Flax as a Structural Reinforcement for Polymers

by
Haley McGeorge

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Chemical Engineering
(Honors Scholar)

Presented November 30, 2021
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AN ABSTRACT OF THE THESIS OF

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Abstract approved:____

Roberto Albertani

Flax fibers are frequently used as a sustainable and recyclable reinforcement for composite materials in aesthetic applications (ex. car interiors). Flax fibers are biodegradable and can be sustainably harvested. Furthermore, the question of how to dispose of flax reinforced materials after the end of their lifetime can be solved in a more environmentally friendly way. However, flax fibers as reinforcements for composites in structural applications is far less frequent. This study aims to investigate and summarize a few unique challenges associated with flax fibers and provides an experimental study that compares flax performance to those of carbon fiber, fiberglass, and basalt as reinforcements in epoxy resins composites. Although work in the literature review suggested flax would perform similarly to fiberglass, flax underperformed in comparison to the other materials tested. Reasons for this underperformance include sub-optimal layup and probably low fiber volume fraction due to the wet layup fabrication method, a challenge for a non-expert operator. Professionally resin-infused samples are planned for the continuation of this research.

Key Words: Fiber Reinforced Polymers, Flax, Composite, Sustainability

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Honors Baccalaureate of Science in Chemical Engineering project of Haley McGeorge presented on November 30, 2021.

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Haley McGeorge, Author

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Chapter 1: Introduction and Literature Review

1.1 Introduction to Fiber Reinforced Polymers

Fiber reinforced polymers (FRP) provide a substitute for traditionally heavier materials in a wide range of applications—both structural and aesthetic. In simplest terms, a composite material is a reinforcement suspended within a matrix, and mechanical properties should be considered as a function of both components together. Reinforcement can take the form of fibers, particulates, or flakes with the most typical reinforcement form being fibers. The main fiber materials are fiberglass, carbon, and aramid, and can be structured as unidirectional, woven, or braid [1]. Matrices are separated into the categories of either thermoplastics or thermosets. The former is defined by its reversible nature, and toughness, while the latter is defined by crosslinking, the need for curing, and its irreversible nature. Two main forms of matrices are thermoset resins films (non-liquid films that can be hand placed) and liquid resin for wet-layup manufacturing. The most limiting factor for the use of composite materials is the manufacturing of the part, which is often more expensive and complex than the traditional materials they replace [1].

1.2 Sustainability of Composite Materials

The ever-growing emphasis on environmental considerations leads to questions about the life cycle and recyclability of composite materials. Similar to that of plastics themselves, the boom of fiber reinforced polymers born from their strength and lightness lead to their wide implementation in products with little consideration for their end of life. One common example of this is the use of fiberglass reinforced polymers in boat hulls [2]. The two traditional methods of regaining worth from these materials (incineration and pyrolysis) are inefficient and create different waste material that is difficult to dispose of [2]. Flax has similar mechanical properties to fiberglass, and thus is often chosen as fiberglass' bio-composite counterpart [3]. Bio-composites like flax reinforced polymers can be made degradable or recyclable.

Due to their reversible nature, thermoplastics lend to easier reuse than thermosets. However, manufacturing engineering components using fiber reinforced thermoplastic matrices still represents a challenge. The end life of fiber reinforced thermoset composites is widely considered a critical topic in the environmental study of composite materials. Replacing traditionally used fiber materials with natural plant fibers allows for greater environmental consideration due to their biodegradability and combustibility. Plant fiber composites are already used in many applications for aesthetic purposes and have already largely replaced wood fiber composites in the interior of automobiles in the EU [4].

1.3 Flax as Fiber Reinforcements

Of possible plant-based fiber options, the most attractive for reinforcement in structural use is flax due to its similarity to fiberglass in strength and stiffness. However, actual implementation of flax fiber reinforcement in structural applications is still low because research is still in the development phase and the flax market has not reached maturity.

Some flax plant anatomy knowledge is helpful in understanding how the mechanical properties of flax fibers change with different conditions. The cell wall is comprised of four layers: P, S1, S2, and S3. The notable of these is the S2 layer because it is the structural layer and so is the main contributor to the strength and stiffness of the fibers [5]. The S2 layer is comprised of long cellulose chains called microfibrils that are at an angle from the vertical axis. This angle plays largely into the overall properties of the fiber [5]. Flax has a very low microfibril angle and a thick gelatinous cell wall layer with a high amount of cellulose.

A case study performed by the Wind Energy Materials Group at the University of Nottingham explored the possibility of using flax/polyester composite in place of E-glass/polyester composite in the blade of a small wind turbine [4]. The group found that for a 3.5 m rotor blade designed for an 11 kW turbine, both the E-glass and flax composite blades achieved the requirements for ultimate strength and fatigue. While both blades had the same fiber volume fraction, the flax blade was 10% lighter by mass than the E-glass blade due to flax's lower density. However, even with similar costs of raw fiber between E-glass and flax, the cost of the flax blade was significantly higher because of the expense of the flax roving (separation of fibers from the stem) and flax weaving. The flexural rigidity of the E-glass blade was also nearly double that of the flax, meaning the comparable stiffness of the raw fiber did not translate to the composite itself. This study also highlighted a key difference in the stress-strain curves in that E-glass has a virtually linear curve in early loading while flax does not [4]. An example demonstrating the meaning of a linear stress vs. strain curve is shown in Figure 1.1.

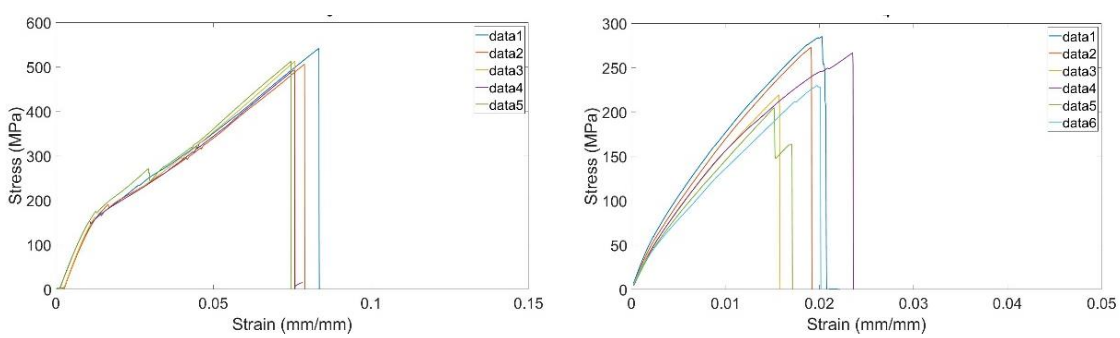

Figure 1.1: Stress vs strain curves for a fiberglass composite of layup $[(0/90)]_6$ (top) and for a flax composite of layup $[0]_4$ (bottom) [6].

The design of the blade can be altered relatively easily to account for any difference in flexural rigidity (as stated in the study). However, there are a variety of other factors which can influence the mechanical properties of flax in composite applications.

1.4 Factors Influencing Flax Fiber Mechanical Properties

1.41 Fiber Separation

An influential factor in the performance of flax fibers is how they are extracted from the plant stem where they occur in bundles in the inner bark. The most common technique for the extraction process is retting, which is the rotting of the plant to separate out the fibers [7]. The effect of fiber individualization on mechanical properties was examined in a study, and fibers bundles were shown to have substantially worse mechanical properties as compared to elementary fibers. Therefore, the amount of fiber individualization is highly influential on the strength and stiffness of flax reinforced composites. Additionally, the non-linear stress strain curve is explained in this study to be a result of the microfibril angle in the S2 layer of the cell wall changing as the load is applied. The study also found that the groups of flax fibers that performed the best underwent both retting and hackling (separation of long and short fibers) and not just retting [7]. The retting process often also can degrade the cellulose in the cell wall of the flax fibers, which negatively affects mechanical properties. Other enzymatic processes for fiber extraction have been tested in order to mitigate the degradation of cellulose including treatment with polygalacturonase and with a pectate lyase (PaL). The latter was shown to have similar results to dew-retting (common type of retting), while the former was found to have worse results because of contaminating glycanases [8]. This study demonstrates the room for improvement in fiber extraction techniques. However, the difference in cost of raw flax fiber vs flax fiber roving suggest current extraction process (mainly retting and hackling) and fiber weaving are limiting steps of flax fiber production.

1.42 Hygrothermal Ageing

The next largest factor for strength and stiffness of flax fiber composites is hygrothermal ageing. Both strength and stiffness are decreased with increased moisture content, although stiffness is much more greatly impacted. There seems to be three distinct ways that water affects flax composites: water (1) acts as a plasticizing agent for the matrix, (2) changes flax microfibril orientation, and (3) negatively impacts bonding between the matrix (hydrophobic) and fiber (hydrophilic) [9]. The effect of moisture content also explains why most current structural uses of flax as a replacement for fiberglass is for applications like automobiles and wind turbines rather than for boats. However, a procedure for making bio-composite racing sailboats was designed, to manufacture a prototype vessel called the *Areté* made of a flax-epoxy and balsa wood structure and hull. Notably these racing sailboats are stored out of the water and so water exposure is in bursts. The design team notes that an added gel coating is suggested for more intense applications, although no specific suggestions are supplied [10]. A Finnish boat company called Baltic yachts has employed one solution to the problem of a difference in final laminate strength when using carbon fiber vs. flax fiber reinforcement in one of their models called the Café Racer. The Café Racer uses flax in common non-structural applications such as the interior floorboards, but also uses a combination of flax and carbon fiber laminates for the hull outer-skin as a structural reinforcement, which both makes the overall build more sustainable and provides extra thickness to the hull [11].

1.5 Summary of Conducted Experiments

The literature review determined that more documentation of flax mechanical properties in different applications and forms is required for better implementation of the reinforcement type into more structural applications. This research was conducted in part toward that goal and consists of experimental estimation of tensile properties of flax, carbon-fiber, and fiberglass composites in both simple laminate structure and in application of reinforcing 3D printed PA12 components. The difference in performance properties after different manufacturing methods of prepreg (preformed impregnated film matrix) use vs. wet layup is also examined with the simple laminate samples.

Chapter 2: Experimental Materials and Methods

2.1 Simple Laminates

Tests on laminates were conducted for basic experimental material characterization. The first samples consisted of laminates manufactured in two separate methods: with the first using epoxy matrix prepreg and the second using wet layup [6]. Samples general characteristics were according to ASTM D3039. For both manufacturing techniques, the samples were obtained from larger plates 152 x 178 mm and were later cut for tensile testing. Three prepreg basic materials each reinforced with carbon, fiberglass, and flax were used. Three types of laminates were made in wet layup each reinforced with basalt, fiberglass, and flax.

Layup schedule and other sample dimensions are shown in Tables 1 and 2 [6]. After layup, prepreg samples were vacuum-bagged and cured according to manufacturer recommendation. For the wet layup, an epoxy resin (Fibre Glast System 2000 laminating epoxy with a 60-minute pot life) was used in a 50% fiber volume ratio with the resin and hardener in a ratio of 100:27 (as recommended by the manufacturer). The wet layup samples were cured at room temperature overnight and then put in the oven at 100˚C for 1 hour to ensure complete curing. The notation used to describe the layup orientation consists of the angle of the ply shown by the degree number (ex. 0, 45, or 90), the direction of the angle shown by a positive or negative sign (ex. -45 or 45), and the number of times the set is repeated with a subscript on the brackets. Parenthesis within the brackets indicate that a fabric is used.

Table 1 – Fiber prepreg materials, weave type, and layup schedules [6].

Material	Supplier	Weave Type	Layup Schedule
Carbon	Fibre Glast	2x2 Twill	$[(0/90)]_3$, $[(-45/45)]_4$
Fiberglass	Fibre Glast	8H Satin	$[(0/90)]_6$, $[(-45/45)]_6$
Flax	Rockwest Composites	Unidirectional	$[0]_4$, $[90]_4$, $[-45/45]_S$

Table 2 – Wet layup fiber materials, properties, and layup schedules [6].					
Material	Supplier	Weave Type	Area Density (g/m^2)	Dry Ply Thickness (mm)	Layup Schedule
Basalt	Innovative Composites	Plain	356	0.24	$[(0/90)]_4$, $[(-45/45)]_4$
Fiberglass	Fibre Glast	Plain	254	0.20	$[(0/90)]_4$, $[(-45/45)]_4$
Flax	Rockwest Composites	2x2 Twill	365	0.75	$[(0/90)]_2$, $[(-45/45)]_2$

Following curing, all laminate samples were cut to a 25 mm width using a band saw (with the outside 13 mm of each laminate side removed from testing to ensure uniformity) [6]. Aluminum tabs were added to the ends of each sample to limit stresses concentration and shear on samples and allow for more accurate measurement. Axial tensile testing was performed according to ASTM D3039 using a 100 kN Instron 5982 universal testing machine at room temperature. An extensometer with a 25 mm gauge length measured linear strain before sample failure. This strain was used to determine the axial Young's modulus.

2.2 Tests on Machine Components

Tests on components were conducted for the experimental validation of the application of flax-reinforced epoxy as structural stiffener of pure polymer (PA 12) components [6]. PA 12 was chosen for study because it is the main 3D printing material used by RapidMade. RapidMade's additive manufacturing technique is Fusion Deposition Molding (FDM), which is a popular choice due to its precision and wide range of applications. However, this method means that fibers within the products printed will be anisotropic and thus mechanical properties are not optimal. One method of improving these properties is by composite reinforcement. This study aimed to examine the effects of different fiber reinforcement with the use of a prepreg film epoxy as well as the bonding characteristics between the PA12, the adhesive, and the fiber.

As a practical application of FRPs material a study on reinforcing 3D-printed plastic part for agricultural applications, funded by a NIFA SBIR Phase I was conducted. As part of the NIFA project, two typical machinery component parts were added to the laminate samples. Such components were printed using an HP Multijet Fusion platform 3D printer and were made from PA12 by RapidMade, the company that was principal recipient of the NIFA SBIR. The two components, selected for their relevance in agricultural applications, were a linkage arm of a tractor's engine mechanical controls and half of a robotic fruit picker.

One sample of each type of component was reinforced with one type of composite material, including carbon fiber weave (CFRP)-epoxy prepreg, fiberglass weave (GFRP)-epoxy prepreg, and unidirectional flax fiber – epoxy prepreg.

2.21 Linkage Arm

The linkage arm was reinforced along the length of the wide side as shown in Figure 2.1. Prepreg epoxy film was used as the adhesive between the PA12 component and the fiber reinforcement.

Figure 2.1 – Linkage arm prepreg film [6].

The components were then vacuum bagged and cured according to manufacturer recommendations. The curing cycle can be seen in Figure 2.2 (page 18).

After manufacture, the linkage arm was tested under a bending load as shown in Figure 2.3 [6]. A total mass of 4 kg using calibrated weights was placed on the end of the arm, added 0.5 kg at a time. Unloading was performed in reverse manner. Displacement was measured using digital image correlation (DIC) [12, 13]. All components were tested as PA12-only prior to applying the reinforcement as well as after reinforcement. The three reinforced samples were each tested 5 times using this procedure.

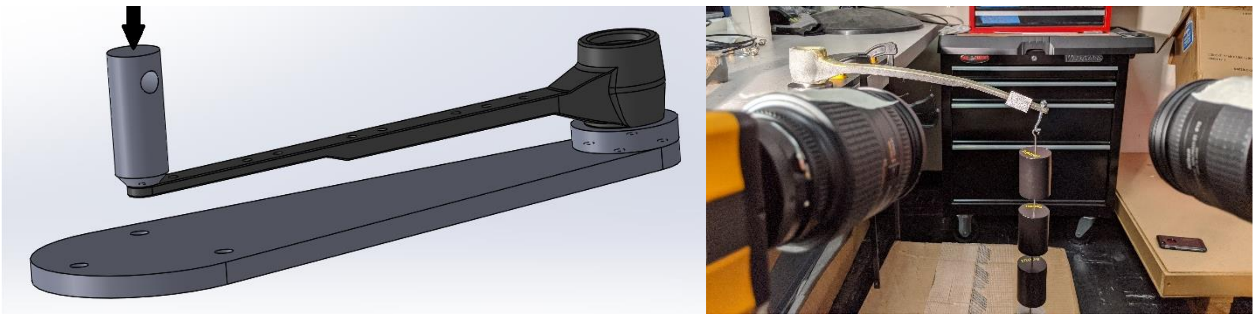

Figure 2.3 – Linkage arm initial testing design (left) and DIC testing setup (right). Black arrow on test design indicates direction of loading [6].

2.22 Picker Body

The fruit picker body was reinforced along the edges and top as shown in Figure 2.4.

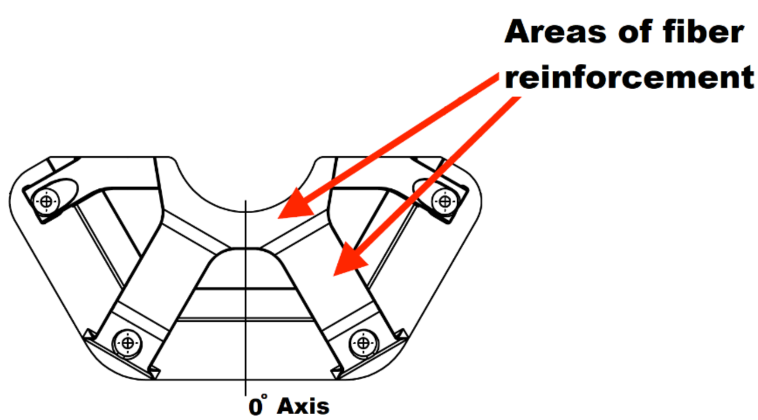

Figure 2.4 – The reinforcement areas for the picker body are shown. Note all four edges were reinforced [6].

This was done by applying prepreg film cut to shape along the reinforcement area followed by the fiber in the same manner. The components were then vacuum sealed in an envelope bag before curing as shown in Figure 2.5.

Figure 2.5 – Envelope bag vacuum sealed picker body components [6].

Testing of the picker body was performed using an Instron universal testing machine with loads of 100, 250, 400, 600, 800, and 1000 N applied to the smaller, semi-circle side of the component body as shown in Figure 2.6. Each sample was tested 5 times.

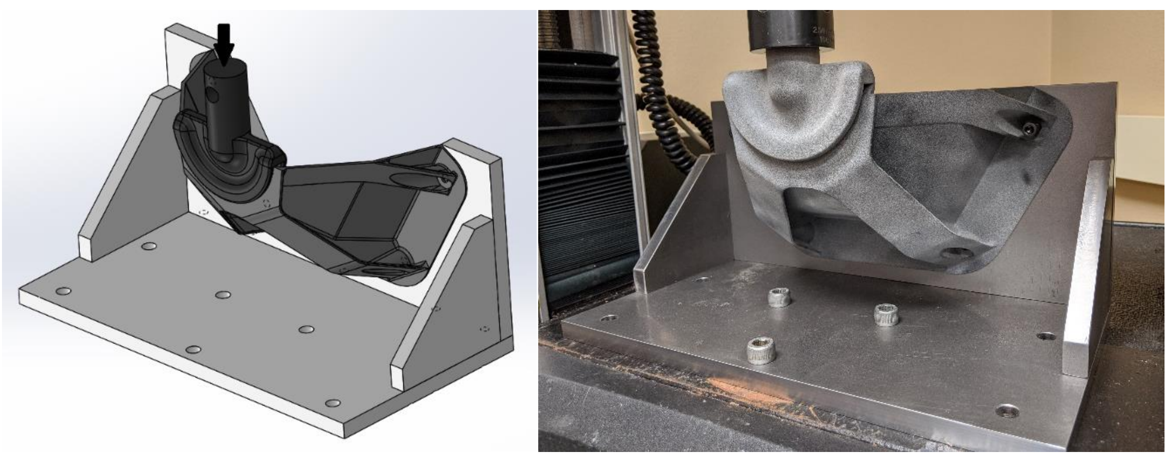

Figure 2.6 – Test design for picker body (left) and actual test setup (right). Black arrow on test design indicates direction of loading [6].

The fixture used to apply the load was a 3D printed fixture and reinforced with a 2 mm thick aluminum strip to avoid local stress concentrations, as shown in Figure 2.7.

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Figure 2.7 – Reinforced picker body testing fixture.

2.23 Layup on Components

Fiber reinforcement and prepreg was fitted to the linkage arm before the layup procedure and was applied to both long faces of the linkage arm as well as along the edges [6]. With respect to the long axis of the linkage arm, the carbon-fiber reinforced polymer (CRFP) and the fiberglass reinforced polymer (GFRP) samples had fiber reinforcement orientation $[0/90]_{ns}$, while the flax fiber sample has [0]. Fiber reinforcement on the picker body was placed only on the outside supporting arms with the same orientations of $[0/90]_{ns}$ for weave and $[0]_n$ for unidirectional.

2.3 Curing Cycles for Prepreg

An epoxy matrix needs curing for consolidation. Oven cure cycles for the prepreg can be seen in Figure 2.2.

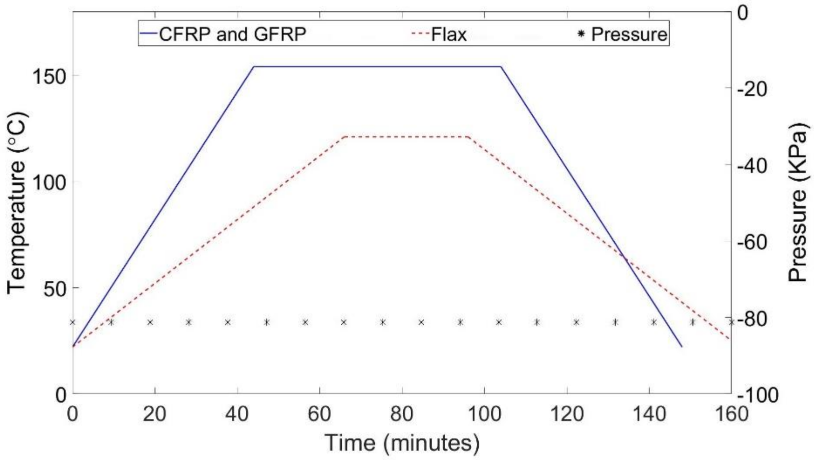

Figure 2.2 – Cure cycles for CFRP, GFRP, and flax fiber prepreg [6].

Chapter 3: Results

3.1 Simple Laminates

3.11 Prepreg

The results of tensile tests on prepreg samples for all three fiber reinforcement types provided an experimental tensile strength, Young's Modulus, and elongation [6]. Samples of stress-strain experimental plots are illustrated in Figure 3.1.

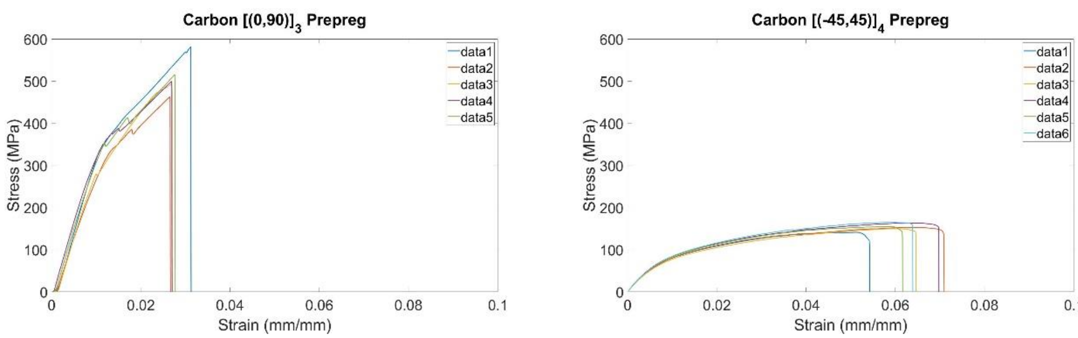

Figure 3.1 – Stress vs strain curves for the CRFP with the orientation $[0/90]_3$ and $[45/45]_4$ [6].

A summary of results can be seen in Table 3.

Table 3 - Mechanical properties in axial direction of carbon, fiberglass, and flax prepreg materials with different fiber orientations [6].

Material	Orientation	Tensile Strength (MPa)	Young's Modulus E_x or E_1 for fabric (GPa)	Elongation (mm)
Carbon	[(0/90)]	511.07 ± 54.31	58.59 ± 1.29	2.92 ± 0.30
Carbon	[(-45/45)]	154.67 ± 9.40	11.00 ± 0.43	6.61 ± 0.63
Fiberglass	[(0/90)]	513.42 ± 22.23	31.55 ± 3.01	8.25 ± 0.75
Fiberglass	[(-45/45)]	177.14 ± 13.14	13.52 ± 0.18	8.75 ± 1.77
Flax	[0]	246.59 ± 34.29	24.59 ± 2.27	2.13 ± 0.33
Flax	[90]	6.37 ± 1.54	2.23 ± 0.25	0.52 ± 0.15
Flax	[-45/45]	50.78 ± 2.26	4.63 ± 0.49	2.42 ± 0.14

The specific tensile strength was calculated by dividing the tensile strength by the density of the fiber and prepreg composite. These results are shown in Figure 3.2.

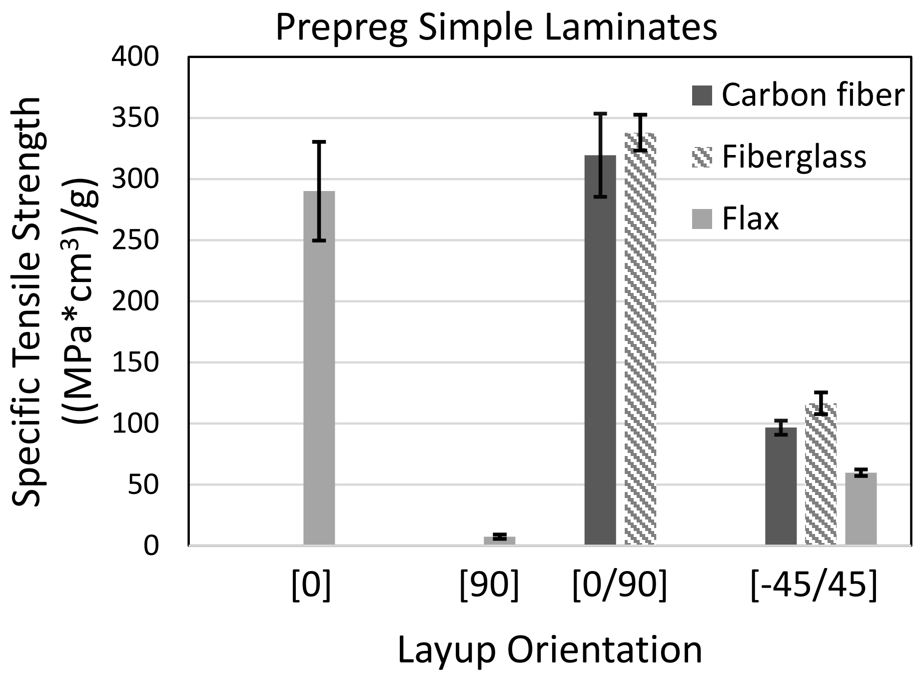

Figure 3.2 – Specific yield strength for prepreg samples of carbon fiber (dark gray), fiberglass (striped), and flax (gray). Error bars represent a 95% confidence interval.

Literature data suggests that flax fiber stiffness can be similar to fiberglass fiber stiffness [4]. The results of the simple tensile tests show that flax laminate Young's modulus is on the same order of magnitude as that of the fiberglass but is about 8 GPa lower. This result is consistent with the study performed with the wind turbine, which showed that there was greater similarity in mechanical properties between the two fibers; the composites with flax were inferior possibly due to adverse fiber-matrix interactions [4].

3.12 Wet Layup

Basalt fibers (produced from basalt rock) were introduced as a reinforcement type during the wet layup tests because they are another good example of a natural fiber that is recyclable, chemically, and thermally resistant, and affordable [14].

The results of tensile tests on the wet layup samples for all three fiber reinforcement types provided an experimental tensile strength, Young's modulus, yield at 1% strain, and elongation, which can be seen in Table 4. QI stands for quasi-isotropic, and all samples are comprised of four plies of the correct orientation [6].

Table 4 - Mechanical properties of basalt, fiberglass, and flax wet layup materials [6].

Material	Orientation	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (mm)
Basalt	[(0/90)]	510.65 ± 34.07	24.88 ± 0.93	9.97 ± 1.09
Basalt	[(-45/45)]	116.68 ± 11.89	9.58 ± 0.70	15.51 ± 2.53
Basalt	QI	198.96 ± 16.16	11.73 ± 1.16	4.83 ± 0.34
Fiberglass	[(0/90)]	187.57 ± 10.55	14.34 ± 1.10	3.05 ± 0.55
Fiberglass	[(-45/45)]	61.97 ± 12.36	5.34 ± 0.53	5.65 ± 1.47
Flax	[(0/90)]	42.61 ± 6.44	6.66 ± 0.61	1.16 ± 0.08
Flax	[(-45/45)]	36.76 ± 3.99	3.37 ± 0.61	2.36 ± 0.36

The specific tensile strength was calculated by dividing the tensile strength by the density of the wet layup (with a 50% volume fraction). These results can be seen in Figure 3.3.

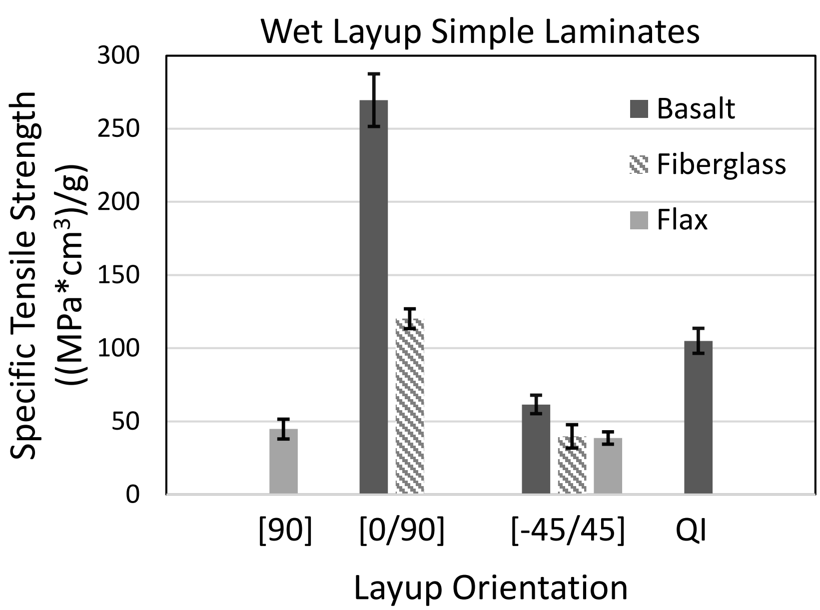

Figure 3.3 – Specific yield strength for wet layup samples of basalt (dark gray), fiberglass (striped), and flax (gray). Error bars represent a 95% confidence interval.

Flax is shown to have significantly lower specific yield strength when compared to basalt and fiberglass when applied in wet layup form. One reason for this may have been the difficulty in wetting the flax fiber material with resin in the wet layup process, a not forgiving method for inexperienced operators. The difficulty wetting meant that more resin was required than the planned 50% volume fraction originally calculated, which would have changed some of the mechanical properties.

3.2 Component Laminates

3.21 Linkage Arm

Since the components were mock-ups of real components, tests could not be conducted according to standards. The first of the PA12-only (without composite reinforcement) component samples tested was the linkage arm, which provided a different loading opportunity (bending) for testing the composite materials. Displacement of the component at different loading states was measured at the tip using DIC. The linkage arm was tested initially and found to have no permanent plastic deformation after testing at the planned loads. The initial displacement data is provided in Figure 3.4.

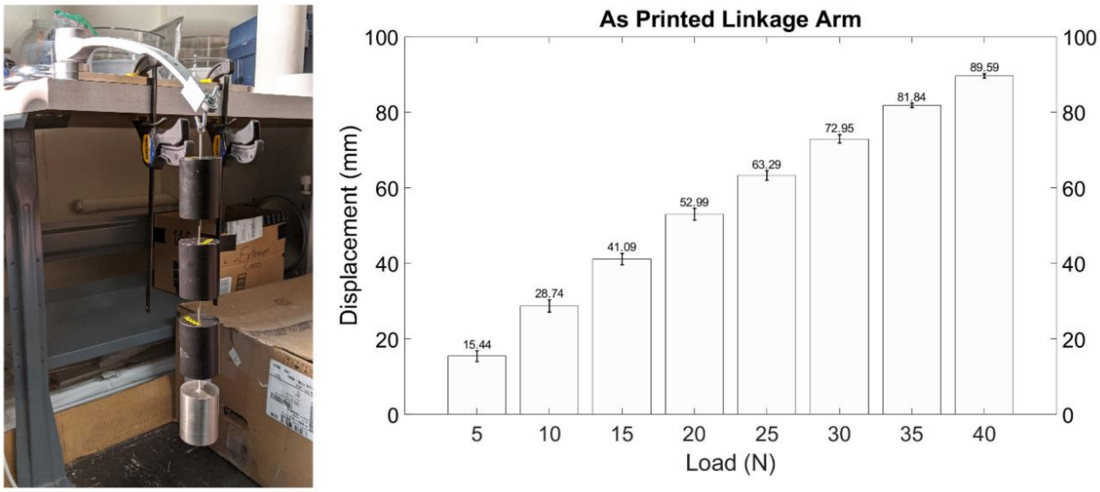

Figure 3.4 – The as-printed linkage arm loaded with 4 kg is shown on the left. The linkage arm displacement with respect to load results is shown on the right [6].

The shape of the linkage arm allowed for easy hand application of the fiber reinforcement and adhesive. After curing, the CFRP and GFRP laminated linkage arm components showed visually some thermal warping, with the CFRP sample showing the most change from the as-printed. Figure 3.5 shows the laminated arms as compared to the as-printed.

Figure 3.5 – The order of components from top to bottom is as-printed, CFRP, GFRP, and flax fiber reinforcement [6]. Warpage in the CFRP and GFRP is evident.

Notably, the flax reinforced sample showed no visible warping. A lower temperature was used to cure the flax sample, which may have been the reason for the retainment of shape. All reinforced samples showed significant increase in stiffness as shown in Figure 3.6. The components were tested in the same conditions as the previous PA12-only parts. Results, illustrated in Figure 3.6 showed significant increase in stiffness, in respect to PA12-only parts, as expected.

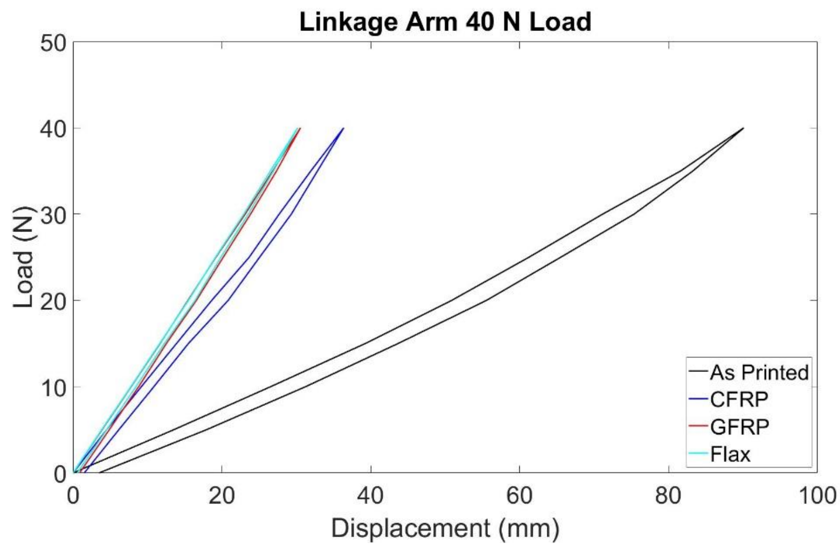

Figure 3.6 – Load vs. displacement curves for as-printed, CFRP, GFRP, and flax reinforced linkage arms [6].

The curves of the GFRP and flax are very similar, which follows the literature. This similarity is far more pronounced within the component study as compared to both the prepreg and wet layup laminate samples [6]. The large difference in the CFRP curve can likely be attributed to warping during the cooling after curing with a possible delamination or defective bonding between plies. There was also debonding of the CFRP from PA12 that was audibly heard during testing. This was confirmed after testing as shown in Figure 3.7. In the latter case the arm would lose stiffness owing to the loss of bending stiffness from the sandwich effect present with good bonding.

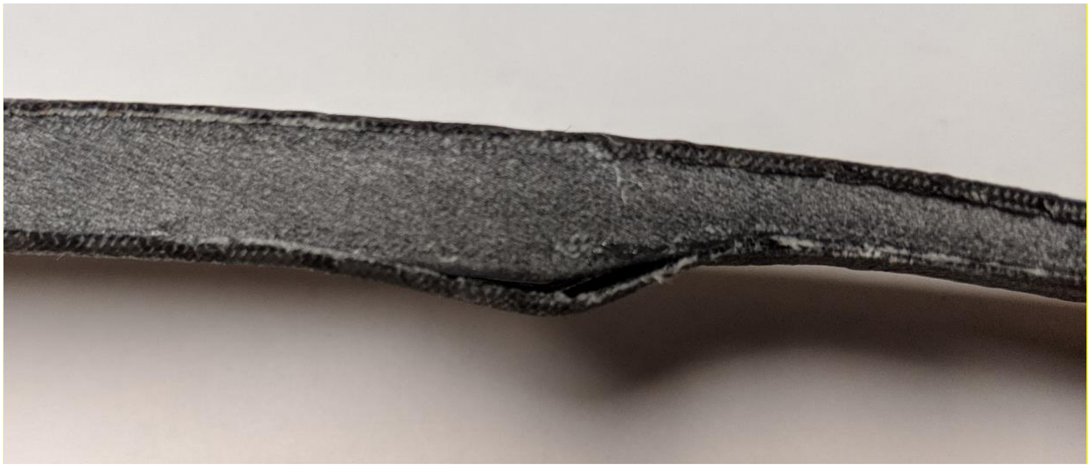

Figure 3.7 – Fiber and matrix debonding is shown after testing in the CFRP linkage arm [6].

The bending stiffness for the component was calculated from the linear slope of each displacement vs load curve shown in Figure 3.6, with the results shown in Figure 3.8.

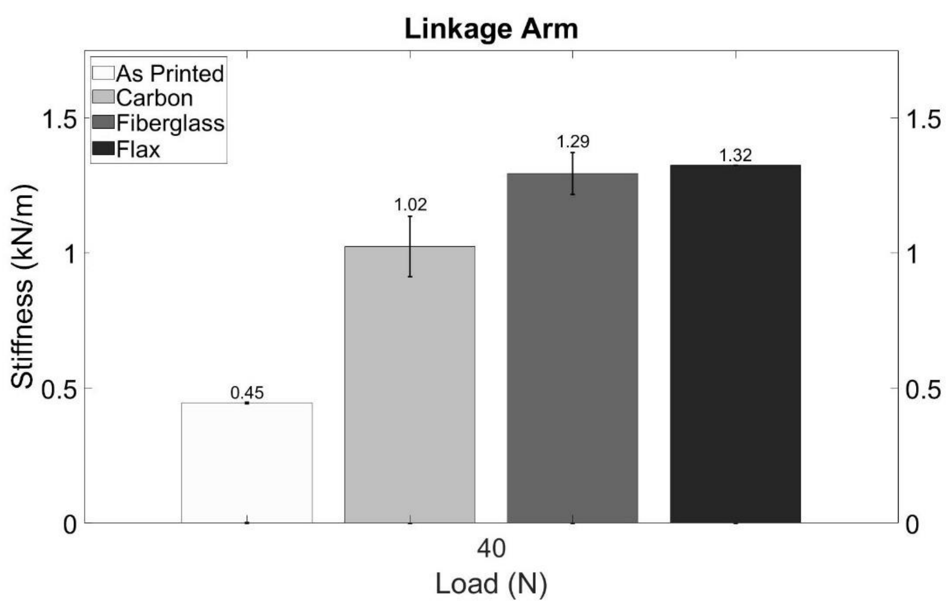

Figure 3.8 – The stiffness of as-printed, carbon, fiberglass, and flax reinforced linkage arms [6].

3.22 Picker Body

As another agricultural-relevant component, a part of a manipulator of a robotic fruit-picker was selected. The fruit-picker body component printed by RapidMade out of PA12 was another opportunity to evaluate flax performance and its bonding with PA12 in a practical application. The load vs displacement results on the as-printed picker body is shown in Figure 3.9 [6].

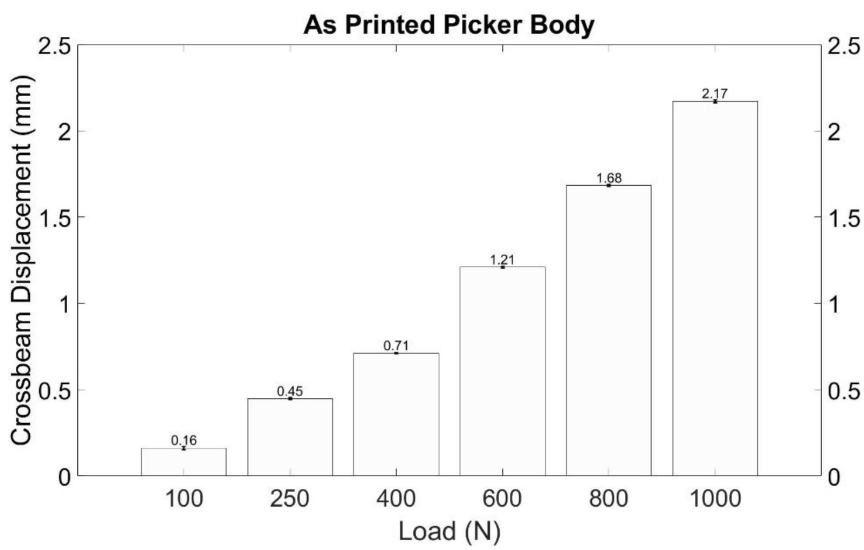

Figure 3.9 – Maximum displacement measured for the as-printed picker body component at loads 100-1000 N [6].

Warping was observed in all fiber reinforced pickers components after curing [6]. The effects of warping in the CFRP and the GFRP were far more pronounced as compared to the flax (which was cured at a lower temperature). The base flange in all samples also had slight warping. This warping can be seen in Figure 3.10.

Figure 3.10 – Warped picker bodies reinforced with carbon fiber (top left), fiberglass (top right), and flax (bottom) [6].

The aforementioned warping of each of the reinforced picker body components meant that it was difficult to attach the component to the testing apparatus. The components were adapted to the testing jig to obtain preliminary results and validate the experimental apparatus. The displacement of the samples did not differ significantly from each other possibly due to the warping and possible delamination of the composite-reinforced parts during curing [6], thus vanishing the effect of the reinforcement. The results have been mainly attributed to the deformation of the 3D printed testing fixture for applying the load, resulting in a clear flaw in the testing apparatus that needs to be corrected for future work. All displacement preliminary results can be seen in Figure 3.11.

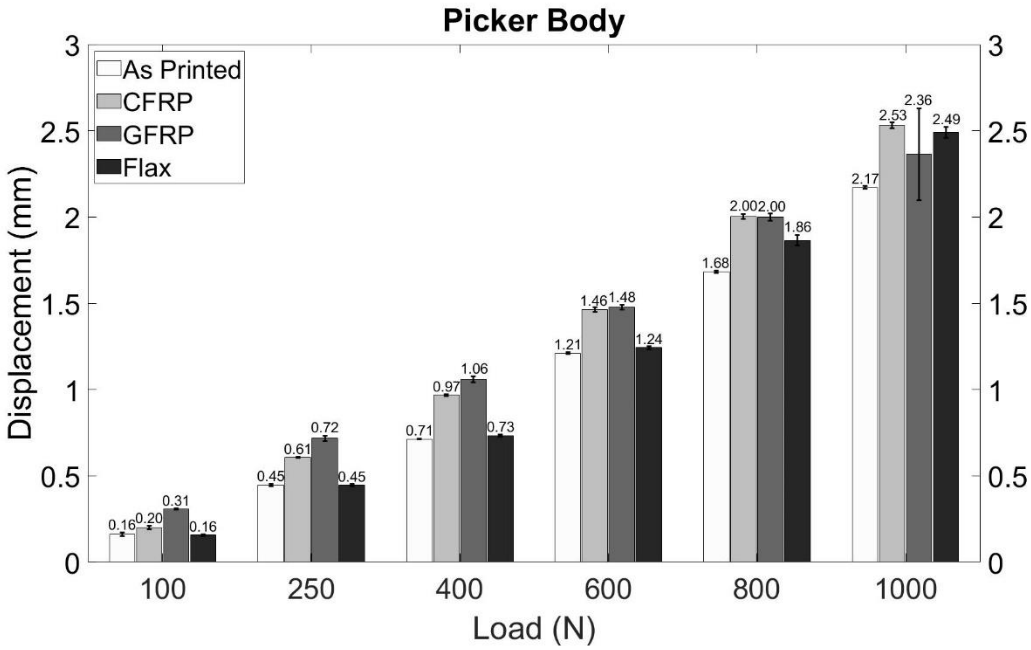

Figure 3.11 – The displacement vs load results for the as-printed, CFRP, GFRP and flax fiber reinforced picker body components [6].

Due to the 3D printed fixture weakness likely altering results, the picker body was also tested with an improved fixture made of aluminum. The loads tested with this new fixture were only 100 and 250 kN. These results showed the CFRP and GFRP components had displacement and stiffness very similar to the as-printed component (see Figure 3.12), indicating a significant debonding between PA12 core and composites reinforcement.

The flax fiber reinforced sample had two to three times the displacement of the other samples (and therefore significantly lower stiffness) [6]. Debonding and damage to the PA12 flange and stiffeners were later discovered. Even with the presence of manufacturing flaws (debonding) and possible damage to the flax-reinforced component, specific results were estimated and illustrated in Figure 3.12.

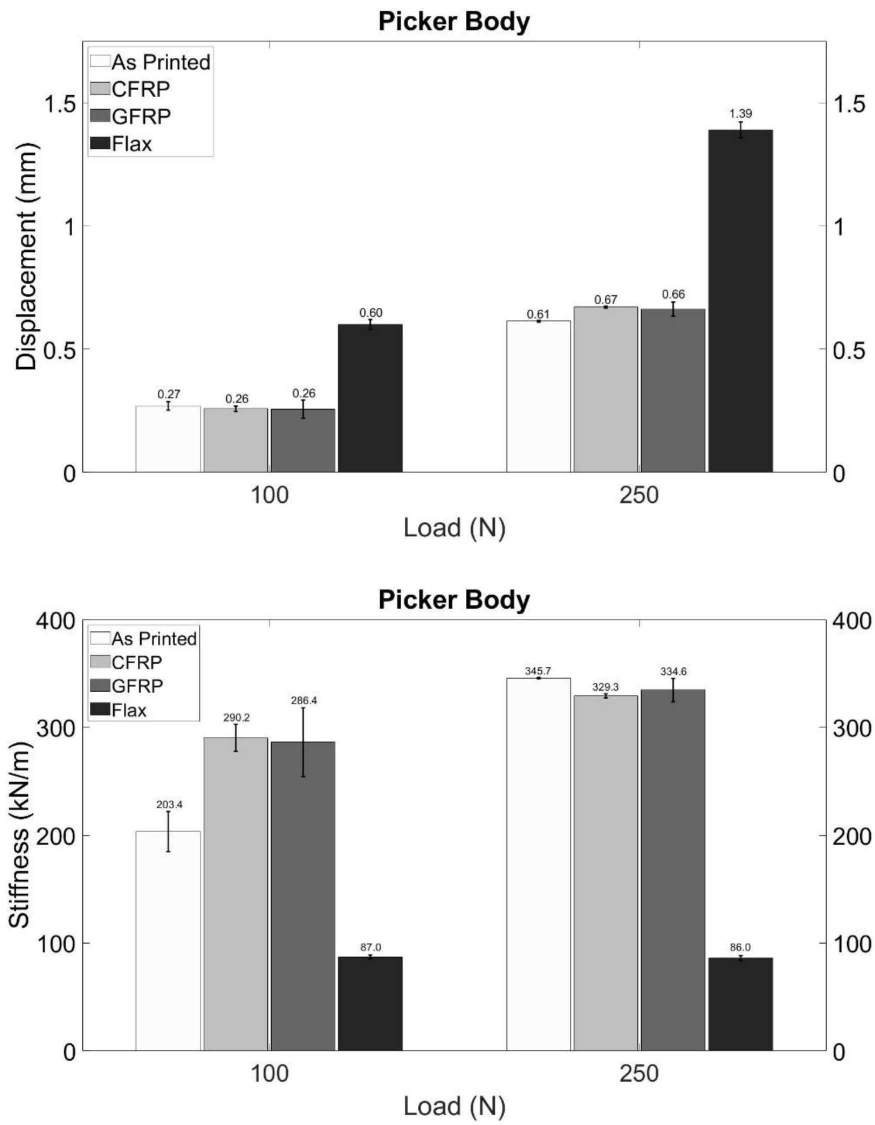

Figure 3.12 – Displacement vs load when an aluminum fixture is used to apply load to the as-printed and reinforced picker body samples (top). Stiffness vs load using the above conditions for the picker body samples (bottom) [6].

Considering the already somewhat existent defects in the fiber-reinforced components, the picker bodies were then tested to until their ultimate failure point was reached. The as-printed sample failed at a higher load than both the fiberglass and flax reinforced components likely because of warping in the reinforced component parts. However, the carbon fiber ultimate displacement was approximately double that of the as-printed sample. These curves can be seen in Figure 3.13.

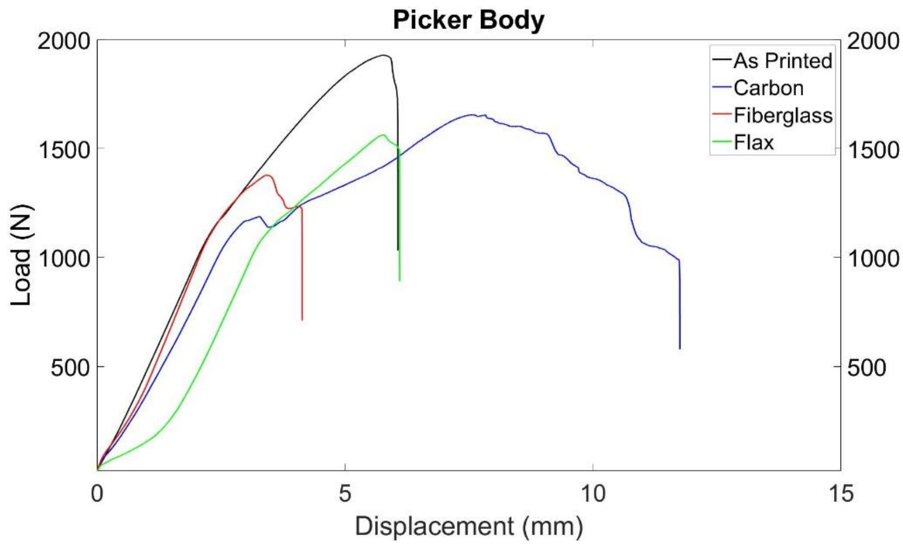

Figure 3.13 – Load vs displacement curve for the failure testing of the picker body samples [6].

The failure mechanism for such components is a complex phenomenon and its deep examination is beyond the scope of this work. With perfect bonding between PA12 and composites, the load-displacement curve should strongly resemble one for a sandwich panel. However, attachment points at the flange are experiencing relatively high stress concentrations. Indeed, upon the observation of the samples after failure (Figure 3.14), it was evident that the ultimate failure mode was catastrophic failure at the flange with the bolt holes rather than the fiber reinforcement. This would indicate that reinforcement should have been extended to support the component at the attachment points. This would be a required improvement for future research on this subject.

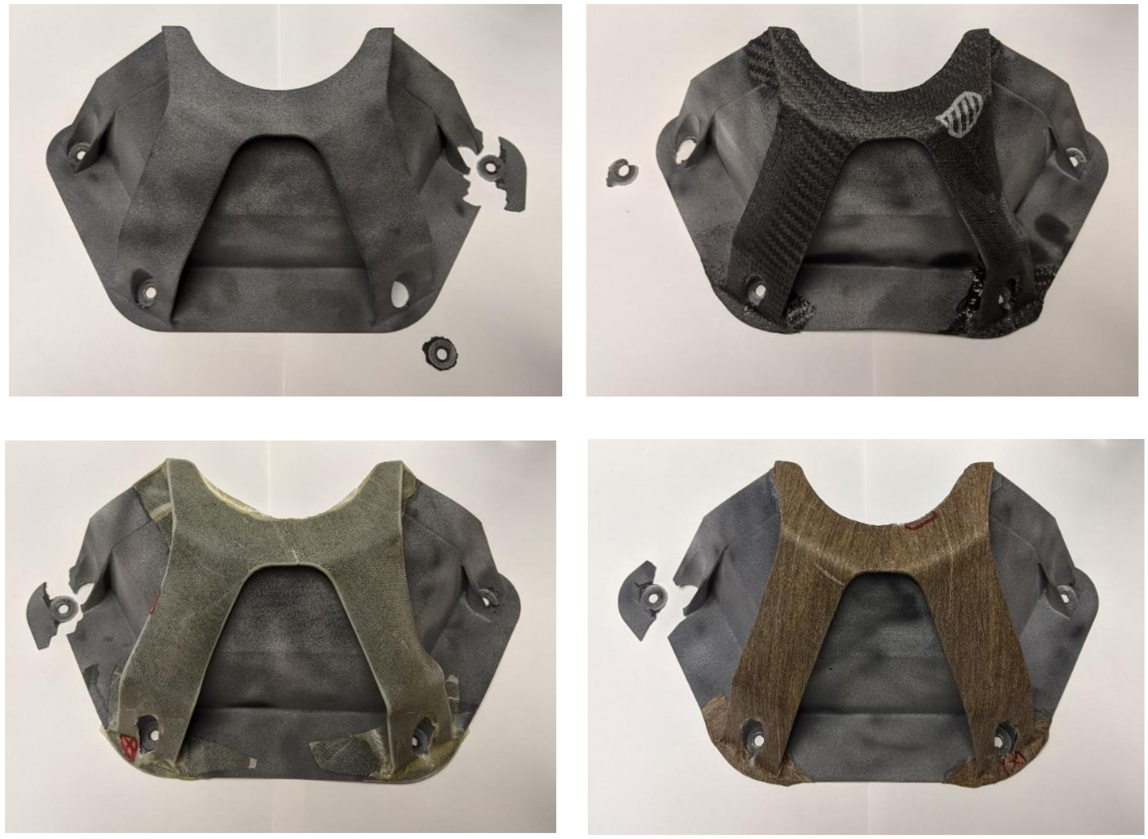

Figure 3.14 – As-printed (top left), carbon fiber (top right), fiberglass (bottom left), and flax reinforced (bottom right) picker body samples after failure [6].

Chapter 4: Conclusion and Suggestions for Future Work

Flax fiber remains with great potential to be a preferable option for structural reinforcement in polymer composites due to its sustainability. Obstacles in current application include the cost of fiber separation, the variability due to fiber individualization, and the lifetime of parts due to environmental conditions. Lower curing temperatures could be favorable for applications where other materials may be heat sensitive.

The results of the sample laminates as well as the component laminates showed that flax has the potential to be a lighter substitute for fiberglass and carbon fiber. More research on manufacturing techniques, specifically thermal effects during cure and bonding between core and FRP is needed for applications into real structural components.

A series of reinforced 3D printed composite-reinforced components is highly suggested, with simpler components first that should be designed in function of thermal strain during curing. Different bonding strategies should also be considered and tested.

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