UNIVERSITY OF WATERLOO

Non-Metallic and Composite Materials Laboratory Research Project

ME 533

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Project Background

The purpose of this project is to analyze and assess a pre-existing composite using working principles learned, like the effect of fiber orientation on tensile strength and the Rule of Mixture. In addition, the purpose includes illustrating the fundamental aspects of composite behaviour through physical experimentation.

For this project, the composite of interest is a fibre-reinforced polymer such as carbon-fibre or glass-fibre reinforced polymer. For simplicity and accessibility of materials, the materials used for testing are wood-fibre reinforced polymer with 1/8th inch wooden dowels acting as wood-fibre and hot glue (common base material of ethylene-vinyl acetate, EVA [1]) acting as the polymer and matrix.

The samples are created using a 3D printed mould designed for easy extraction and setting of the hot glue. The pictures shown below illustrate the sample making process. A total of 8 samples were tested including 2x wood-fibres, 2x polymer matrix, 2x wood-fibre (oriented parallel to load) reinforced polymer, and 2x wood-fibre (oriented transverse to load) reinforced polymer. This illustrates a complete picture of the stress-strain behaviour of the individual components of the composite along with the composite behaviour with different fibre orientation.

The testing is done at the Materials Lab E3-2119 using the Instron machine for tensile strength testing. The samples are loaded into the machine one by one and clamped down using the jigs provided from the Instron machine. The machine is then activated to pull the sample until fracture and the stress-strain data is collected through a computer system linked to the Instron machine. The test setup is shown in Figure 1 below.

Figure 1: Tensile Test setup on Instron

Chosen Composite & Test Setup

For this lab, the chosen composite was hardwood dowel as the fiber, and hot glue as the matrix. A ⅛" diameter hardwood dowel and ProjectMate® hot glue were used to create the composite.
The dog bone is modelled according to the ASTM D638 Type IV standard with a thickness of 4mm and the dimensions outlined in Figure 2 below. [2]

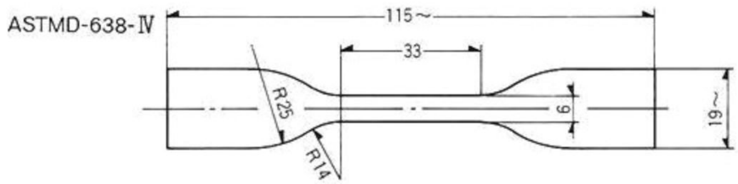

Figure 2: ASTM D638 Type IV Dimensions

A 3D printed mould, shown in Figure 3 below, is used to create the composite samples for tensile testing. The outline of the dog bone shape can be seen, along with vertical and horizontal slots that align the wooden dowels in the matrix during fabrication.

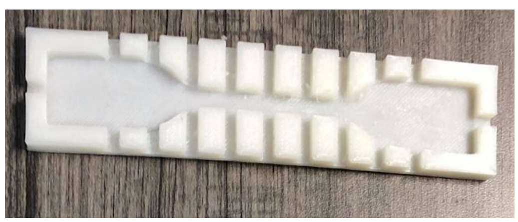

Figure 3: 3D-Printed Composite Mould

In order to create the samples, the inside of the mould is lubricated with Vaseline to allow for easy specimen removal. This also ensures that the specimen is not pre-stressed or strained while taking it out of the mould. First, the mould is filled with hot glue to create the matrix-only specimens. The mould is slightly overfilled, then compressed with a flat metal block to ensure uniform thickness. Then, after cooling, the block is lifted off, the specimen carefully extracted with a flathead, and extra hot glue is trimmed off. This process is repeated for the other two versions with the fibers aligned and perpendicular to the loading condition. The final specimens are depicted in Figure 4 below.

Figure 4: Specimen in mould (left), final specimens for testing (right)

Results

The matrix, fiber, and composite specimens, shown in Figure 5, are tested using the Instron machine in the materials laboratory in E3-2119.

Figure 5: Items tested on Instron

After the test were finished, the data was plotted to show the stress strain relationship of the fiber, matrix and the composite, this is shown in Figure 6 below. Additional images from the experiment can be found in the Appendix.

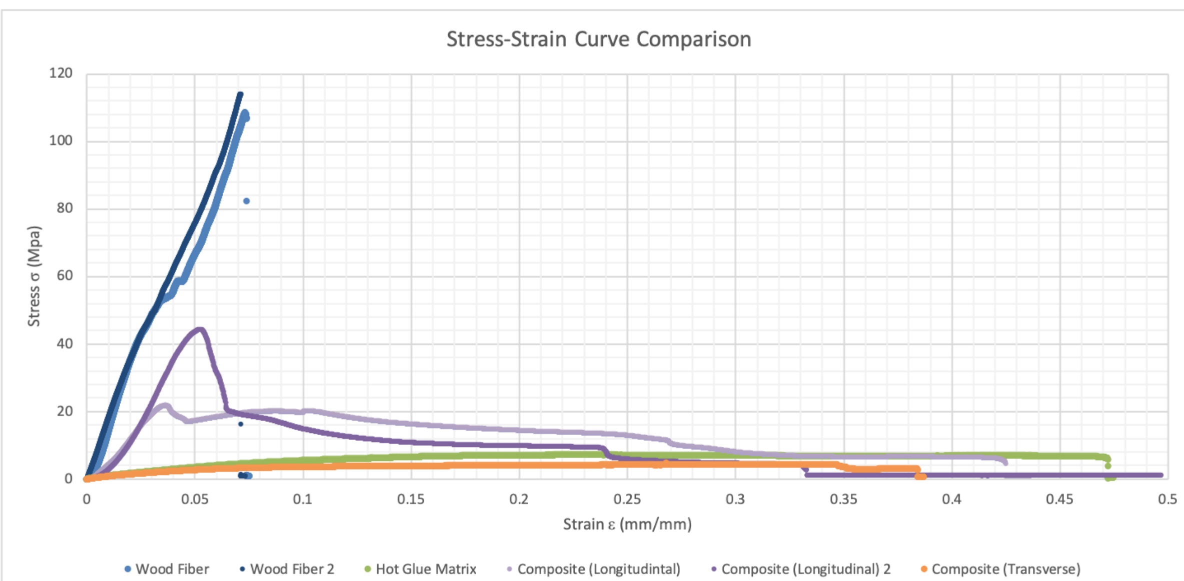

Figure 6: Stress-Strain relationship shown for fiber, matrix, and composite

From the data plotted it is evident that the data for the wood fiber (dowel) is repeatable and thus have good validity. The two samples tested show very close stress-strain behaviour and approximately failing at the same strain value. The wood fiber performed as expected with high strength of 111 MPa and relatively low strain of 0.074. As testing time was limited, not all samples were tested. Only one matrix sample was tested, but it performed as expected with a relatively lower strength of 7.19MPa and high strain of 0.474.

As discussed in class, there is a minimum volume fraction of the fiber in the matrix, V_m. If the amount of fiber added is below V_m, then the strength of the composite is lower than that of the matrix. Since $\varepsilon_f * < \varepsilon_m *$, the following calculation determines the minimum volume fraction required.

$$V_{min} = \frac{\sigma_m * - \sigma_m'(\varepsilon_f *)}{\sigma_f * - \sigma_m'(\varepsilon_f *)} = \frac{7.19 - 4.577}{111 - 4.577} = 0.02455 \text{, or } 2.455\%.$$

Using the Solidworks measurement function, the volume of each dog bone is $6076.81mm^3$. For the specimens with the wooden dowels oriented parallel to the load, the cylindrical dowel takes up $910.49mm^3$ of the mould volume, so the volume fraction is: $\frac{910.49}{6076.81} = 0.1498$, or 14.98%. For the specimens with the wooden dowels oriented transverse to the load direction, the dowels take up $866.79mm^3$ of the volume, so its volume fraction is: $\frac{866.79}{6076.81} = 0.1427$, or 14.27%. Hence, both specimens have a volume fraction greater than V_m, so they are expected to be stronger than the matrix.

Both longitudinal fiber composite samples were tested and produced varying results with low repeatability. This is mainly due to the fact that the manufacturing method used to create the composite sample was not accurately controlled and thus had low repeatability. However, the data still strongly correlates to the theory of rule of mixture learned in class and demonstrates an improvement in strength and stiffness as compared to the raw matrix.

Using the ROM equation below, and extrapolating data from the tensile strength, the theoretical strength of the composite is calculated to be as follow.

Material Property (from experiment)	Value
$\sigma_{UTS-Fiber}$	111 [MPa]
$\sigma_{UTS-Matrix}$	0.074
$\varepsilon_{UTS-Fiber}$	5.39 [MPa]
$\varepsilon_{UTS-Matrix}$	0.47
$f_{volume-fraction-trans}$	14.27 [%]
$f_{volume-fraction-longi}$	14.98 [%]

From then on, the ROM equation was used to calculate the tensile strength of the mixture.

$$\sigma_{UTS-comp} = f * \sigma_{UTS-fiber} + (1 - f) * \sigma_{UTS-Matrix}$$

$$\sigma^*_{22} \approx \sigma^*_{Matrix}[1 - (f/\pi)^{1/2}]$$

This resulted as the following:

	Theoretical Value	Experimental Value	Error [%]
$\sigma_{UTS-Comp-Longi}$	21.69 [MPa]	33.11 [MPa]	34 [%]
$\sigma_{UTS-Comp-Trans}$	7.86 [MPa]	4.76 [MPa]	65 [%]

From, the results obtained from the experiment, there is a lot of discrepancy between the theoretical and experimental values. In addition, it can be noticed, that the actual drop in strength occurs at a point earlier than the failure strain seen from the wood fibers. After closer examination of the failed composite, it is clear that the wood fiber did not actually fail, instead the wood fiber debonded with the hot glue matrix and this results in the sudden drop of the strength. This is followed by the tensile load being purely handled by the hot glue matrix which is why the stress-strain profile of the composite starts to match the stress-strain profile of the hot glue matrix tested earlier after the debonding occurs. After the debonding, there is essentially a long hole in the matrix which creates a stress concentration and early failure of the composite compared to the hot glue matrix by itself as seen in Figure 9.

Although the composite has a volume fraction that is greater than V_m, the composite material has a strength that is worse than that of the matrix. This is mainly due to the poor bonding between the fibers and the matrix. As seen from the previous longitudinal fiber composite, the bonding between the fiber and hot glue matrix is not great. Thus, if we consider similar poor bonding conditions for the transverse fiber composite, the added wood fibers essentially act as holes in the hot glue matrix and create large stress concentrations. Looking at Figure 8, it clearly illustrate the debonding between the matrix and fiber resulting in holes and stress concentrations during tensile strength testing. These holes and stress concentrations result in lower strength and also earlier failure of the composite as shown in Figure 9 for both the transverse and longitudinal fiber case.

Transverse strength considering perfect bonding is given as equation 1 and worst case bonding being the fibers aren't connected and essentially create a reduction in area and stress concentration factors for the matrix strength is given as equation 2. Equations are derived from class notes.

Equation 1: $\sigma^*_{22} \approx \sigma^*_m$

Equation 2: $\sigma^*_{22} \approx \sigma^*_m \left[1 - 2\left(\frac{f}{\pi}\right)^{\frac{1}{2}}\right]$

The transverse strength as noted by the experimental data is shown to be below the matrix ultimate tensile strength of 10 MPa. Thus we cannot use equation 1 in our calculations since we know that the bond strength between the matrix and fiber is not ideal. Thus, using equation 2, it is shown that the resulting composite transverse strength is around 7.8MPa which approximately follows the data collected from the tensile test.

Conclusion and Recommendations

Hence, this experiment demonstrates the behaviour of the matrix, fiber, and composites with parallel and transverse fibers. The wood fiber itself performed well, with a tensile strength of 111 MPa at a strain of 0.074. Next, the matrix also behaves as expected with a lower strength of 5.93 MPa and higher strain of 0.47. Most notably, the composite with the fibers oriented parallel to the load has tensile strength that is between the wooden dowels and the hot-glue matrix, but a strain that is much larger than that of the fiber. This demonstrates the Rule of Mixture theory, where there is an improvement in strength and stiffness when compared with the original matrix. However, the wooden dowels are not well-bonded with the hot-glue matrix. As such, there is a sudden drop in strength when the dowel separates from the hot-glue, causing the load to be carried exclusively by the hot-glue matrix. Finally, the tensile test with the composite with its fibers oriented transverse to the load has a tensile strength lower than that of the matrix on its own. This is due to weak bonding between the fiber and the matrix, and the fiber forming stress concentrations within the composite. After examining the stress-strain curves and observing the behaviour of each of the samples, the effect of fiber orientation, volume fraction, and the concept of Rule of Mixture is clearly illustrated through this experiment.

For future studies, the following recommendations are made. To ensure better consistency in test results, the dog bone samples need a more repeatable production method. The 3D printed mould is a quick and easy method for the purposes of this investigation, but using traditional dog bone manufacturing methods like extrusion and injection moulding can increase the uniformity between samples. [3] Advanced manufacturing techniques can also allow for more precise control on the volume fraction of the composites. On top of more consistent samples, the bonding between the fibers and the matrix can be improved. Currently, it relies on mechanical bonding like friction. To increase this bonding, the wooden dowels can be “roughed up”, using sandpaper before putting it into the matrix. Additionally, sizing in the form of bonding agents can be applied to the wooden dowels to aid in adhesion with the matrix. These methods can be utilized in future studies for more repeatable test results and to better understand the effect of fiber orientation in composites with better bonding between the fibers and matrix.

References

[1] "EVA Hot Melt Adhesives - Overview and Guide," *Hotmelt.com*. [Online]. Available: https://www.hotmelt.com/blogs/blog/eva-hot-melt-adhesives-overview-and-guide. [Accessed: 01-Apr-2019].

[2] "Tensile Test Methods for Plastics: ASTM D638 : SHIMADZU (Shimadzu Corporation)." [Online]. Available: https://www.shimadzu.com/an/industry/petrochemicalchemical/n9j25k00000pyu05.html. [Accessed: 01-Apr-2019].

[3] "Website." [Online]. Available: https://www.testresources.net/blog/making-dogbone-tensile-test-samples/. [Accessed: 01-Apr-2019].

Appendix

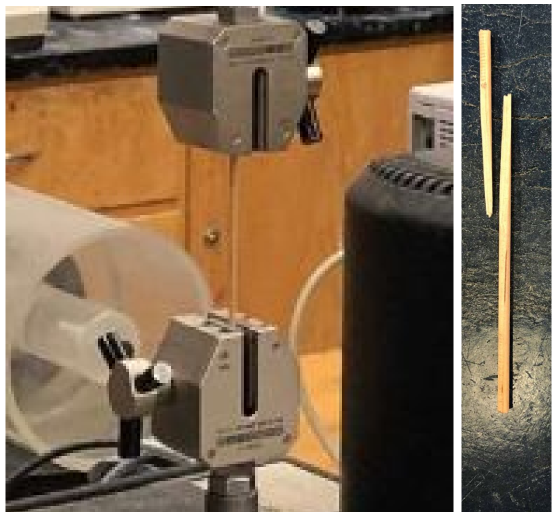

Figure 7: Fiber loaded for tensile test in process (left), failed fiber (right)

Figure 8: Matrix sample going through tensile testing and comparing before and after conditions

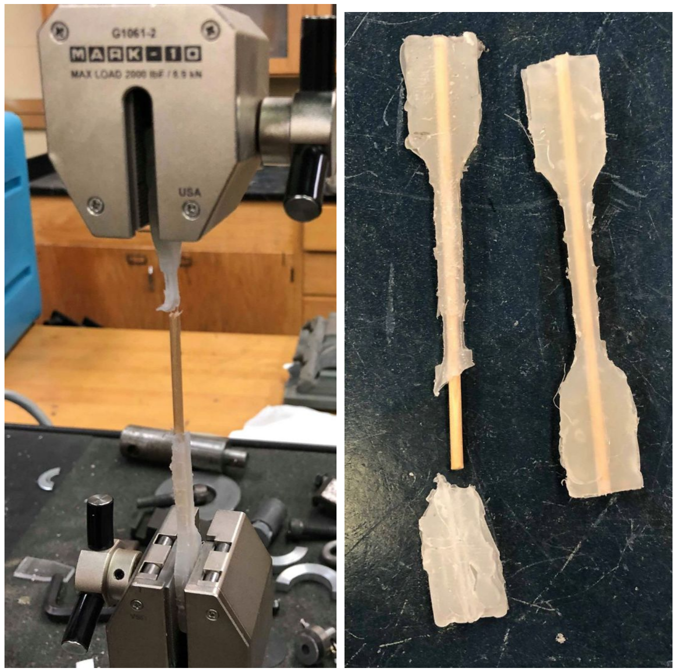

Figure 9: Tensile testing longitudinal composite and comparing before and after conditions

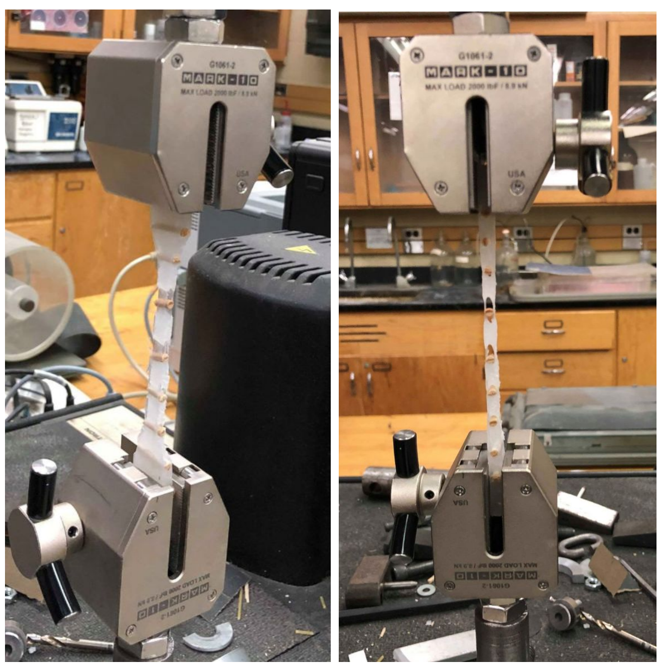

Figure 10: Tensile testing transverse composite and comparing before and after conditions