Investigation into the Fiber Orientation of a 3D Discontinuous Fiber Composite Bracket Representing a Real-Life Application

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1. Abstract

Composite materials are changing the world. Specifically, discontinuous fiber composites (DFCs) are evolving rapidly and allowing for the creation of parts with complex three-dimensional geometries through injection and compression molding. Consequently, it is crucial to understand how DFCs behave while being molded as well as once applied to a use case. This research presents an investigation into the mechanical performance and flow induced fiber orientation of a three-dimensional bracket made from one of two platelet morphologies: square platelet (SP) which are 12.7 mm by 12.7 mm and narrow platelet (NP) which are 12.7 mm long by a proprietary width. The fiber orientation is determined using µCT scan data which is processed by an in-house python code to extract fiber, matrix, and void data. The orientations from this are then analyzed platelet recognition algorithms, also developed in-house with python. These provide insights into fiber orientation and platelet morphology in various regions of the bracket. Mechanical testing comes in the form of tension and bending tests where strain is evaluated with digital image correlation (DIC). Test results show that NP brackets substantially outperform SP brackets in both strength and stiffness under tensile loading. On the other hand, NP brackets only mildly outperform SP brackets in bending with little difference in stiffness. This begs the question of why? Why are NPs better in tension, why not in bending? Building off prior work, largely from the University of Washington (UW) and Purdue University, this research seeks to characterize the underlying mechanisms behind the performance differences in NP and SP compression molded brackets.

2. Introduction

Fiber reinforced polymer composites are a growing class of materials working to change the world we live in. However, irrespective of the fiber or matrix selected, there are limitations associated with composite materials. One major limitation of traditional composites is the scope and versatility of manufacturing. By nature, continuous composites lend themselves to relatively easy creation of large parts with simple geometry, such as an airplane's fuselage or paneling. There are serval techniques to make such parts, notably automated fiber placement (AFP) [1]. However, smaller and complex parts are much more difficult to manufacture using traditional methods. It is unfeasible to use AFP or manual layup of continuous plies to create three-dimensional brackets or other intricate small parts which brings us to the implementation of discontinuous fiber composites

(DFCs). DFCs are excellent for high volume manufacturing of small parts because they can be injection and compression molded [2, 3].

In addition to their superb manufacturability, DFCs have demonstrated interesting mechanical properties comparable to aluminums or Quasi-Isotropic (QI) composites made with pristine prepreg [2, 4]. Notwithstanding, it is important to recognize that these are not absolute truths of discontinuous composites. Mechanical properties of DFCs depend substantially on the mesostructure of the part and some properties even depend on size and geometry of the specific structure [2, 5]. Structures made from DFCs generally begin life as a roll of prepreg tape which is chopped into small pieces known as platelets. The platelets can then be molded into their final form. From these processes two alternate names for DFCs arise; chopped fiber composites (CMCs) and prepreg platelet molded composites (PPMCs). Beyond manufacturability, there are several other notable differences of DFCs as compared with continuous composites. For example, DFCs tend to demonstrate greater fracture energy as well as more quasi-ductile behavior [2, 4, 6-10]. Figure 1 illustrates a Boeing 787 window frame made with DFCs. Here, one may notice how easily identifiable unpainted DFCs are by the shapes of platelets on the surface of the part [3, 11].

Figure 1. DFC Use Case: Boeing 787 Window Frame [3, 11]

With all these great advantages to DFCs, there are also drawbacks. By their nature, injection and compression molded DFCs most often have random platelet distribution which makes it difficult to tailor properties in the loading direction as can be done with traditional composites [12-14]. Nonetheless, they may also be formed into a highly ordered system as Kravchenko et al. have investigated [12]. In this study, the researchers showed that a greater overlap between platelets and longer length platelets outperformed short overlaps or lengths.

In either case, mechanical properties significantly depend on the orientation of fibers throughout a part and the positions of platelets relative to one another. Furthermore, DFCs are relatively new, and their collective understanding is immature. Focusing on the more common case of random mesostructures, we can discuss why they are fundamentally more complex than continuous fiber layups. Regardless of the geometrical constraints, when a continuous composite is made through AFP or hand layup, each ply remains where it is placed and all the fibers in each ply remain parallel to one another. DFCs on the other hand have much more variability. Figure 2 (left) shows a charge of platelets in a compression mold waiting for the molding cycle, where they lay loose. During molding, these platelets are heated and allowed to flow into place to obtain the geometry of the final part, because of this, orientation dependent properties are flow dependent [15]. Differently shaped platelets will flow differently and thus flow dependent properties likewise depend on platelet geometry. Moreover, there are multiple types of flow. Figure 2 (right) is a complete molded part. There is a low flow condition at the base of the bracket where the platelets are squished directly. Alternatively, there exists a high flow condition where the charge of platelets is forced from one location to another and thus significant platelet movement. For the bracket, this is condition is present in the top flanges. Nakagawa et al. [16] found that platelet morphology, specifically width, has a larger impact under low flow conditions than high flow while the latter allows for more intentional fiber orientation with the direction of flow. Favaloro et al. [13] were able to model flow into a three-dimensional pin bracket using smooth particle hydrodynamics (SPH). They validated their flow simulation using micro computed tomography (μCT) scanning to identify actual fiber orientation in the bracket. Showing the novel ability to accurately predict both fiber and platelet normal directions is a major advancement in DFC modelling.

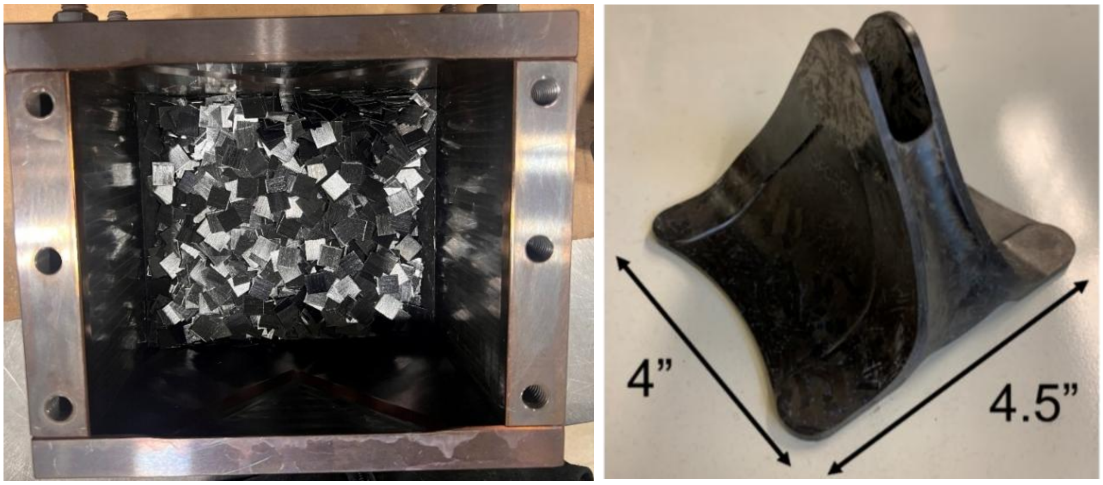

Figure 2. Charge of Platelets in Compression Mold (Left) and Molded DFC Bracket (Right)

Considering the various orientation possibilities, it is important to consider what can be controlled more easily such as platelet morphology and structure size. Pipes' group at Purdue studied PPMCs made from platelets with two [17] and three [18, 19] different platelet widths. Gutierrez [18] considered 1.56 mm, 3.18 mm, and 12.7 mm wide platelets all 12.7 mm long. They found for both open hole and unnotched tension that narrower platelets produced greater stiffness and strength for the same specimen geometry. Furthermore, Kravchenko [19] studied pin brackets made of the same three platelet sizes. He discovered that for this bracket, the platelet width had a small impact on tensile strength with 12.7 mm x 12.7 mm platelet bracket loading to 10.58 kN, 12.7 x 3.18 mm platelets loading to 10.93 kN, and 12.7 mm x 1.59 mm platelets loading to 10.97 mm. Kravchenko et al [17] also found that controlled PPCM orientations tend to outperform random ones when fibers are oriented in a preferred direction but even do, fail to reach the same strength as continuous unidirectional composites. The tendency for NPs to outperform wider platelets has been corroborated by Nakagawa et al. for both high and low flow conditions of flat tensile coupons [16, 20]. Nakagawa's work also extended to a three-dimensional bracket in which NPs immensely outperformed SPs in tension, but bot in bending to the surprise of the researchers [20].

It is here where the work for this paper begins. We consider the same brackets as Nakagawa which were made from an AS4D/PEKK thermoplastic tape. The goal herein is to better understand these brackets and answer the following important questions: Why do narrow platelet brackets outperform square platelets in tension but not so much in bending? What sort of effect might the geometry of the bracket itself have here? How has the platelet flow been informed by platelet morphology and how has that affected the orientation dependent properties of these DFC brackets?

3. Materials and Testing

The brackets analyzed herein were manufactured by Sekisui Aerospace [21] with raw materials from Synesqo [22]. Sekisui provided UW with a total of 28 brackets. Half were made with 12.7 mm x 12.7 mm SPs and half with 12.7 mm long NPs. The NPs' width is Boeing's intellectual property and cannot be disclosed beyond that it is smaller than 12.7 mm.

3.1. µCT Scanning

Before any testing began, the brackets underwent µCT scanning to determine their fiber orientation direction inspired by the work of Favaloro and Sommer [13, 15]. For this, each bracket was subjected to subpixel radiography and reconstruction with an NSI X5000 scanning system. The subpixel scanning allows for a finer resolution than standard scanning by taking four offset radiographs per pixel and stitching them together. The scanned voxel size is 38 µm. A slice from the reconstructed scan is shown in Figure 3. The left side is from an NP bracket, and the right is from an SP bracket with the upper images showing the flange and lower images showing the base.

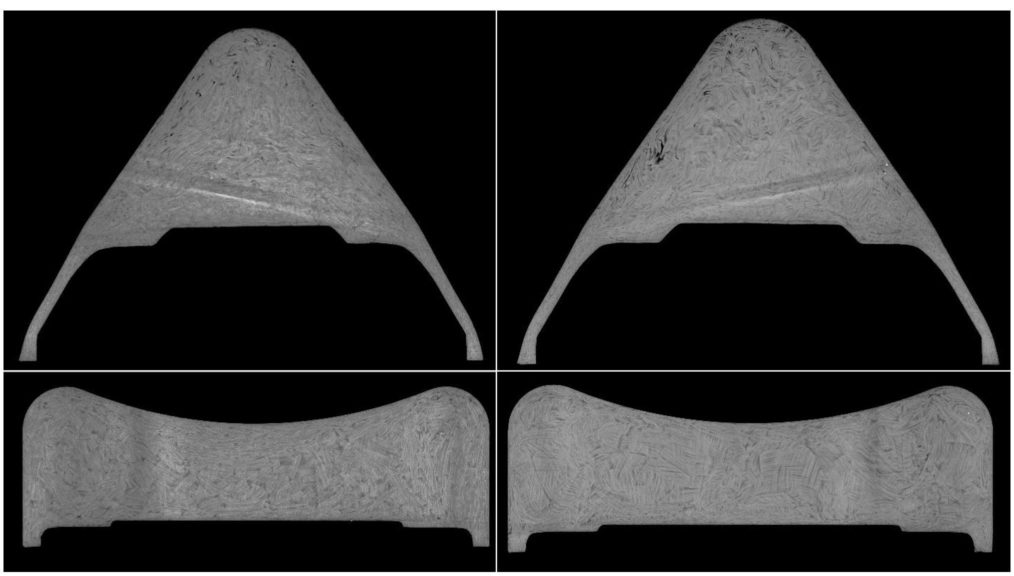

Figure 3. CT Scan Slices of the Body (Top) and Base (Bottom) of NP-3 (Left) and SP-7 (Right) Specimens

Looking at these, one can see that platelets are more clearly identifiable in the base of the brackets than the tops of the brackets. This stands to reason as the flow direction of the mold is from the base to the top, thus, the base experiences relatively low flow while the flanges of the bracket undergo the highest flow conditions. From here, a custom Python code determines the orientations in each voxel based on the color intensity gradient. In CT scanning, different densities (such as carbon fiber versus polymer) show themselves as different intensities. The direction of least change in intensity corresponds to the fiber direction of a platelet as the fibers run the length of the platelet. The direction with the greatest change in intensity is mapped as the matrix direction as we have alternating fiber (bright) no fiber (dark). Due to RAM limitations, every other voxel was skipped at this step yielding an effective voxel size of 76 µm. Next, an in-house Matlab code maps the orientation field from voxel data to an Abaqus mesh. At this point, the mesh with orientation data is a digital twin of the bracket ready for further processing or simulations. Having been scanned, the brackets themselves are now ready for testing.

3.2. Mechanical Testing

With 14 brackets of each platelet size, half were tested under tensile loading and half under bending. Figure 4 illustrates the tension test on the left and bending on the right. In both cases, the bolts holding the base of the bracket to the fixture were torqued to 13.56 N-m. Tension tests were conducted at a rate of 0.3 mm/s while bending tests were prescribed 0.6 mm/s. All tests were performed on a Shore Western servo-hydraulic axial-torsion load frame with closed-loop control and capacity of 445 kN with a 10 Hz sampling rate. To capture true displacements for future modelling validation without influence of the test machine's compliance DIC was implemented. For this, a Nikon D5600 DSLR and D7500 DSLR cameras with Nikon AF 200 mm and Sigma 135 mm DG HSM lenses were positioned on opposite sides of the bracket to observe two-dimensional stochastic field of black paint speckles over a white painted background in the pinned region of the bracket. The images were processed with GOM Correlate [24].

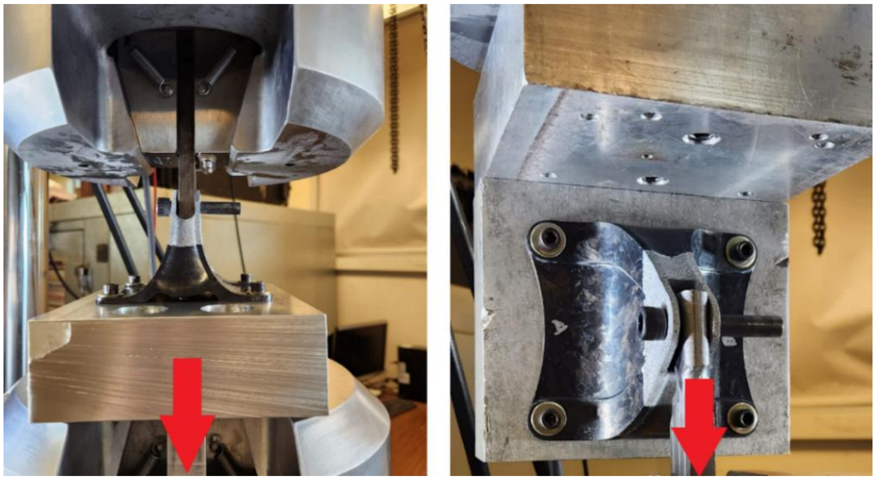

Figure 4. Tension (Left) and Bending (Right) Test Setup

Figures 5 and 6 showcase the load frame's load-displacement curves for the tensile and bending tests, respectively. Under tension testing the NP brackets achieved 14.64 kN ±12.4% while the SP brackets loaded to 9.92 kN ± 14.3%. Additionally, the NP brackets were about 31% stiffer than the SP brackets. The story for bending, however, is different. While NPs maintained a slightly higher peak load, the strength and stiffness differences between NP and SP brackets are significantly reduced in bending as is the difference in stiffness. But why? Ultimately, these brackets differ only in flow dependent properties and platelet morphology, so one may claim with confidence that the difference lies between these two attributes.

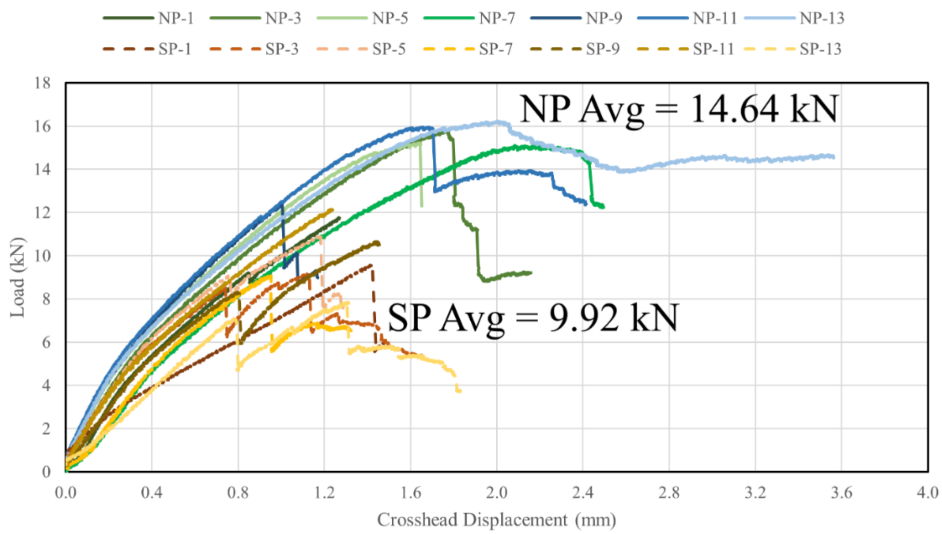

Figure 5. Tensile Test Results

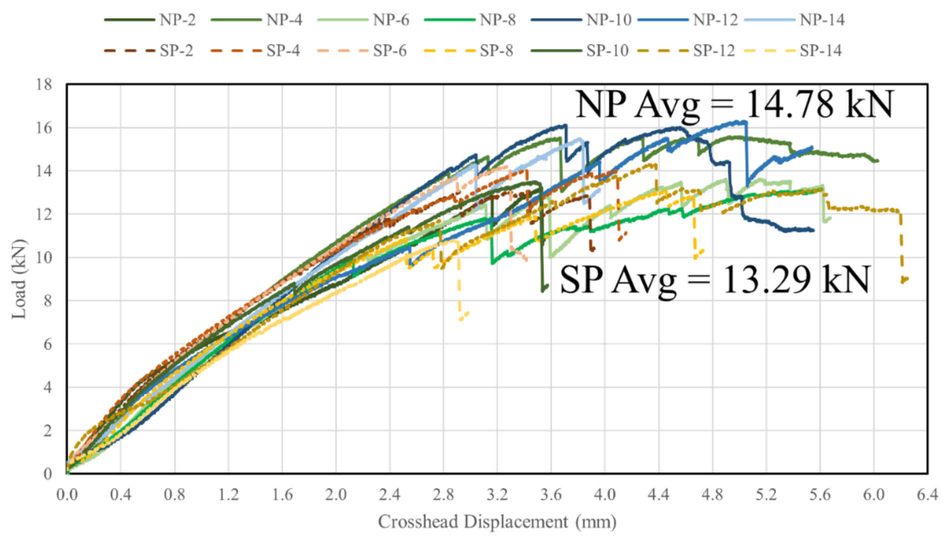

Figure 6. Bending Test Results

It makes sense that NPs were the stronger ones as narrower platelets have been shown to be stronger than wider ones under uniaxial testing [10, 16-20]. Notably, Ko et al. [10] found that NP DFCs greatly outperform SP DFCs for material thickness less than 6.3 mm, and the thinner the material, the larger the relative difference. Nearing 10 mm of thickness, this gap is much smaller though NPs remain slightly stronger. How does this trend apply to our case? The crucial detail here is that the tensile brackets all failed at the pin and only at the pin whereas the bending brackets first failed in bending tension at a radius leaving the base. Moreover, the driving mechanism for tension failures at the pin are matrix crushing and fiber breakage. Alternatively, the bending failure initiations are rooted in delamination. We may refer to Figure 7 to see a typical tension and bending fracture. The pin region where tension coupons fractured is made of two flanges, each 3.1 mm thick, well within the range Ko found to favor NPs. The radius at bending fracture exhibits a minimum thickness of 3.6 mm, which grows to 4.7 mm on the smaller side and exceeds 7 mm platelet normal thickness through the main part of the crack. Following Ko's thickness effect research [10], it is reasonable that the narrow and square PPMCs have a closer peak load to each other however, the observed strength and stiffness differences are closer than expected. To understand the role which the radius itself plays in this equation, a series of four-point bend experiments investigating various inner radii, thicknesses, platelet morphologies, and flow conditions are forthcoming. These will adhere to ASTM-6415 [23].

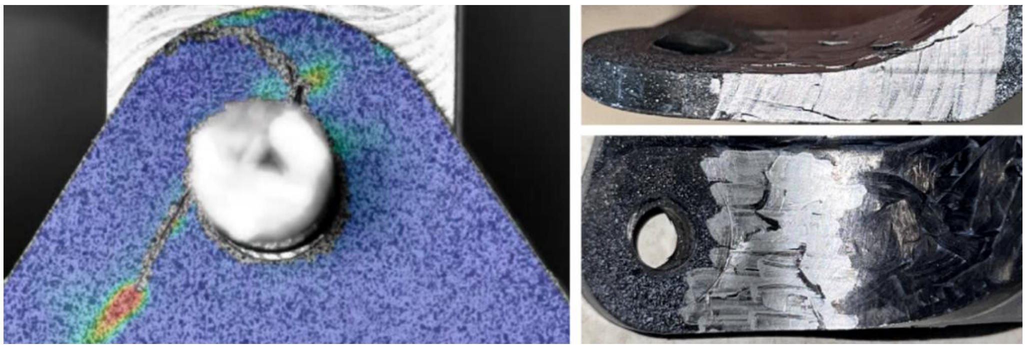

Figure 7. Typical Tension (Left) and Bending (Right) Fracture Surfaces

4. Platelet Recognition and Orientation Analysis

For a deeper look into NP and SP differences in molding, the orientations at the base and flanges of the brackets are under investigation. For this, CT scan data is used to identify partially or fully intact platelets based on their A_{ii}. We may visually inspect the base and pin regions in Figures 8 and 9, respectively, and see NPs and SPs are more preserved in the base of the brackets than around the pin. It is worth noting that SPs are much easier to visually identify in the base than NPs. This can be attributed to more NPs being required to fill a given volume than SPs. Combing this with the fact that NPs are narrower, it is intuitive that NPs will overlap each other and orient slightly out of plane more than SPs. From the figures, we can see some clear boundaries of platelets at the base, more easily for square platelets. Additionally, we see that the high flow region of the bracket exhibits fiber alignment with the flow direction for both NP and SP in the wide central area which is consistent with Nakagawa's findings [16]. Nonetheless, it is difficult to make out many clear platelet shapes in this region indicating that the platelets are curved, bent, or broken. The fiber alignment near the edges of this region likewise follows the edges.

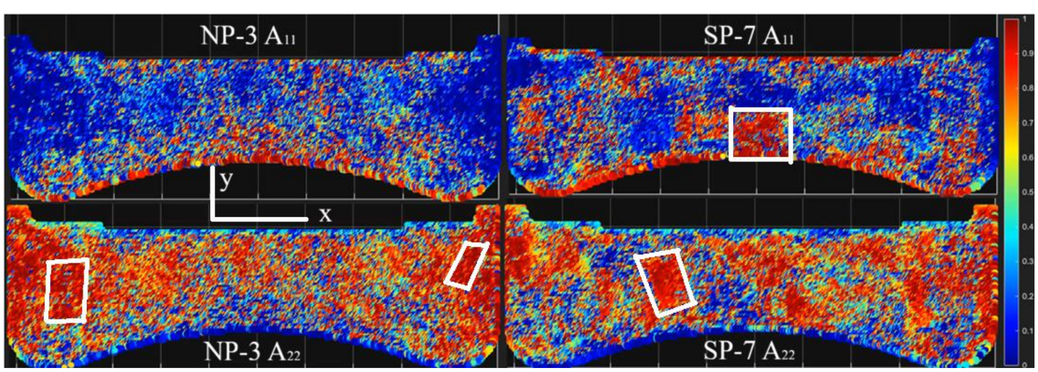

Figure 8. Orientation Alignment in Section of Bracket Base

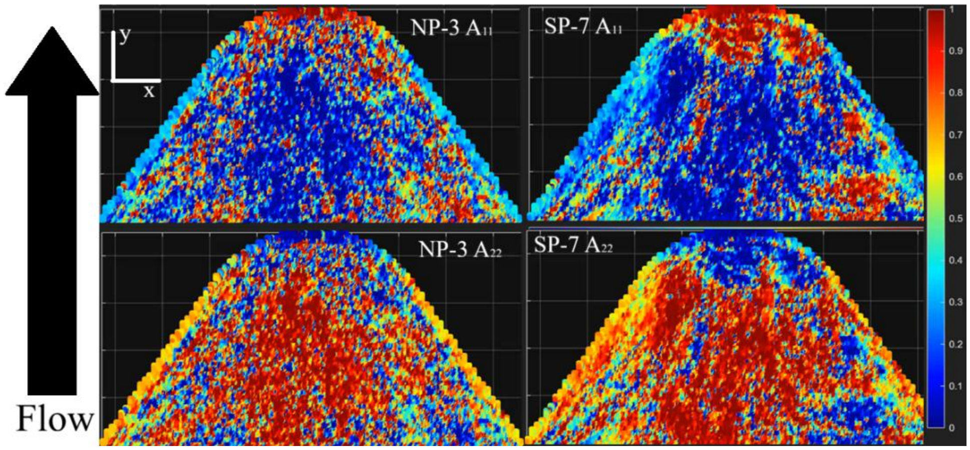

Figure 9. Orientation Alignment in Section of Bracket Pin Region

One area of particular interest in Figure 9 is in the top center of the flange. Here, we see that NPs better align with the loading axis than SPs which helps explain why NPs are so much stronger here: a stronger fiber bias in the loading direction. To keep the platelet data robust, very small clusters of similar orientations are ignored as are any that exceed a dimension greater than 50 mm. The latter is the result of platelet runaway where many platelets with similar orientations artificially create an extremely large platelet. The filter is set to four times greater than the length of an individual platelet as this study should recognize when platelets are similarly oriented due to flow conditions as described in Figure 9. The orientation analysis results are in Figure 10. Focusing on dimensions ≤ 13 mm, we see that the lengths of recognized NPs and SPs follow a normal trend for both the base and flanges with some locally aligned platelets found for each. These locally aligned platelets are much more prominent in the flanges due to the high flow condition versus the base as evidenced by the relatively large number of oversized platelet lengths found for both NP and SP flanges. Platelet width (NP width redacted from the chart) however, decreases in the flanges. This is evidence of platelets breaking apart between fibers from the flow. Here we see an increase in shorter SP widths and a relative decrease in SP widths above nominal. Most of the recognized platelets are shorter than nominal which is to be expected because this study specifically looks for intact platelets with their geometry largely preserved.

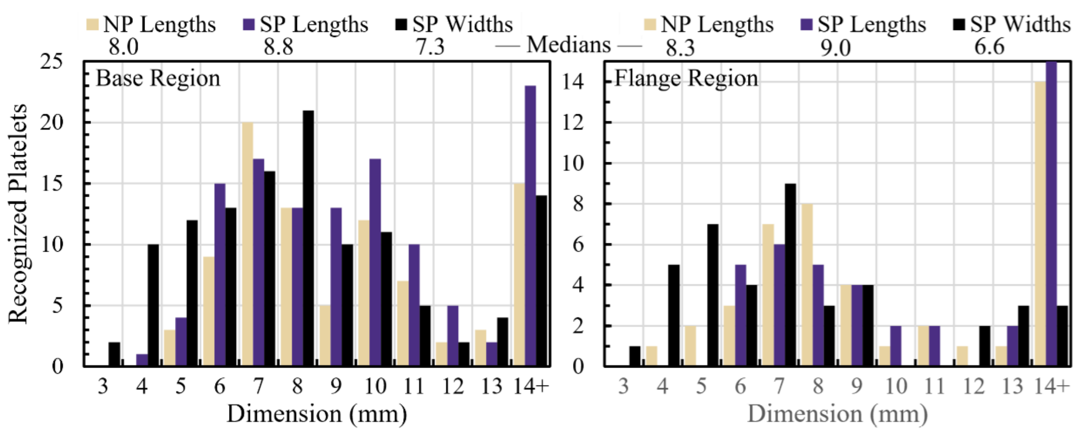

Figure 10. Recognized Platelet Dimensions in the Base (Left) and Clevis Flange (Right) Regions

5. Conclusions and Future Work

5.1. Primary Conclusions

From the testing and studies discussed herein, we have observed that three-dimensional brackets made from NPs vastly outperform SP brackets in tensile stiffness and strength. When tested in bending, this difference diminishes to be much smaller. The structural redundancy present in narrow PPCMs and thickness effect which have been shown in literature are a driving force behind this performance difference. The bending results are much closer between NP and SP due to a different failure mechanism: delamination at a radius in a thicker, lower flow section of the bracket. More than a different failure mode alone, the flange region of the bracket was shown to orient NPs more favorably than SPs. The researchers used μCT to analyze the fiber orientations within the bracket. It was determined that platelets' original geometry is less preserved in the higher flow regions where platelet lengths tend to follow the flow direction. In the high flow region, fiber orientation is substantially flow dependent while the lower flow areas hold more visually intact and identifiable platelets.

5.2. Future Work

This research is ongoing and next steps are already underway. First, the researchers seek to improve platelet recognition function and analyze the rest of the brackets. With a better understanding of the flow dependent properties of these brackets, modelling studies are underway to recreate the tests on digital twins of the brackets. The goal is to capture both NP and SP brackets with one homogenized model. Finally, to fully understand the influence of the radius and delamination, bending tests per ASTM D6415 [23] will be used to investigate the impacts of flow, platelet morphology, thickness, and radius.

6. References

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