folds under the cellulose nowoven; (Top Right) GFPP lattice sample exhibits strong wrinkling at deep draw corner, single fold; (Bottom Left) Control sample exhibits strong, multifold wrinkling at deep draw corner, as well as minor wrinkles throughout the part; (Bottom Right) NFPP lattice exhibits strong, multifold wrinkling at deep draw corner.

VW Feedback

The drapability of flat preforms on doubly curved geometries depends on various properties of the preform and some processing parameters. Even if all parameters are optimized, there is a physical limit in formability that is significantly influenced by fiber length. Materials with longer fibers tend to allow for more local strain before noticeable thinning or tearing.

Working with relatively short cellulose fibers, that drapability limit is reached earlier than in the case of longer bast fibers. The ability to counteract this is of major importance. This effect was clearly shown in the case of these lab-scale forming trials employing the lattice structures. With the drapability improvement shown, the applicability of flat preforms is expanded, and scrap rates in production can be reduced. Some factors must be optimized for a given geometry, which was the goal of the work outlined in the following chapter.

Process Modelling

Working with VW, WEAV3D developed a process workflow (Table 1) to evaluate the impact of adding lattice reinforcement to the forming process and identify the tooling and CAPEX required for the work cell (green is same, white is new). Overall, the addition of lattice is only expected to increase cycle time by 40 seconds (19%) and will only require the addition of an US welding end effector and die cut tool to the forming work cell. Cost estimations contain partner proprietary information and will not be included in this report.

Table 1: Process Analysis of Cellulose Nonwoven Forming Workflow

	Automated Time (s)	Tooling?	CAPEX?
Diecut Sheets	2 (stack cut)	Yes	Clicker Press
Diecut Lattice	2 (stack cut)	Maybe	Same Clicker Press
Stack Sheets	10	Gripper	Robot
Locate Lattice	10	No	Same Robot
Tack Lattice	30	Welding End Effector	Same Robot
Heating	120	No	Laminator/Oven
Transfer	15	Gripper	Robot
Consolidation	60	Mold	Press
Total	249		
w/o Lattice	209		
% change	19%		

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Task 4: Forming and Validation of Full-Scale Demonstrator

Task Objectives

WEAV3D produced lattice materials suitable for the demonstrator part (GFPP and NFPP) and supplied these lattices to VW's designated Tier 1 molder, Antolin. UTK supplied cellulose nonwoven blanks to Antolin. A representative from WEAV3D travelled to Antolin's molding facility in Burgos, Spain to observe the forming behavior of the lattice reinforced cellulose nonwovens and provide guidance to the molder on handling and forming the material.

Once the parts are molded, VW and UTK characterized forming defects (including read through and tape-induced defects) relative to the unreinforced cellulose nonwoven baseline (previously observed as tearing, wrinkles, and melt fracture). VW directed UTK to cut specimens from the part for testing. VW made a final determination as to whether the addition of lattice reinforcement has resolved the performance and formability limitations that were present in the baseline material.

Methods

VW had previously completed a forming trial for the cellulose nonwoven material at Antolin, a Tier 1 supplier headquartered in Burgos, Spain. This part geometry, originally intended for needle punched natural fiber PP mats, proved too complex for the cellulose nonwoven on its own, resulting in several tears throughout the part. The project team agreed to reattempt this complex geometry using our lattice reinforced approach, as it represents a challenging, yet practical, forming target that should allow us to explore the limits of the lattice reinforced approach. All images of the referenced component have been cropped at the request of VW to avoid proprietary disclosure.

Before producing lattices, WEAV3D manufactured a half-scale model of the part using 3D printing (Figures 17-20,. Tape locations were determined by reviewing images of the prior trial and focusing on locations where tearing had been observed. Half-inch fiberglass reinforced adhesive tape was used as a surrogate for the thermoplastic UD tapes in the lattice, as it exhibits similar semirigid behavior. By laying out the fiberglass tape as a flat pattern and then draping it onto the surface of the scale model, we were able to observe distortions and wrinkles that occurred and adjust the tape positions slightly to relieve the worst issues. The accuracy of this mock-up technique was validated against the lab-scale forming tool and exhibited good correlation in the location and severity of distortions.

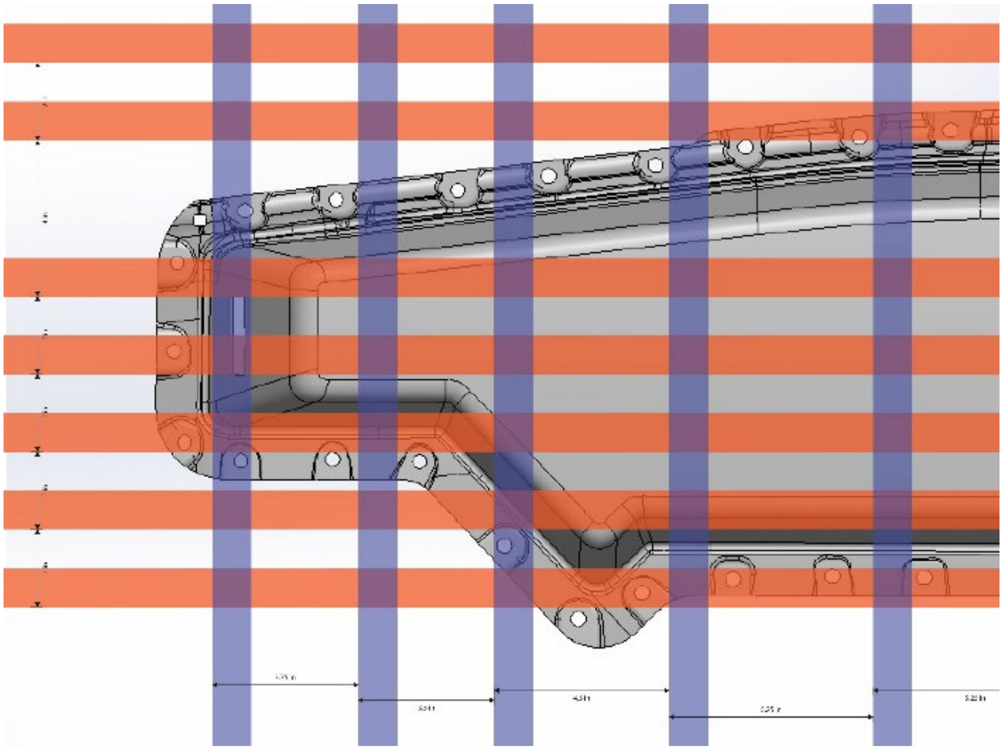

Figure 17: Digital superposition of flat lattice pattern over 3D part model

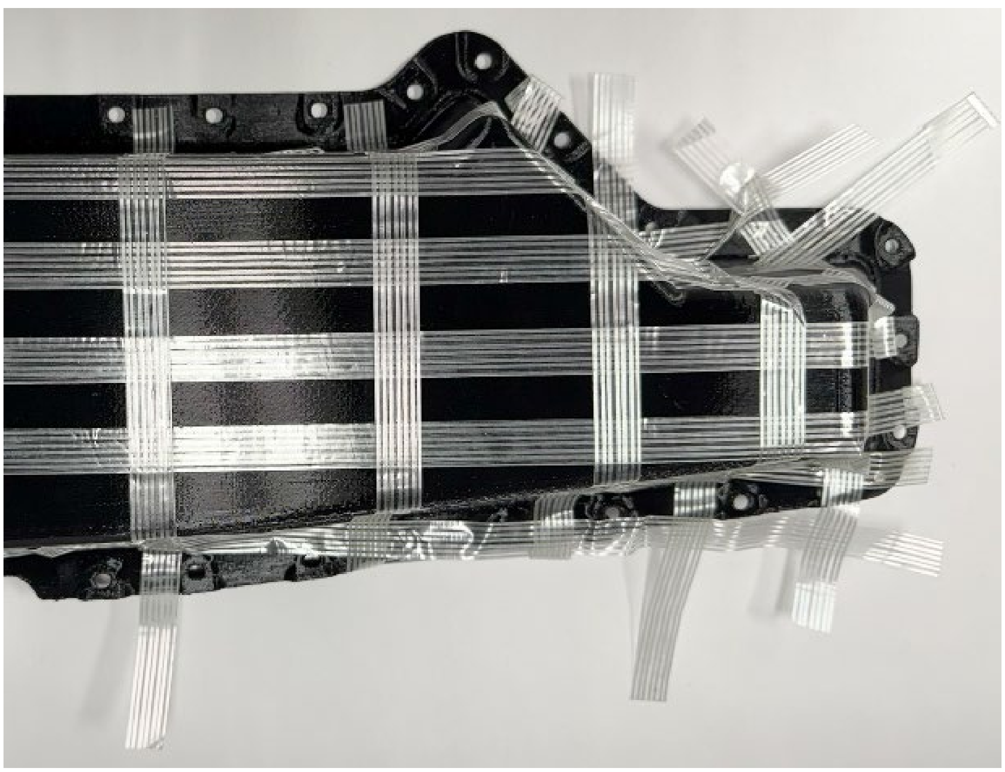

Figure 18: Top view of part, showing overall geometric complexity

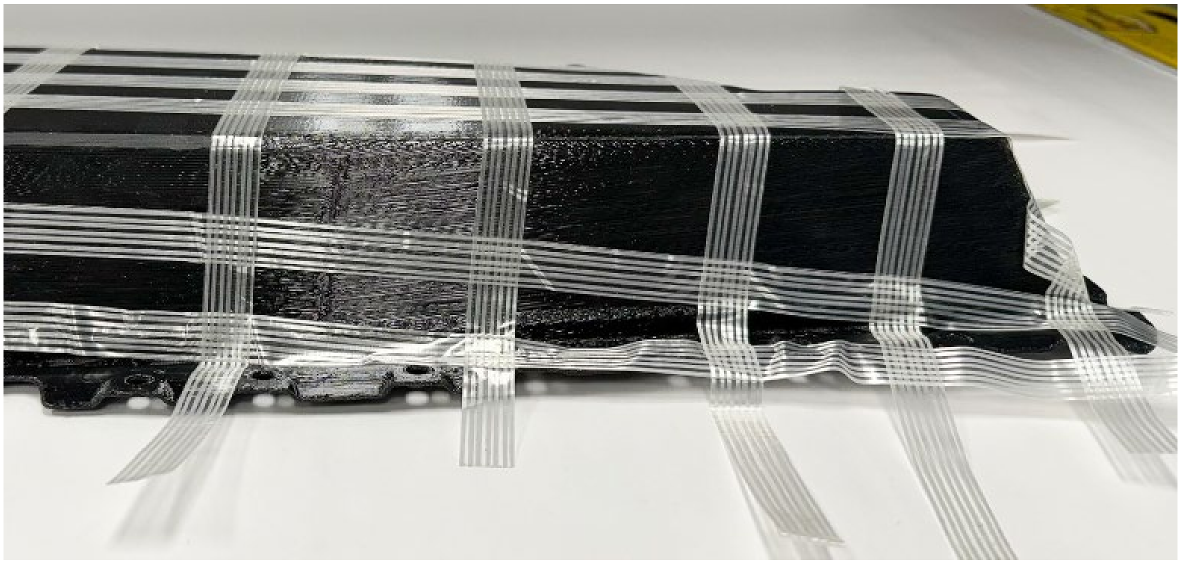

Figure 19: View of the least complex side of part, showing tape curvature on simple curves.

Figure 20: View of complex side of part, showing wrinkling at convergence of corners.

Once the pattern was finalized, WEAV3D manufactured lattice patterns from both GFPP and NFPP tapes, in a 2-unit wide configuration on our pilot line (Figure 22). A total of 20 lattices of each material were produced, packaged, and shipped to Antolin in Spain.

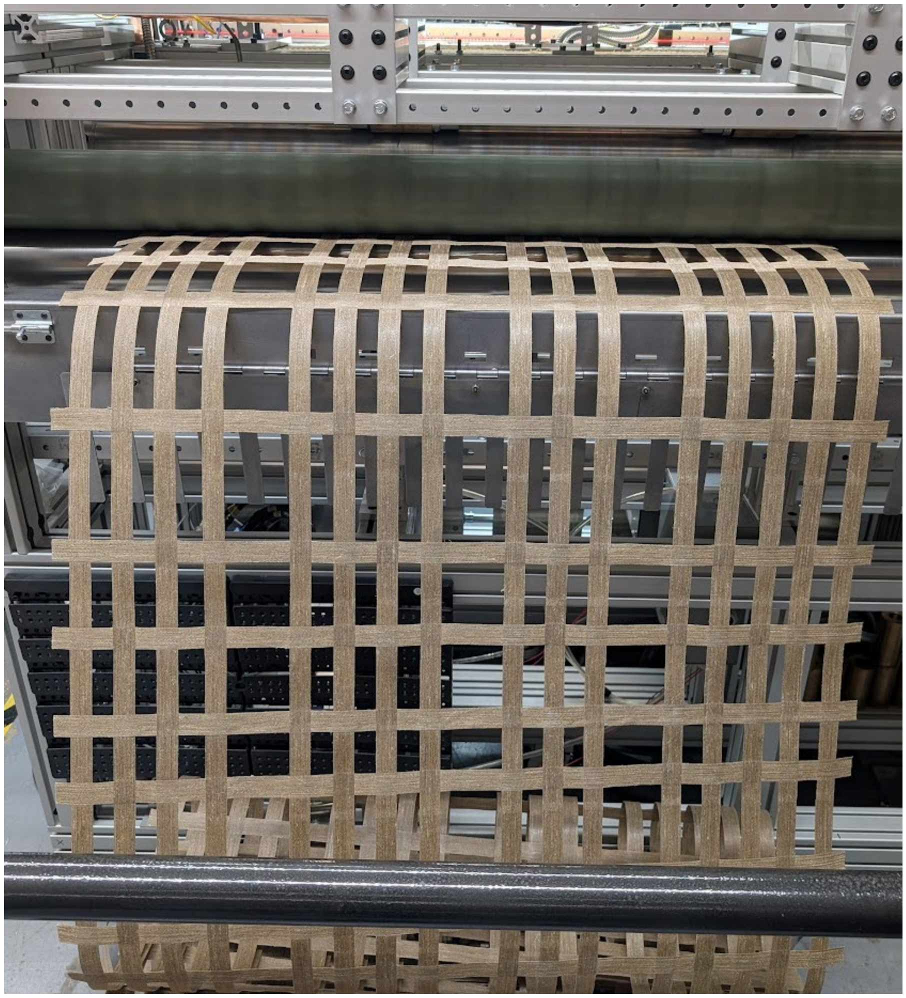

Figure 21: Lattice pattern, produced using NFPP unidirectional tapes in 2x parallel configuration

WEAV3D traveled to the Antolin facility in Burgos, Spain, to support the trial over a three-and-a-half-day period. On the first day, the trial team developed a technique to trim and assemble blanks from the rolls of cellulose nonwoven and lattice, with the lattices positioned and tack-welded within the blank via a handheld ultrasonic welder (Figure 22).

Figure 22: (Top Left) Marking of blanks from master rolls; (Top Right) Ultrasonic tack welding of lattice to blanks; (Bottom) Approximate alignment of tapes against top surface silhouette of part

We also spent considerable time developing a heating profile for the contact oven, utilizing thermocouples to monitor the change in temperature near the surface of the stack, as well as in the middle. As Antolin did not have the facilities to dry the sheets before forming, we observed steam entrapment in the middle of the stack that slowed the heating cycle, as it was necessary to stay in the heated press until all the water vapor escaped the cellulose nonwoven and the core was hot enough to melt the polypropylene (Figure 23). While the heating rate for both sets of thermocouples starts similar, the surface thermocouple heating rate flattens around 170°C, while the middle thermocouple exhibits a lagging heating rate even after the boiling point of water is exceeded. Measuring the cooling rate (Figure 24), with the hot blank sitting on the lower mold with the press open so as not to cut the thermocouples with the shear edge, we observed that the surface is below the target melt temp at 26 seconds (closing time).

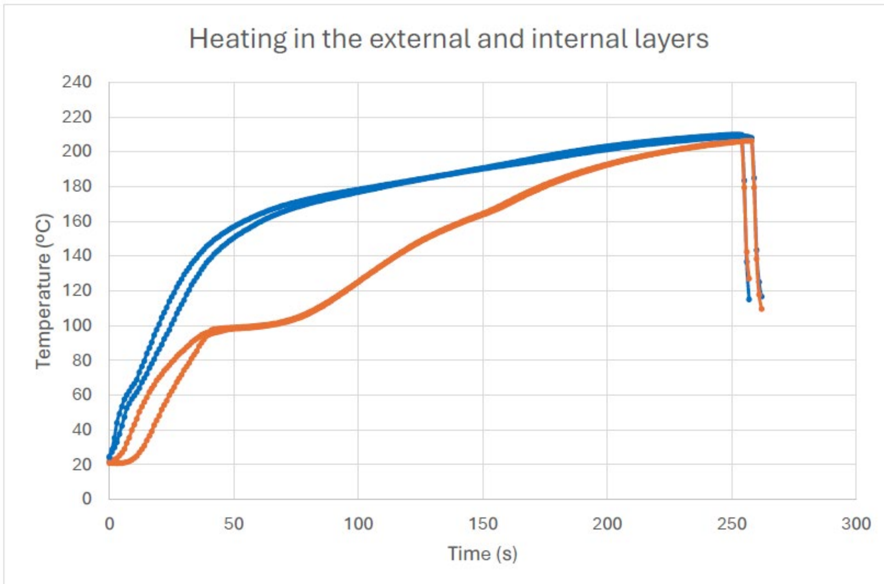

Figure 23: Comparison of thermocouple reading near the surface of the stack (blue) and thermocouples in the middle (orange). Note the clear plateau at 100°C from 40-70 seconds in the orange lines.

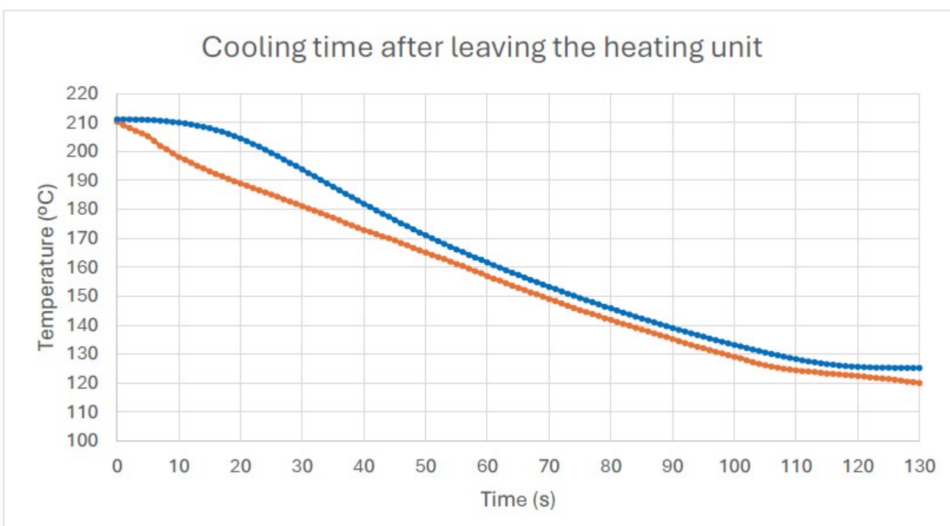

Figure 24: Comparison of cooling behavior for heated blank sitting on open forming tool. In this chart, the colors are inverted from previous – orange is surface, and blue is middle.

Due to the increased heating time and the manual process of cutting and assembling the ply stacks, the observed time to form each part was significantly higher than the process model developed in Task 3 (Table 2). With sheet drying and automation, we expect the cycle time will approach the original estimate, as other process steps (tacking, transfer, and consolidation) were very close to the original estimate.

Table 2: Comparison of automated forming time (Table 1) against manual forming observed during trial

	Automated Time (s)	Observed Time (s)
Diecut Sheets	2 (stack cut)	15-20 minutes
Diecut Lattice	2 (stack cut)	
Stack Sheets	10	
Locate Lattice	10	
Tack Lattice	30	30
Heating	120	300
Transfer	15	20
Consolidation	60	60
Total	249	410 + 15-20min
w/o Lattice	209	
% change	19%	

Based on the cavity gap of the tool, we decided to use 11 layers of cellulose nonwoven with one layer of lattice underneath the outermost nonwoven layer. While this molded well, we discovered a small corner feature in the part that induces local tensile stress on the inner face during forming, which occasionally caused a partial thickness tear. To reliably eliminate this defect, we opted to reduce the cellulose nonwoven layer count to 10 and add one more lattice under the innermost nonwoven layer. This 10+2 configuration worked remarkably well if the blank was positioned correctly on the tool. Figure 25 shows representative examples of the 11-layer cellulose control versus two 10+2 configurations with the lattice either on the outside surface or under the outside surface.

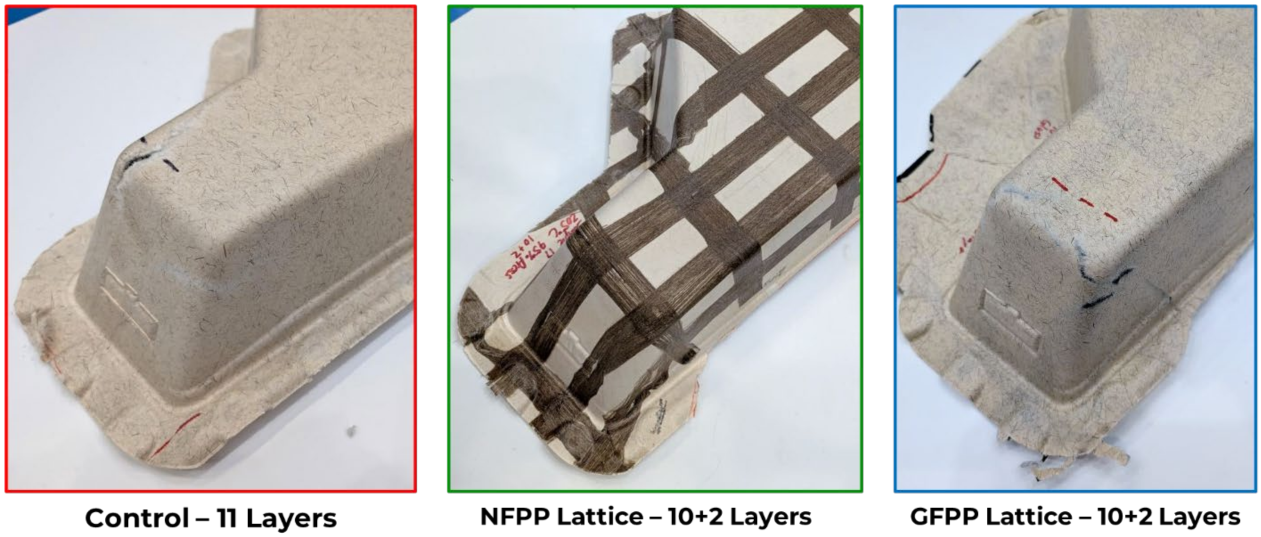

Figure 25: Representative examples of Control, NFPP (external),
and GFPP (under 1 sheet of cellulose nonwoven)

Results

Once we dialed in the stack-up and heating profile, we were able to successfully mold 10 NFPP lattice reinforced parts and 3 GFPP lattice reinforced parts, as well as 3 controls (Figure 26). While not every lattice reinforced part was free of tearing, it was consistently observed that the tearing only occurred if the lattice was out of position in the tool. This misposition was caused by two interacting factors – human error and material draw. Human error occurred in two steps of the process 1) initial lattice placement within the blank, and 2) placement of the heated blank on the tool. The first error was solved by measuring a specific tape within the lattice about the edge of the blank. The second error was more difficult to compensate for, as the window for placement of the heated blank is very small due to the rapid cooling of the blank, requiring the operator to quickly approximate the correct position and then step clear of the light curtain to close the press. We attempted to mitigate the error by repositioning a higher-density area of the lattice to the region of the part that was most commonly mispositioned. In production, this can be solved via robotic placement, and the lattice itself can be adjusted to have more tolerance for small deviations of position.

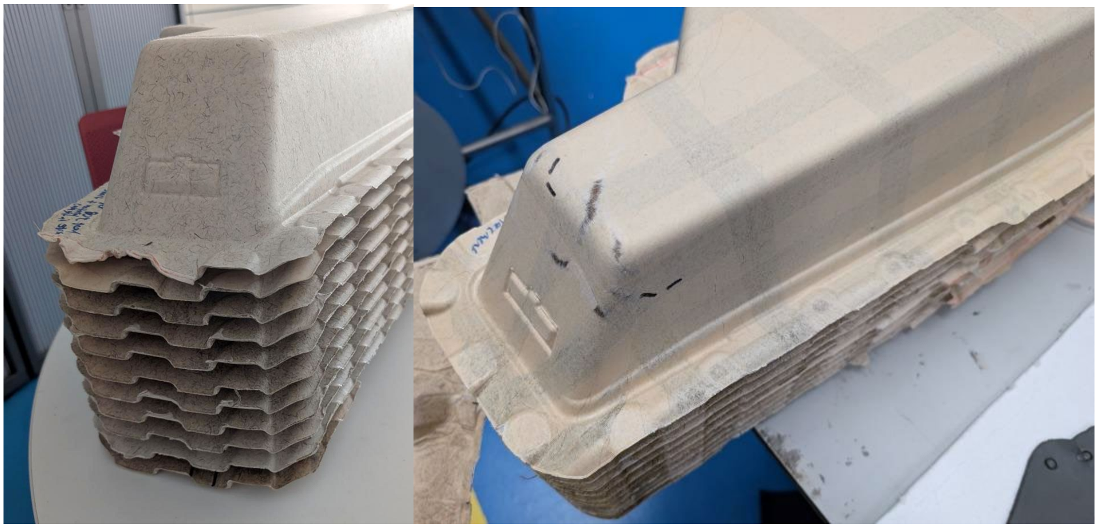

Figure 26: Stack of parts produced during the forming trial

As the lattice was under one layer of the cellulose nonwoven, this outer layer does tear in high-stress locations; however, the lattice prevents the tear from propagating any further through the thickness. This surface tearing is acceptable as the part is not intended to be Class A, and the tearing has little to no impact on the physical performance of the part.

During the lab-scale forming phase, we experienced an intermittent issue with lattices adhering to the peel ply material on our contact oven. This observation led us to start the full-scale parts with the lattice located under the outermost layer of cellulose nonwoven; however, we decided to attempt 1 lattice with NFPP lattice on the outside and were pleasantly surprised that it exhibited no sticking on Antolin's contact oven, despite having a very similar peel ply setup. With the lattice on the outside, all tearing was eliminated in the cellulose nonwoven, though the lattice shows evidence of shearing and micro-wrinkling caused by the biaxial stresses (Figure 27).

Figure 27: Close-up of complex corner features that exhibit major tearing in the control, but are fully controlled with the NFPP lattice on the outside, and only show surface layer tearing in the lattice under configurations.

Forming Challenges

The tool used for this trial was intended for use with needle-punch nonwoven NFPP mats, which are a lofted nonwoven material. Compared to the cellulose nonwoven, these materials are not intended to achieve full consolidation during forming and exhibit both compressibility and stretchability during forming, which reduces the size of wrinkles that occur. The tool, therefore, only needs to provide a slight relief of the gap between the upper and lower mold past the shear trim edge. This lack of relief was a noticeable challenge for the paper composite as it would frequently wrinkle to 3x the base stack thickness, causing the tool to fail to close completely to the stops on all sides. We believe this pinching/shimming effect prevented consolidation throughout the part, and increased the biaxial stresses experienced by the cellulose nonwoven. This hypothesis was validated by UTK and is illustrated in Figure 35 later in this chapter.

During the first day of the trial, we discovered that Antolin had mixed up two similar tools, loading one with more complex features than the intended part. This was discovered after molding 2 control parts and 1 lattice-reinforced part (Figure 28). Due to a much larger jog inset in the part, large tearing was observed, even in the lattice reinforced parts. This indicates that even though the lattice significantly enhances the formability of the cellulose nonwoven, there are limits on the maximum biaxial stress that the lattice can resist, up to the tensile strength of the tapes. While we did not attempt to form this geometry using glass lattices, it is possible they may have been successful due to their yield strength which is 3x greater than that of the NFPP tapes.

Nonetheless, parts with extremely deep draws or edge clamping effects will still present a challenge for the adoption of cellulose nonwovens. However, careful tool and part designs optimized for these materials can produce defect-free parts.

Figure 28: Comparison of control sample (Left) and NFPP lattice reinforced sample (Right) in higher complexity tool (deep draw, high complexity). NFPP lattice reduced through-tear of the sharp outer corner (Top Right vs. Top Left) but failed to prevent inner corner face tear (Bottom Right vs. Bottom Left).

While the ideal blank size for this part is 550mm wide, the cellulose nonwoven rolls provided to Antolin were only 900 mm wide. As we could not afford to waste nearly half of the roll, we opted to reduce our blank width to 450 mm, allowing us to double the number of sheets per roll. This narrowed the tolerance for proper blank placement, and short flanges (where the edge of the blank was inside the trimline) are observable in the part images. We also noticed that biaxial stresses were significantly reduced when the blank was not aligned properly to simultaneously form all four flanges, resulting in parts that did not show representative tearing. At the end of the trial, we returned to running a couple of full-width blanks to confirm the tearing behavior in the control and confirmed the elimination of tearing in full-size lattice reinforced designs compared to full-sized controls.

Test Methods

After shipping parts from Antolin back to VW, UTK was provided with a selection of parts in order to collect flexural and water absorption specimens. Each part was deconstructed along its major edges, with flexural and water absorption samples cut and collected from the bottom, left, and right sides of three different NFPP lattice-reinforced cellulose nonwoven parts (Figure 29). Samples were collected from the same location and orientation on each of the three parts, and an effort was made to ensure a consistent amount of UD tape was contained in each specimen. Flexural samples were cut to 50.8 x 152.4 mm and tested per ASTM D790 using a dual column Instron 5567 3-point bend apparatus with a span and rate of 140 mm and 8.62 mm/min, respectively. The strain was measured using a linear variable differential transducer (LVDT) up to a displacement of 20 mm, and testing continued up to 50 mm. Flexural samples were conditioned at 25 °C and 65 % RH for a minimum of 48 hours before testing. Water absorption samples were cut to 25.4 x 76.2 mm and tested using ASTM D570, where the length, width, and thickness were measured pre-soak and post-soak in a water bath set at 23 °C for 24 hours. Before water absorption testing, the samples were vacuum dried overnight at 80 °C.

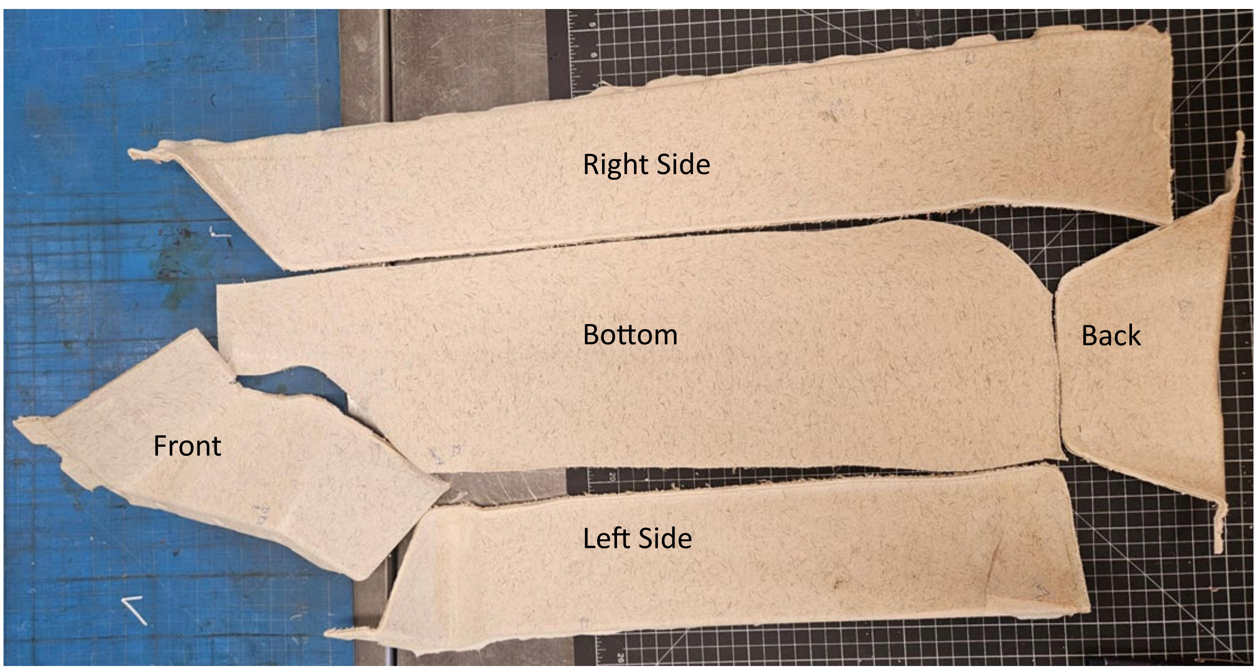

Figure 29: Deconstructed cellulose nonwoven part

Flexural Results

Figure 30, Figure 31, Figure 32, and Figure 33 show the flexural performance of parts 4, 5, and 6 with "B", "L", and "R" meaning "Bottom", "Left", and "Right", respectively. Among the parts, part 4 had the best mechanical properties across the material. The right-hand side of part 5 (part 5R) performed better than nearly all of part 4 (part 4R), suggesting non-uniform consolidation across the part manufacturing process, likely due to the wrinkle-induced gaps that were previously described and exaggerated by constrained edge clamping force. The Back region of the part was observed to compress completely to stops, while the Front region is where the 1mm gap was frequently observed.

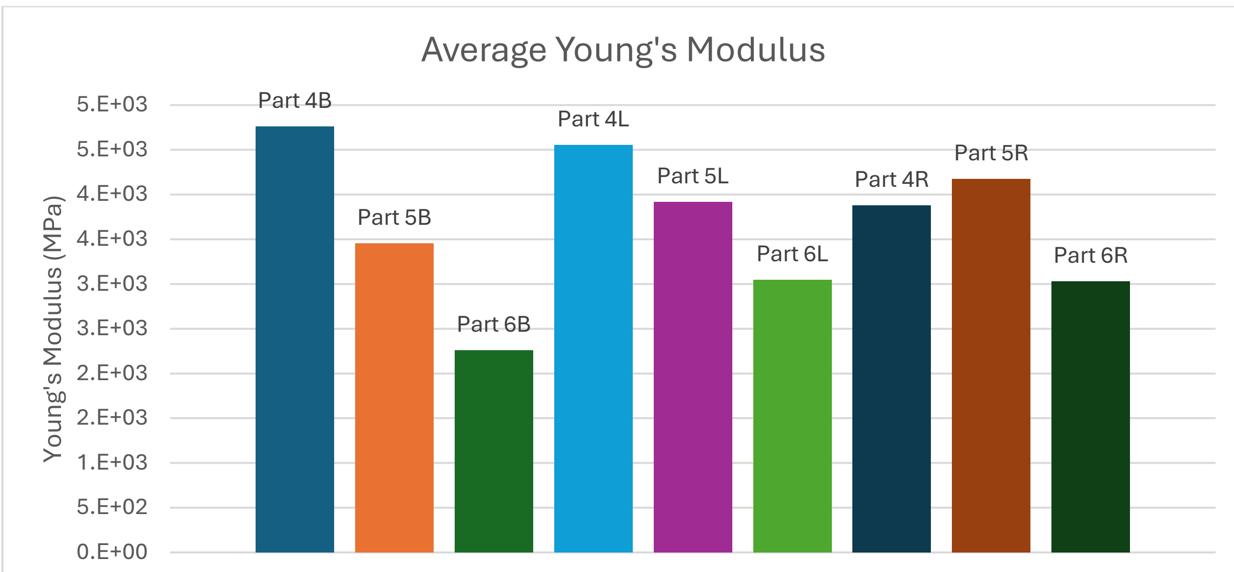

Figure 30: Average Young's modulus.

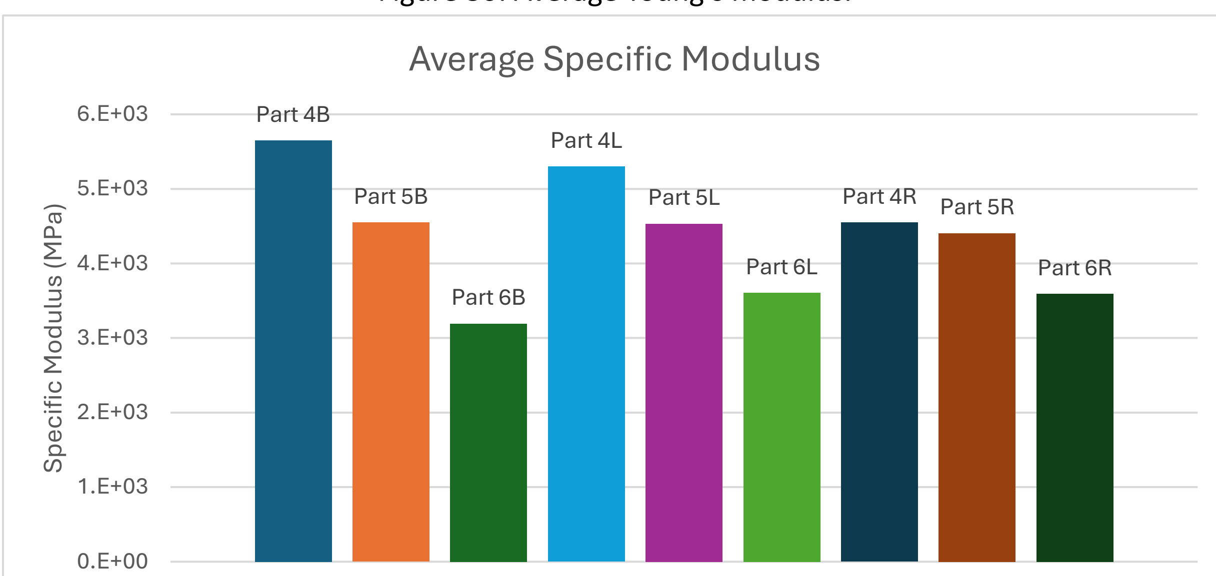

Figure 31: Average specific modulus.

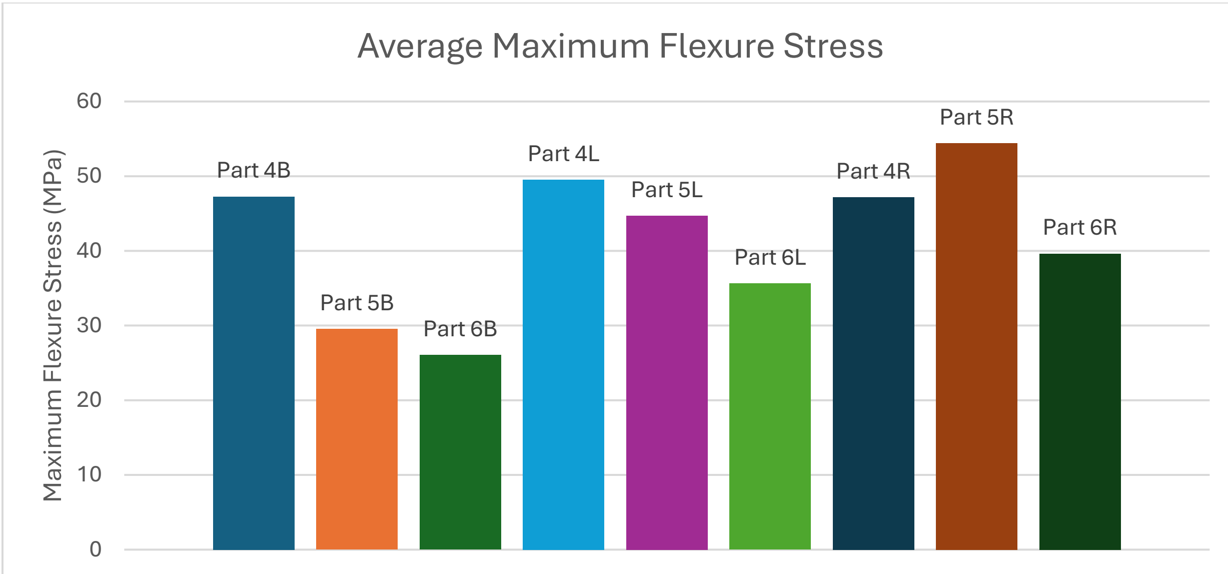

Figure 32: Average maximum flexure stress.

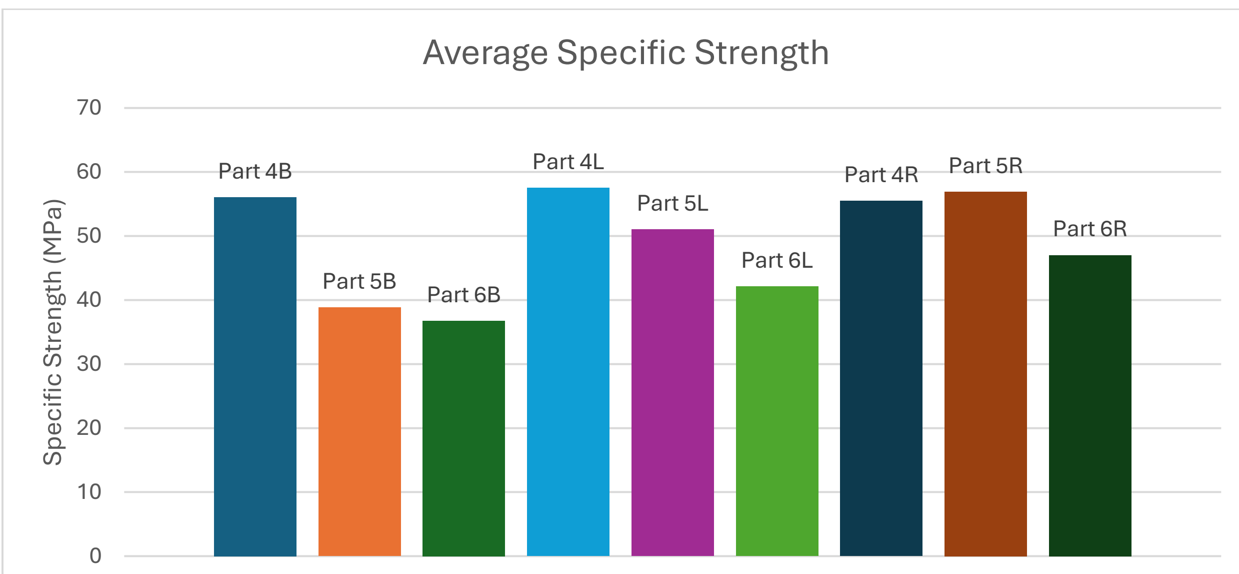

Figure 33: Average specific strength.

Water Absorption Results

Figure 34 shows the percent water uptake of the bottom, left, and right sides of each part, respectively. Due to limited material availability, the right and left datasets are the average of 2 specimens, while the bottom dataset is the average of 3. These specimens are labeled in the format part #, location, "water uptake". Left side samples had the lowest percentage of water uptake, while bottom samples had the highest percentage, more than double the left side samples. This phenomenon aligns with the previous postulate that the drop in mechanical properties and increase in water absorption is caused by non-uniform consolidation. Similar to previous results, these specimens were cut using a band saw, and the edges were not sealed. This allows for water to ingress from the edges when not sealed. Nonuniform consolidation using a tool not designed for this specific material led to poor consolidation in some areas and higher water uptake than previously reported. This inconsistent consolidation is evident when comparing against the density of specimens produced during Task 2 under optimum consolidation conditions, with the deconstructed sections exhibiting densities 15-40% lower than the Task 2 reference (Figure 35).

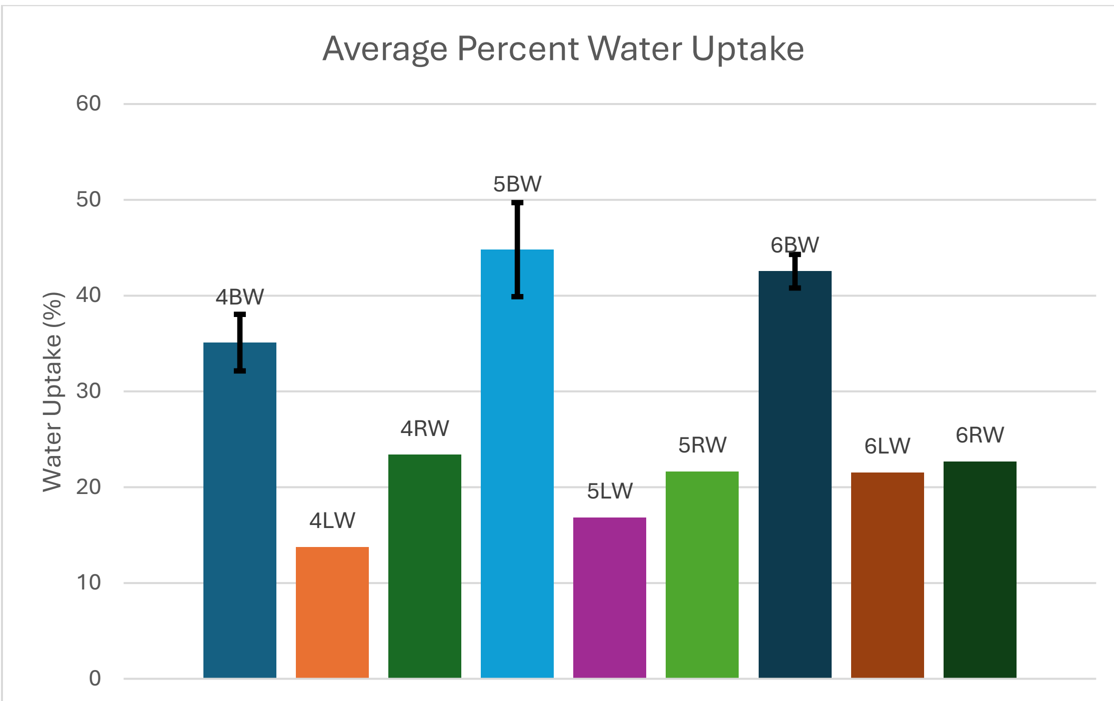

Figure 34: Water uptake of bottom (BW), left (LW) and right (RW) samples.

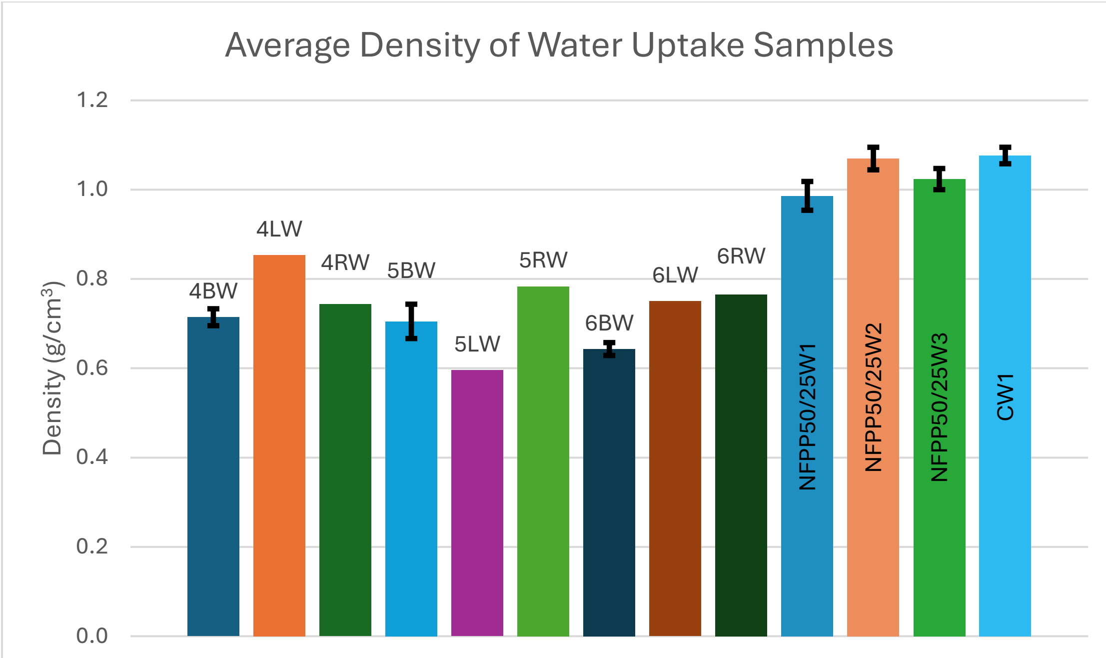

Figure 35: Comparison of sample density between deconstructed panels and Task 2 specimens. CW is representative of paper composite control, NFPP50/25 is representative of lattice reinforced panel.

Conclusion

This project successfully demonstrated that unidirectional tapes, in the form of a WEAV3D composite lattice, are able to improve the formability of cellulose nonwoven composites. More broadly, this work illustrates that unidirectional tapes can be used strategically within low-melt-strength sheet materials that usually struggle to form deep draw or complex features due to the occurrence of tearing or thinning. The unidirectional tape serves to limit strain along its primary axis, allowing more material to draw into the stressed region instead of tearing, provided the maximum stress remains below the tensile strength of the material.

Evaluation of both natural (flax) and synthetic (glass) fiber in the UD tape showed similar forming behavior in the geometries tested, though glass should be able to sustain even more complex geometries due to its much higher tensile strength (3x that of flax). Mechanically, the synthetic UD tapes improved the flexural properties of the cellulose nonwovens more than the natural UD tapes, as we expected; however, most designs containing natural UD tapes still improved the specific stiffness of the panels. Water uptake, which is frequently a concern for natural fiber composites, was observed to be materially the same in control as with natural fiber lattices, while glass lattices demonstrated a significant decrease in water uptake as glass is not hydrophilic.

During the full-scale forming trials, it was demonstrated that adding a lattice to the forming process will only have a minor impact on process time. Process time is primarily driven by assembly time of the blank, which can be automated, and heating time, which is a function of the starting moisture content of the cellulose nonwovens. Wrinkling behavior of the cellulose nonwoven must be accounted for in tool design to prevent inconsistent consolidation of the part, which has the negative effect of reducing mechanical performance and increasing water absorption. Overall, the lab-scale and full-scale trials demonstrated mechanical performance that exceeds the state-of-the-art natural fiber composites and injection molded talc-filled PP. This work demonstrates a path forward for creating defect-free parts with proper tool design for this new class of nonwoven natural fiber composites.