Marine Turbine Project Composite Materials FEA Analysis — Final Report

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05/18/2022

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Introduction

This project evaluates different composite material structures, arrangements, and volume fractions among other factors to identify the ideal composite types and conditions for application in marine turbine blades. Carbon fiber inclusion in an ATSP resin matrix material is the focus due to its high relative strength while lightweight. Several trials, simulations, and sample tests are possible, but this report focuses on a series of FEA simulations with results that have identified ideal conditions for the composite material in our turbine blade application. It provides data from these simulations that can be used to choose or justify chosen qualities such as material, volume fraction, or structure, as well as provide support for any cost-benefit analyses. Along with comparative analysis conclusions, this report provides some recommendations that can expand on current results and help reach a greater understanding of what is needed for a composite material in our turbine blade application.

Evaluated Material Properties

This analysis was performed on a two-phase composite material. One phase contains the carbon fiber, an elastic transversely isotropic material produced with particular strength along the fiber axis. The other phase contains an isotropic resin ATSP material. The mechanical properties of the two materials that form the composite are listed in Table 1.

Table 1: Mechanical Properties of Materials Within the Composite

	Carbon Fiber	**ATSP Resin - Matrix Material**
Density (kg/m^3)	1750	1300
Axial Young's Modulus (GPa)	294	3
In-Plane Young's Modulus (GPa)	15*	
In-Plane Poisson's ratio	0.2*	
Transverse Poisson's ratio	0.3*	0.34
Transverse Shear Modulus (GPa)	7*	*Assumed value in literature

All simulations measure each of the following composite material properties and how they change under certain conditions.

- Longitudinal Elastic modulus E1: The elastic modulus along the axial fiber direction
- Transverse Elastic moduli E2 and E3: Two axes perpendicular to fiber inclusion

These elastic moduli represent the stress over strain of the composite material. Larger elastic moduli on all three axes are ideal, because this means a stiffer material. The blade will be subject to high stresses, and it is ideal for the blade to experience low deformation or strain relative to stress so the blades retain their shape and maintain performance. It is also best for the material to have a high yield strength to reduce the likelihood of permanent deformation.

- Longitudinal and Transverse and Shear moduli

Similar to the elastic moduli, these shear moduli represent a stress over strain ratio but for the three planes of shear. This includes two planes that correspond to the longitudinal direction (G12 and G13) and one transverse (G23) plane. The higher the shear moduli, the stiffer the composite is in the event of stress along shear directions.

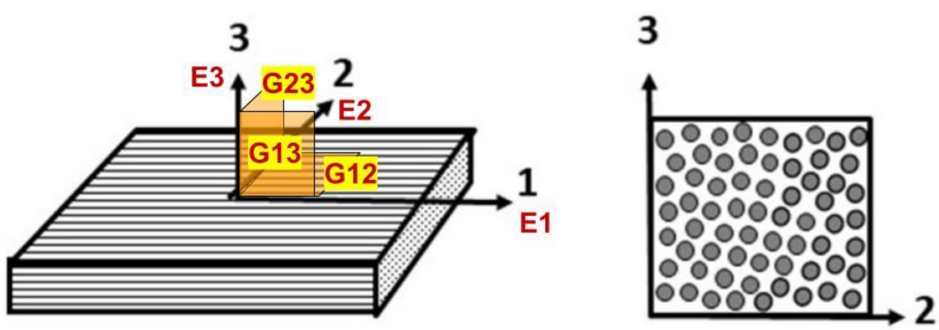

Figure 1: Elastic and Shear Moduli in a Fiber Composite

Simulated Conditions and Considerations

Each of these properties have been calculated through FEA simulation under alterable conditions that are relevant to the composite material. All configurations have periodic boundary conditions, which describes a composite where repeating cells have the same fiber inclusion structure rather than forming a truly random structure. Only one unit cell is simulated per iteration since Digimat is limited to one generated pattern. We therefore cannot simulate a non-periodic truly random arrangement of fibers, but this is not expected to significantly change results.

Uniform fiber arrangement: This describes a fiber inclusion structure with a consistent pattern throughout. All fibers are equal in diameter, oriented the same direction, and equidistant from one another as shown by the unit cell geometry in Figure 2. Assuming the manufacturing process produces a uniform inclusion pattern, the simulation of this condition will be most applicable.

Random fiber arrangement: The manufacturing process may lead to a random distribution of fibers within the composite structure rather than uniform. In this case, a simulation for the condition of random inclusion is applicable. Since random configurations vary, this simulation must be conducted with multiple iterations such as Figure 3 and plotted averages unlike the uniform simulation.

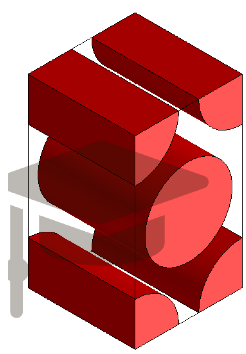

Figure 2: Uniform Arrangement

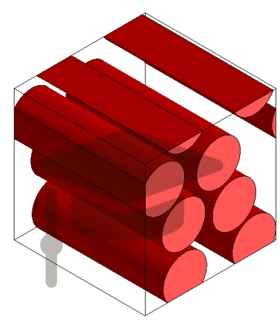

Figure 3: Random Arrangement Iteration

Different volume / mass fractions of fiber: For both uniform and random inclusion, I performed a simulation to see how each of the evaluated properties responds to changes in volume fraction of the included fiber. Each property is expected to increase in value as volume fraction increases, but this quantitative simulation will demonstrate how much volume fraction impacts material properties with plotted data and a comparative model of formulas showing the relationship between these variables. The results of this simulation may be used in a cost-benefit analysis if considering the use of other volume fractions or evaluating current ones.

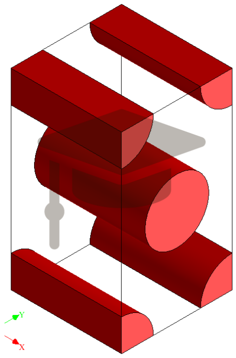

Figure 4: Vol. Fraction = 0.3

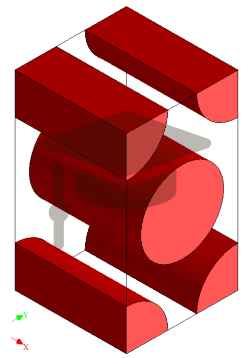

Figure 5: Vol. Fraction = 0.5

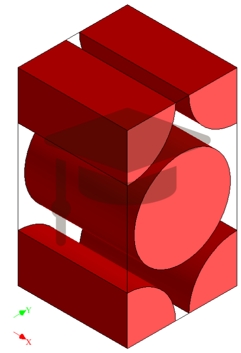

Figure 6: Vol. Fraction = 0.7

Other Considerations: Based on needs identified from my simulation results below, the two factors defined here have a critical impact on current results and are variables in the additional simulations I have recommended to generate a full and accurate set of results.

Delta δ, the window size proportional to fiber diameter:
δ = L/d (window length / fiber diameter). The greater the delta value, the larger the window size proportional to the fiber diameter and the more fiber inclusions present in the window. This value is important to the random arrangement simulation, as a larger delta is expected to yield results with less variation between samples and may converge to the uniform simulation results as delta increases.

Aspect ratio, the ratio of fiber length to diameter:
Fiber length in terms of its size proportional to fiber diameter. Changes in aspect ratio may have an impact on each of the material properties, so we must find the correlation between aspect ratio and these properties. All else constant, we may expect material properties to increase in value as aspect ratio increases.

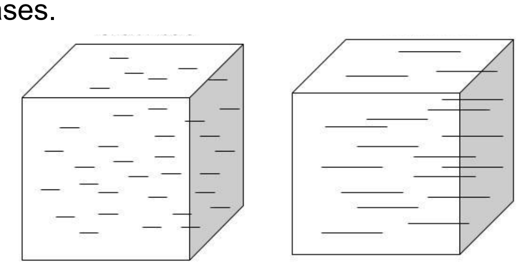

Figure 7: Small vs Large Aspect Ratio

Mesh Size Impact on Results

The smaller a mesh, the more accurate we expect FEA analysis results to be. Due to this, I conducted a simulation to measure each property at different mesh sizes and plot the changes in each property for these changing mesh sizes. Mesh size for this simulation is measured as a percentage of fiber diameter. Delta and volume fraction were both constant for this evaluation and it was conducted on the uniform structure. The purpose of this evaluation is to identify the mesh size at which properties do not experience significant change with further mesh size reduction, as this is the point where the model is likely to have converged to an accurate result.

Of three Digimat mesh types, the Conforming (tetra) mesh was chosen due to its consistent sizing and adaptable elements at the borders between phases.

- **Conforming (tetra)** - evaluated mesh
- Non-conforming (voxel)
- Conforming extruded (hex-dominated)

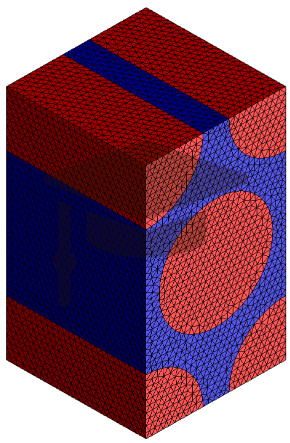

Figure 8: Mesh size = 5%

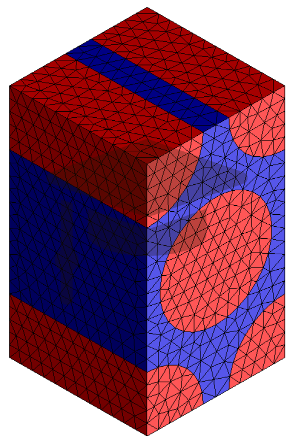

Figure 9: Mesh size = 10%

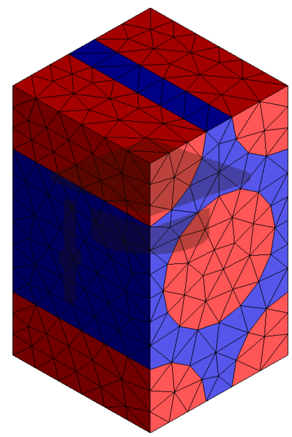

Figure 10: Mesh size = 20%

Figures 11 and 12 show us that each property converges to a likely accurate value as expected when mesh size decreases. All properties apart from the longitudinal elastic modulus E1 seem to cease any significant change below a mesh size of 10% of fiber diameter. The longitudinal modulus, on the other hand, experiences the greatest variation and does not yet converge to a value with the current analysis due to Digimat limitations on mesh size. I could not simulate a mesh size lower than 5% of fiber diameter to find a good convergence point.

Based on these results, I conducted each simulation with a mesh size at or similar to 10% of the fiber diameter.

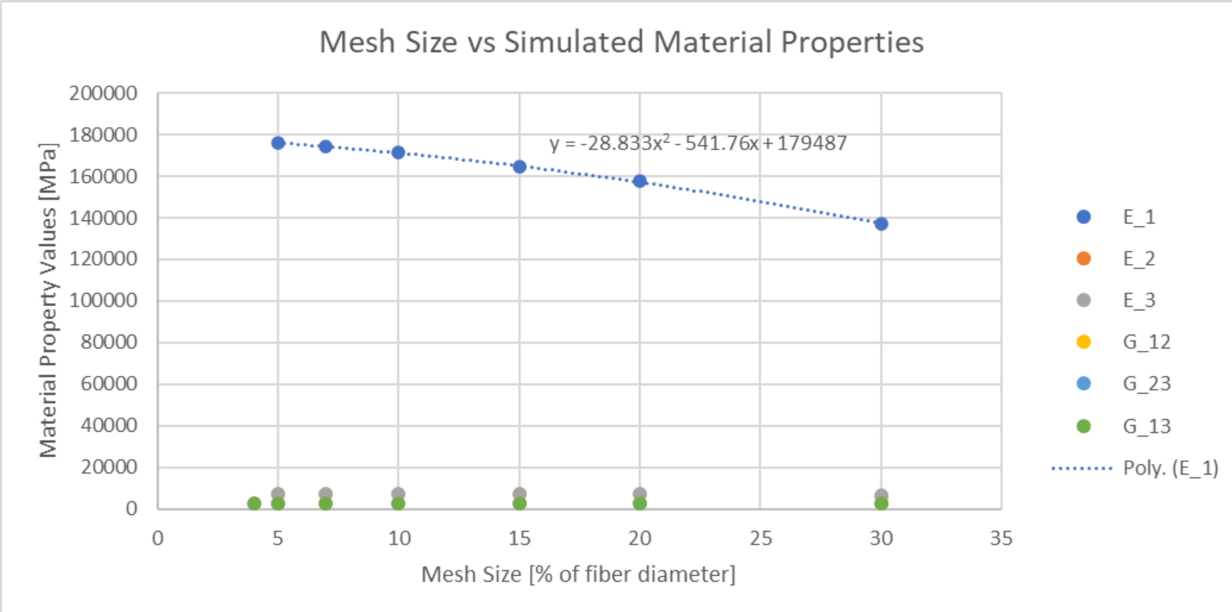

Figure 11

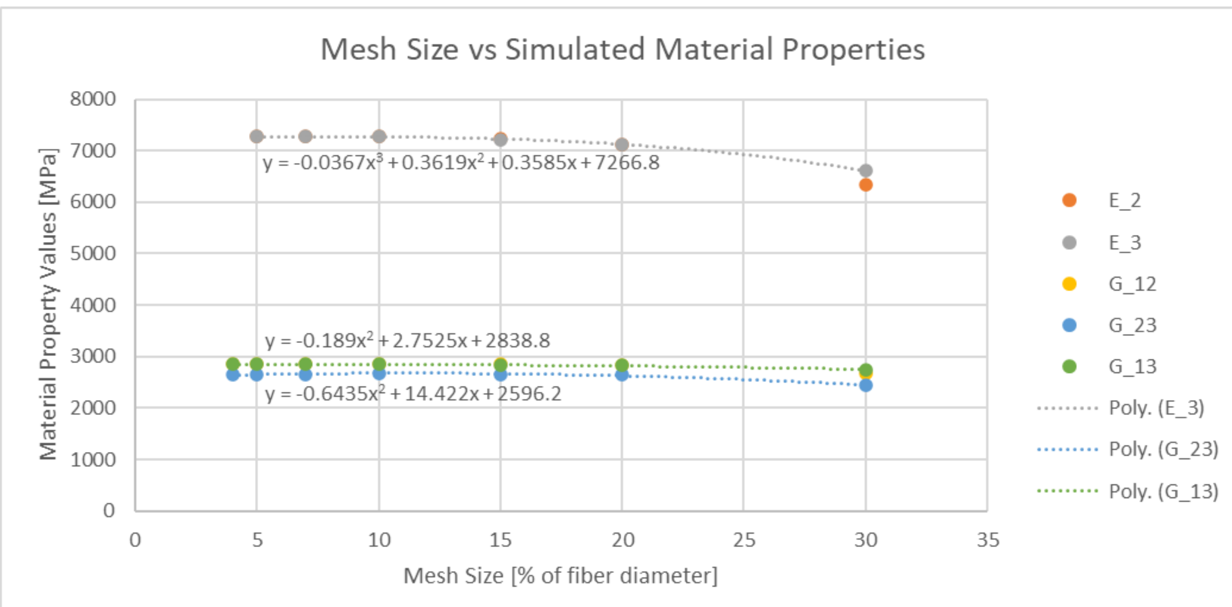

Figure 12

Volume / Mass Fraction vs Material Properties, Uniform Arrangement

Each material property increases as the volume fraction of the fiber increases because the fiber axial and in-plane Young's moduli are greater than that of the ATSP material. The transverse Poisson's ratio of the fiber is similar to the ATSP material Poisson's ratio, so the relationship between the volume fraction and the longitudinal elastic modulus E1 as shown in Figure 13 is approximately linear. The other material properties, however, have a different growth pattern with increases in volume fraction. Each plot is paired with a formula-based model that quantifies the relationship between the material property and volume fraction. This model can be used to perform cost-benefit analysis in the consideration of different volume fractions as needed.

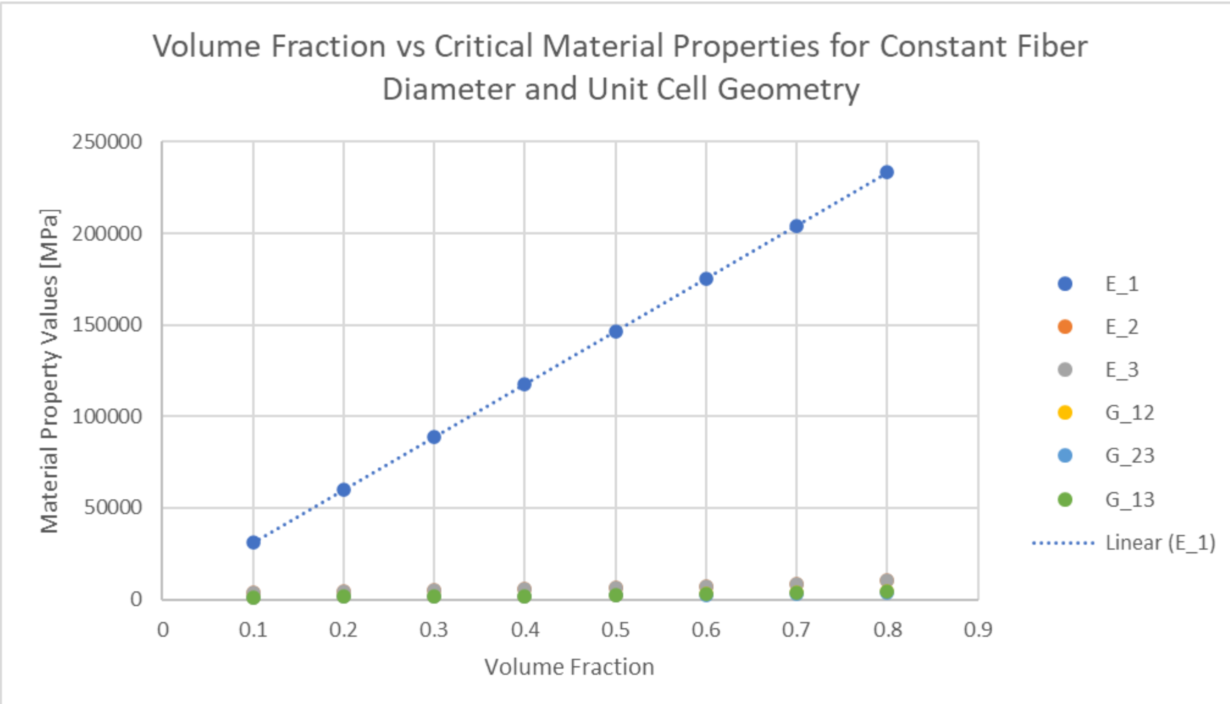

Figure 13

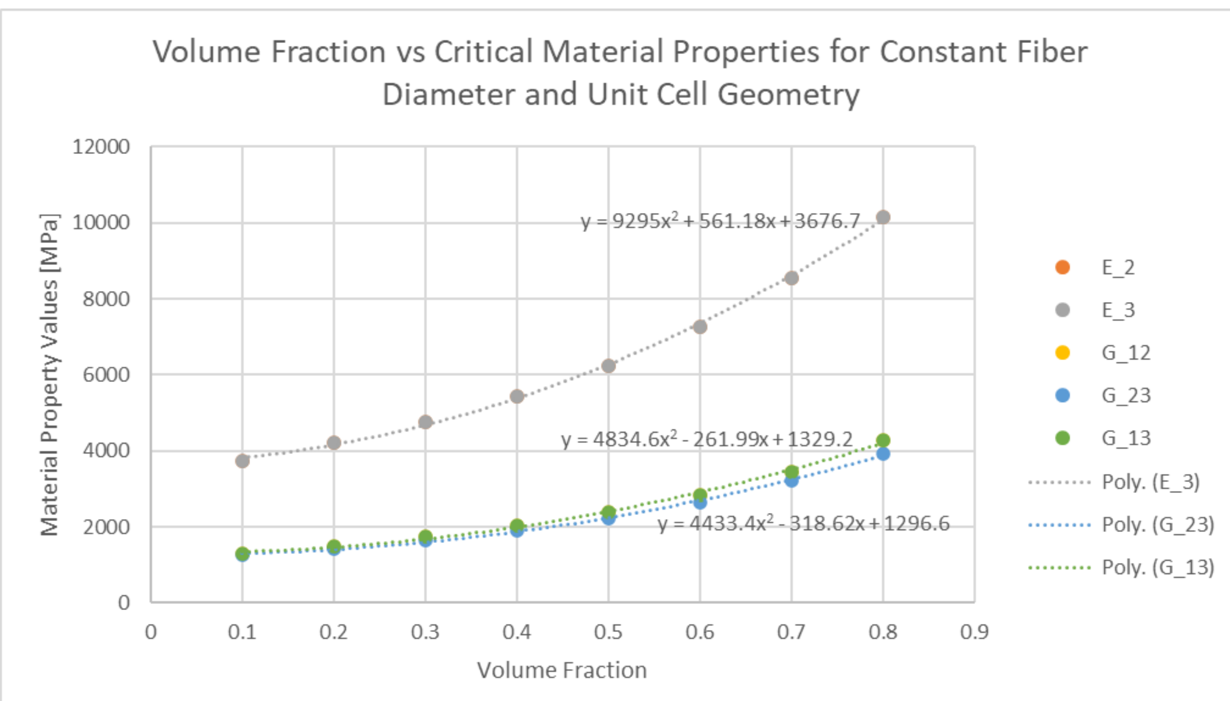

Figure 14

Each volume fraction also corresponds to a mass fraction, but mass fraction has a slightly different relationship to material properties due to the relationship between mass fraction, volume fraction and density. Figures 15 and 16 below show the same material property trends but as a result of changing mass fraction.

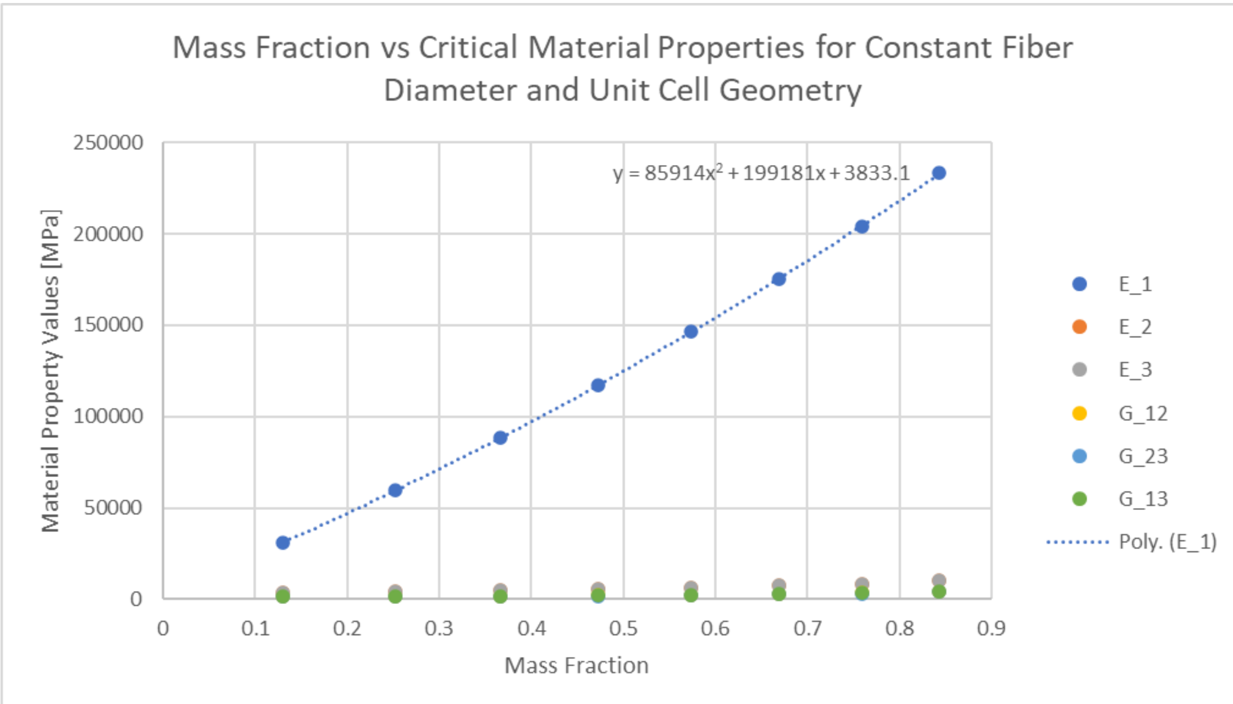

Figure 15

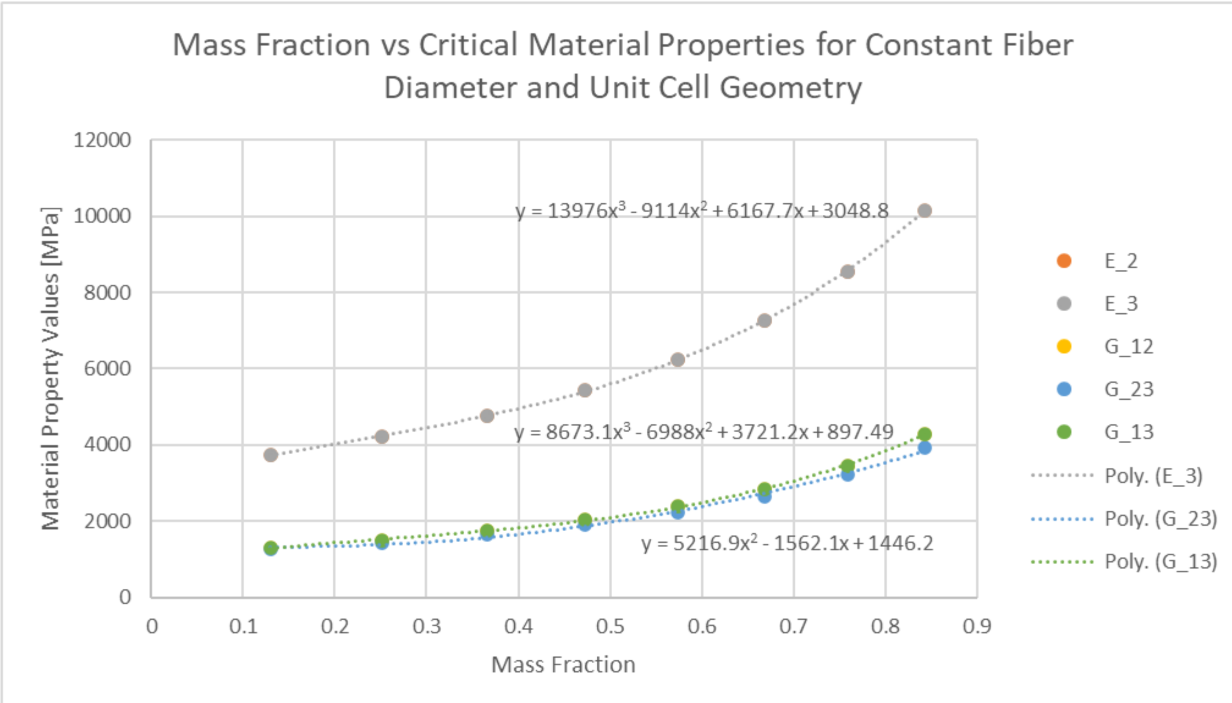

Figure 16

Volume / Mass Fraction vs Material Properties, Random Arrangement

The manufacturing process may generate a composite with random fiber arrangements rather than uniform as assumed in the above simulation. This simulation repeats the volume fraction vs material properties simulation for randomized structure iterations similar to the cell shown in Figure 3. Since random arrangement does not have a specified structure but rather several different possibilities, I generated results for 3 different random iterations and plotted the average of these for each material property. This average can be compared to the Uniform results and the standard deviation gives an idea of variation and accuracy. As seen in Figures 17 and 18, the random arrangement simulation yields similar material property vs volume fraction trends to the uniform results, but the values vary significantly in percent difference shown by Figures 21 and 22.

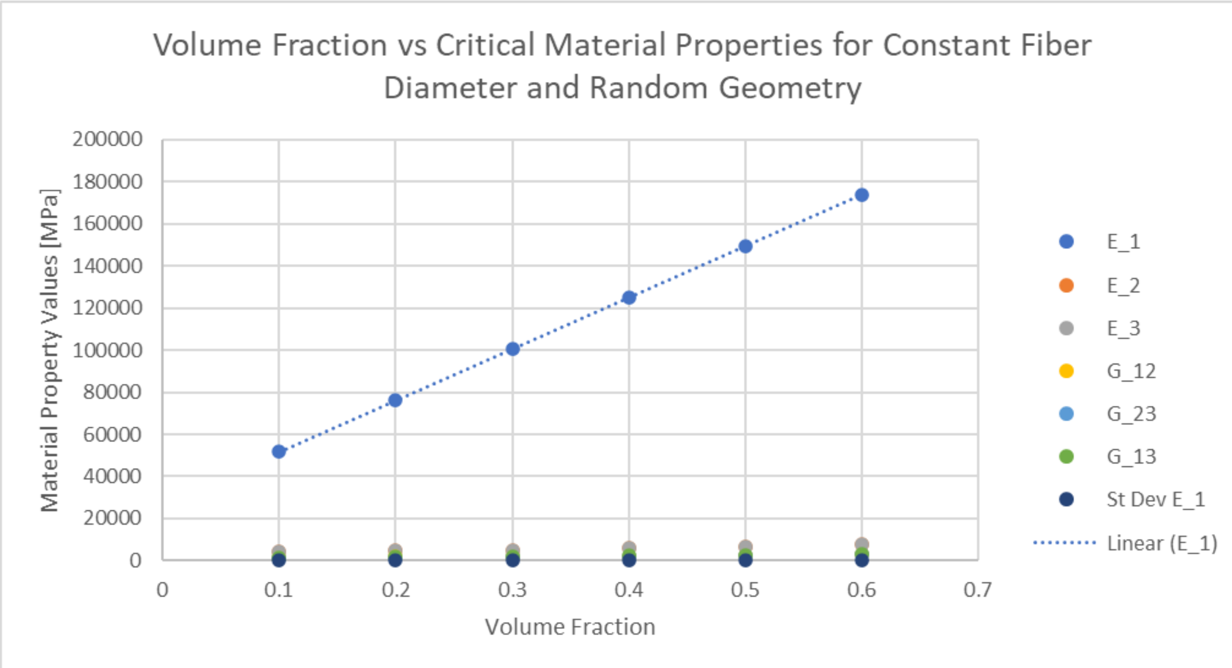

Figure 17

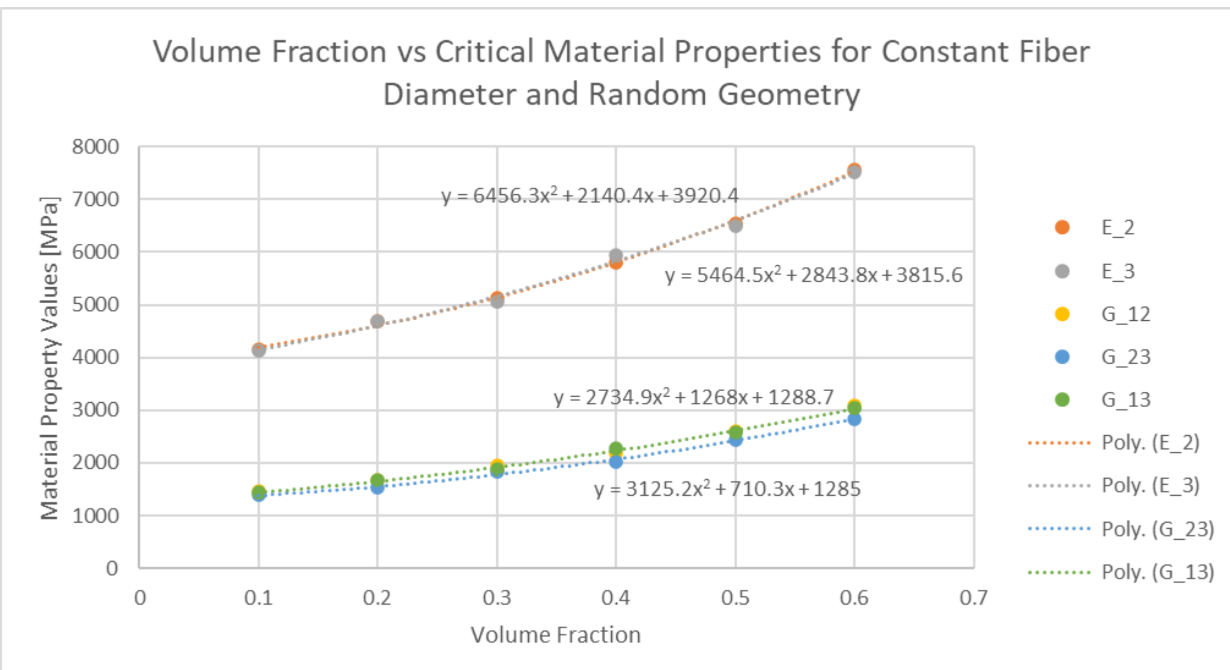

Figure 18

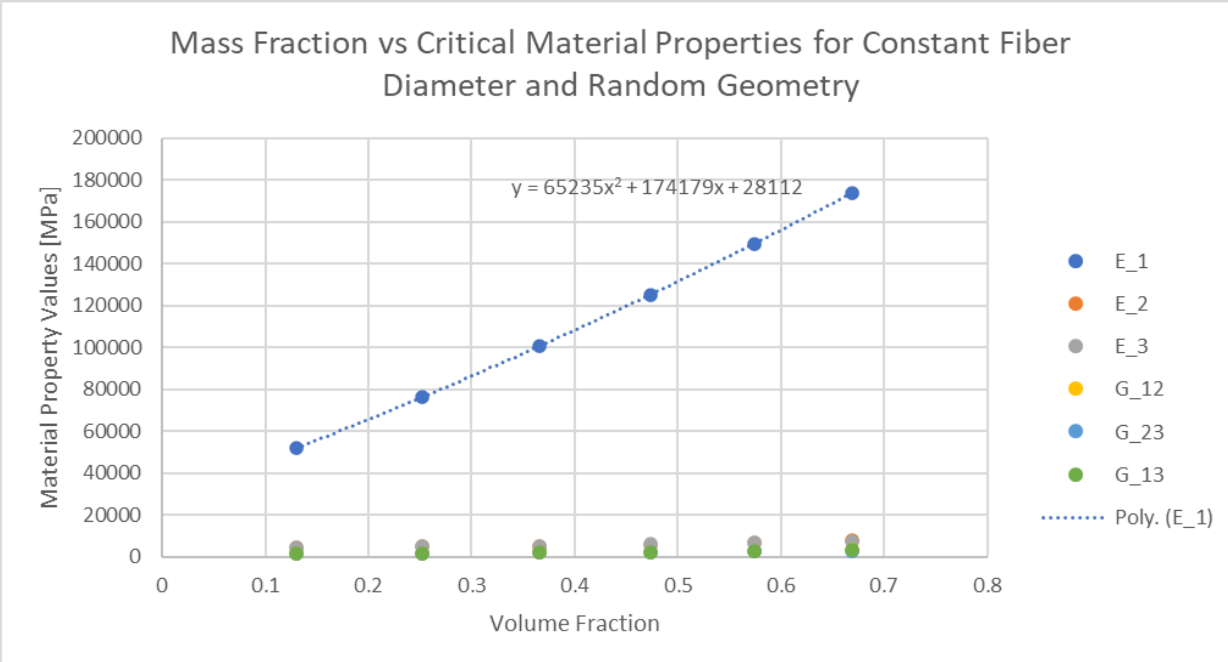

Figure 19

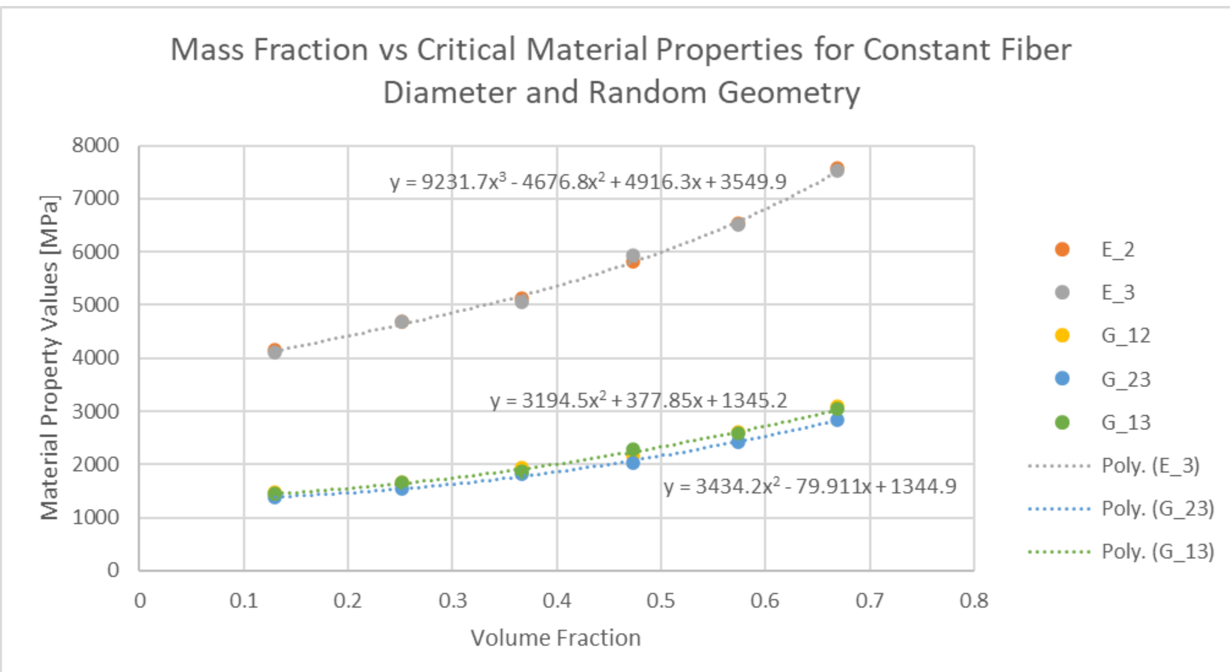

Figure 20

The random arrangement simulation yields consistently higher results, but the difference between the random and uniform results decreases as the volume fraction increases. This is likely due to the fact that there are fewer possible random configurations of the fiber as volume fraction increases. Figures 21 and 22 show this trend by plotting the percent difference between the random and uniform arrangement results vs corresponding volume fraction.

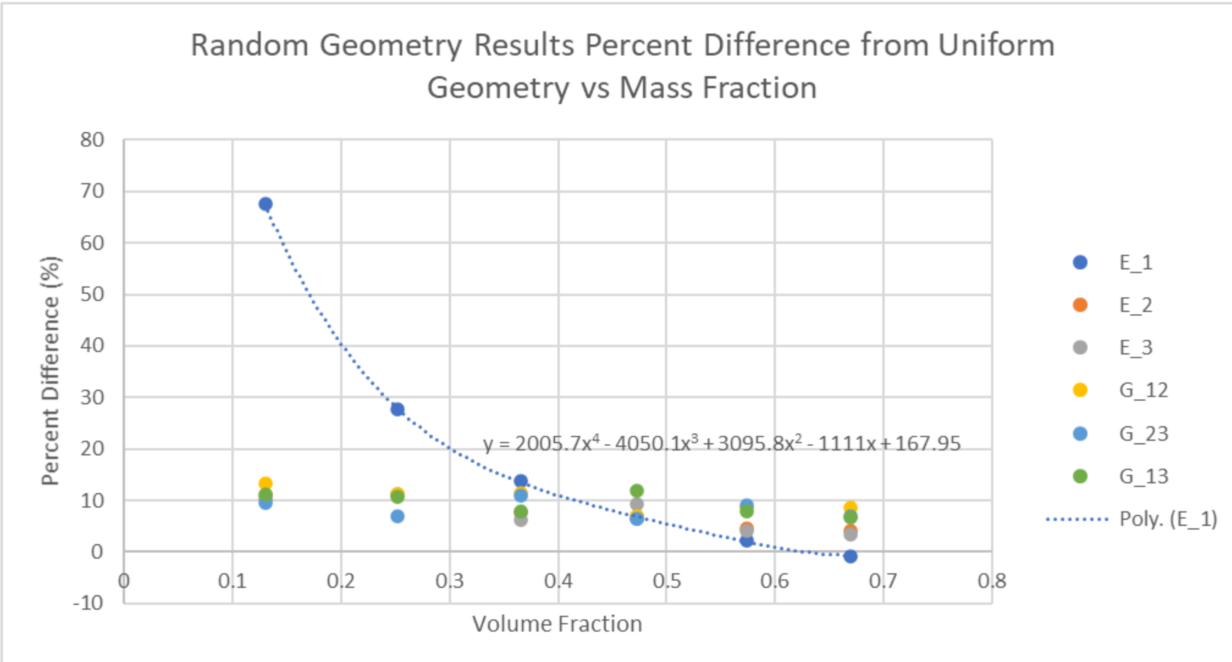

Figure 21

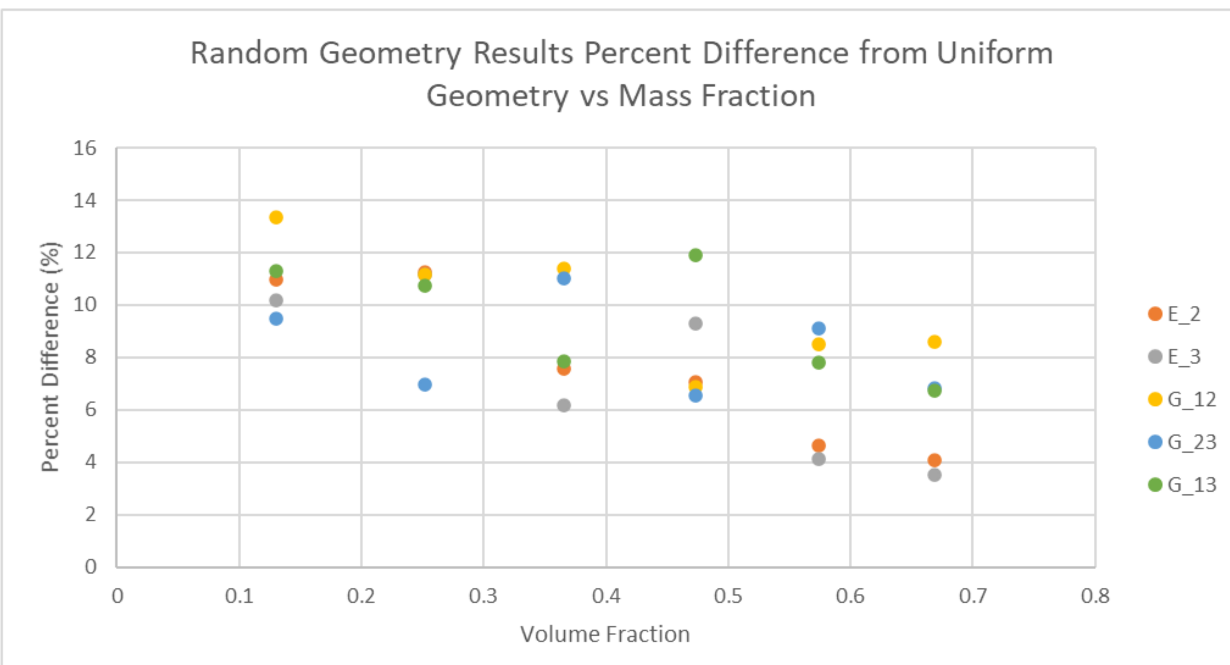

Figure 22

The high standard deviations in the random arrangement simulation and the large variation between the uniform and random results indicate that the random results may not be highly accurate. Standard deviation can be decreased by increasing the sample size, which would require automation of the data collection within the simulation in order to gather results for several iterations. A larger delta would likely decrease standard deviation and the percent difference from the uniform results. This table shows that as delta increases, the sample size necessary for an accurate evaluation decreases.

Table 1. Window sizes and corresponding numbers of samples

Window size δ	3	6	12	24	48
Number of samples	300	200	100	50	20

Using these guidelines, this random arrangement simulation should be performed again at a high delta value with the appropriate corresponding number of samples. This should create small variation and results comparable to the uniform analysis.

Recommended Next Steps

Our composite should be predictable and have consistent material properties, so the high variation seen between iterations of random arrangements must be addressed. Inconsistent properties in manufactured composites can lead to stress failure. We know that a larger delta will likely decrease variation, so any manufactured parts or samples of the composite must have a delta value that ensures minimal possible variation from the predicted material properties. For this, it would be valuable to conduct a simulation that answers the following question: At what delta does variation become negligible, and are the material property results at this size significantly different from uniform geometry results?

It is possible to find this answer by repeating the random geometry simulation for a changing delta vs material properties. Abaqus allows window size to be altered, unlike Digimat. An automated simulation and data collection system must be developed in order to gather an appropriate number of sample sizes for each delta size. Volume fraction becomes a constant, but this simulation can be repeated for different volume fractions.

Differences of fiber length in relation to fiber diameter may also have a small impact on the evaluated material properties. This measurement is the aspect ratio, or ratio of fiber length to fiber diameter. An Abaqus plugin allows for changes in aspect ratio. This simulation would likely be performed at meso scale rather than micro, as fiber length can only be as long as the window allows it to be in micro scale.

At the meso scale, the evaluated two-phase carbon fiber and ATSP material may be organized into layered components or woven yarn. This adds an additional variable that may impact the material properties of the larger composite structure. Volume fraction, delta, and fiber length can be re-evaluated for these meso-scale structures to evaluate if the structures improve or are a detriment to the measured properties of the two-phase composite.

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