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Validation of a finite element method for simulation of components produced by continuous carbon fiber reinforced additive manufacturing

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ABSTRACT

In this research, a method is examined by which the behavior of continuous carbon fiber reinforced additive manufacturing may be simulated using Finite Element Analysis. This technique is used in a simulated tensile test experiment in which the findings are compared to results determined from theoretical calculations according to the Rule of Mixtures method and from existing mechanical testing results. Four different fiber reinforcement configurations are examined with fiber volume fractions ranging from 4% to 32%. It was found that for fiber volume fractions of 11%, the simulation results closely match those predicted theoretically by the Rule of Mixtures as well as the mechanical testing results published in existing research. Lower fiber volume fractions near 4% yield less accurate results, with a 20% error due to the fact that the anisotropic behavior of the polymer matrix is the dominant material trait. Simulation of higher volume fractions near 32% closely approximate theoretical predictions, however neither the theoretical results nor the simulation results accurately reflect real world mechanical testing, indicating that nonideal condition factors such as the effect of micro-voids between the start and end of the fiber reinforcements play a significant role in the overall strength of the material. Thus, for fiber volume fractions near 11%, this simulation method can accurately be used to predict the behavior of end-use components, but more study must be done to increase simulation accuracy in low and high fiber volume fractions.

KEYWORDS

Finite element analysis; additive manufacturing; Markforged®; continuous; carbon fiber reinforced; rule of mixtures

1. Introduction

1.1. Introduction to carbon fiber reinforced additive manufacturing

Additive Manufacturing (AM) has long been heralded as an ideal manufacturing method for concept prototyping or low-volume production of nonloadbearing components. Popular polymer AM methods including Fused Deposition Modeling (FDM) and Stereolithography (SLA) form components using layer-by-layer addition of a polymer matrix [1, 2], feature low tooling costs [2], and are capable of producing incredibly complex geometry when compared to other plastics manufacturing methods such as injection molding [3]. This manufacturing method however has been shown to be unsuitable for end-use applications requiring strength or durability as AM components generally display significantly inferior mechanical properties when compared to non-AM methods [1].

Although traditional AM methods do tend to result in decreased mechanical properties, materials innovations in recent years have pushed to make up for this deficit in unique ways. The addition of chopped fiber reinforcements in AM material for the FDM process has been shown to significantly improve the tensile strength and Young's modulus of the AM components without modifying the FDM printing process [3]. These chopped fibers can be glass, carbon, or other fibers [3]. Chopped fiber additions to the polymer material matrix substantially improve the stiffness and tensile strength of AM components.

In one study performed by Ning et al., the strength increase associated with chopped fiber additions is examined through mechanical testing. ASTM tensile specimens were produced by FDM AM [4]. The feed-stock material used in this study was chopped carbon fiber reinforced ABS thermoplastic custom manufactured to varying fiber weight fractions ranging from 3-15 wt%. Through tensile and flexural tests, it was found that, depending on the weight fraction of CF



Figure 1. Top and side views of ASTM D638 Type 1 CCFRAM tensile specimen. (a) blue color denoting continuous carbon fiber reinforcement strands. (b) Top view (i) denoting number of rings, side view (ii) denoting number of layers. (c) Developed using Markforged Eiger[®] slicing software.

added, the tensile strength and Young's Modulus of the specimen could be increased up to 30.5 wt%, although the trend was not linear and maximum strength was achieved at 7.5 wt% carbon fiber [4]. CF additions up to 10 wt% were observed to result in significant porosity within the material which negatively affected the material performance. In this study, it was also observed that the primary mode of failure was by fiber pullout, and thus the fiber reinforcements failed at the bond interface between the fiber and the plastic rather than by failure through the fiber [4]. This means that the full advantage of the fiber strength was not utilized as the bond failed before the fiber.

While chopped fiber additions to AM materials do improve performance of AM components, a new technology has recently been developed which provides strength in FDM components close to that of aluminum [5]. Continuous Carbon Fiber Reinforced Additive Manufacturing (CCFRAM) uses dual extruders to print both a polymer matrix and continuous fiber reinforcement strands [6]. A layer of the polymer matrix is laid down by one extruder then the fiber extruder imbeds fiber reinforcements into the polymer matrix [6]. The configuration of the reinforcements is defined by the number of layers in which the fiber is imbedded as well as the number of concentric rings which are laid down as shown in Figure 1 [7]. As these reinforcement fibers are continuous, the increase in stiffness and tensile strength which results from imbedding these fibers in the polymer matrix is significantly greater than that which results from chopped fiber additions. Thus, CCFRAM processes offer extraordinary potential for use in low volume production of components requiring high strengths.

The reinforcement potential of continuous carbon fibers in additive manufacturing was analyzed by Fan et al. [8] This researched aimed to address a gap in existing research concerning the failure mode of continuous carbon fiber. Continuous fibers were incorporated into a custom filament and tensile and bending

test samples were printed. Through mechanical testing and analysis of the fracture surface the interfacial bonding potential of the continuous fibers and the polymer matrix was studied. It was found that the effectiveness of the fiber reinforcements was highly dependent on the degree to which the polymer matrix infiltrates and engulfs the fiber reinforcements, as poor fiber-polymer contact reduced the load transfer potential and caused fiber failure by pull-out rather than by fiber tear [8]. Proper infiltration leads to what was termed a "barrier effect" to crack propagation. It was found that amount of infiltration was improved by increasing the nozzle temperature when printing [8].

Because fiber-polymer contact is so critical to the overall performance of the composite, another means of continuous fiber reinforcement was developed which uses a dual extrusion process to implant individual continuous fibers within the polymer matrix. This method was first introduced to the market by Markforged[®] and uses a secondary extruder to iron in and precisely place continuous fibers. This material was studied by Mohammadizadeh et al., with varying fiber materials, infill patterns, and fiber volume fractions studied. Through tensile, fatigue, and creep analysis, it was found that continuous fiber reinforcement yielded improved mechanical properties, with higher fiber volume fractions yielding higher strengths. Additionally, fibers oriented unidirectionally with the loading direction demonstrated superior strength. Overall, Mohammadizadeh et al. concluded this manufacturing method was a promising alternative to conventional polymer and metal processing for a variety of prominent industries.

1.2. Experimental validation of mathematical models for CCFRAM material properties

As CCFRAM components offer such significant advantages for end-use applications, the ability to accurately predict the strengths and behaviors of different reinforcement configurations is essential. Finite

Table 1. Theoretically determined modulus of elasticity compared to mechanical testing results [13].

Sample configuration	$E_{\text{Theoretical}}$	$E_{\text{Experimental}}$	% Error
1R 6L	2.22	2.152	3%
1R 18L	5.79	5.83	1%
3R 6L	5.83	6.20	6%
3R 18L	16.61	10.35	60%

Element Analysis (FEA) is a method which is commonly used in general engineering practice to predict the response of components to given loading conditions. However, the process of simulating the behavior of AM components, whether it be CCFRAM or unreinforced AM, is difficult due to the nature of the additive manufacturing process. The layer by layer addition of filament material results in strengths which differ by deposition orientation [9], infill parameters, layer thickness, and printing speed [10]. Additionally, micro voids and porosity can occur due to imperfections in the printing process which make material properties hard to predict [11, 12]. Thus, care should be taken in developing a method for simulating the behavior of AM materials which accurately simulate real-world conditions.

Mechanical testing of CCFRAM material properties has previously been performed in work done by Naranjo-Lozada et al., in which the tensile strength and stiffness of various CCFRAM configurations were examined experimentally through mechanical testing and compared to theoretically determined material properties using the Rule of Mixtures [13]. In the Rule of Mixtures, it is theorized that the effect of the material properties of each composite material on the overall material properties is proportional to the ratio of the total volume fraction of each composite material (ϕ) [13], as shown in Eq. (1).

$$E_{\text{predicted}} = \phi_1 E_1 + \phi_2 E_2 + \dots + \phi_x E_x \quad (1)$$

It was shown in this study that the theoretical tensile behavior of CCFRAM composites determined according to the Rule of Mixtures accurately predicted the physical results determined through tensile testing within 3% to 10% difference for carbon fractions under 15%, however the percent error does increase significantly for volume fractions over 15% [13]. Selected results from work performed by Naranjo-Lozada et al. are shown in Table 1, in which the mechanical tensile test results have been compared to theoretical results obtained using the Rule of Mixtures [13]. The fiber reinforcement conditions are reported based on the number of reinforcement rings and reinforcement layers, with the lowest carbon fiber

reinforcement (CFR) volume fraction containing 6 layers of CFR and only 1 reinforcement ring [13].

The effectiveness of the Rule of Mixtures has also been examined and verified through research performed by Ghebretinsae et al.[2]. Thus, it has been determined through real world mechanical testing that the Rule of Mixtures is a reliable way to predict the behavior of CCFRAM materials for volume fractions under 15% fiber reinforcement [2, 13]. However, in samples containing higher carbon reinforcement content the model's reliability decreases substantially [13].

1.3. Research focus and statement of purpose

As the Rule of Mixtures has been shown to be a reliable method for approximating the behavior of a moderate volume fraction CCFRAM component undergoing tensile loading, this theoretical approximation method could potentially be combined with FEA technique to develop a way to accurately simulate the behavior of CCFRAM components for design or optimization purposes. This research aims to develop just such a process. In this research, the solid model of a CCFRAM component consisting of two bodies will be analyzed. One body represents the polymer matrix and the other represents the reinforcement fiber. The infill and reinforcement fibers will be modeled according to the form determined within the slicer software. FEA will then be performed on that model, and comparison will be made between the FEA results and results determined from theoretical calculations as well as from mechanical testing obtained through prior research. This research will build upon results obtained by Naranjo et al., and the theoretical results obtained from this work will be compared to FEA simulation results.

This research will specifically address the FEA simulation of CCFRAM components produced by the Markforged® line of commercially available CCFRAM capable 3D printers, specifically the Mark II® 3D printer. The properties of each material are obtained from published material datasheets and existing research [2, 5]. Orthotropic material properties of continuous carbon fiber reinforcement filaments are determined based on research performed on Markforged® proprietary carbon reinforcement material [2, 14]. Nylon material properties were determined from the Markforged® published material data sheet [5]. A tensile specimen will be examined using finite element analysis to determine how closely its simulated behavior conforms to theoretical results in order

Table 2. Tensile test sample configuration.

Configuration designation	CFR ring count	CFR layer count	CFR volume fraction	Infill %
1R 6L	1	6	4%	10%
1R 18L	1	18	11%	
3R 6L	3	6	11%	
3R 18L	3	18	32%	

to obtain a base metric which quantifies the accuracy of FEA simulations on CCFRAM composites.

1.4. Finite element analysis research practical applications

If this simulation method proves to accurately reflect results obtained through theoretical and experimental examination, it can then be effectively implemented in the design and optimization of CCFRAM components for end-use applications. The verification of structural simulation methods is crucial for the AM industry as FEA simulations are necessary for the efficient design of structural components. Additionally, accurate simulation data can be used to geometry optimization for weight and overall mass reduction. As tooling costs are minimal for AM methods, the majority of production costs lie in material and time. Reducing the overall mass of the component through topology optimization is crucial for producing quality low-cost light-weight components. Without accurate simulation data, such optimization can only be performed through prototyping and experimentation, and it is for this reason that the validation of an FEA simulation method for CCFRAM components is vital for the effective implementation of such components.

2. Materials and methods

2.1. Research procedure methodology

In order to establish FEA techniques for the prediction and simulation of CCFRAM component behavior, a simulation system should be developed which accurately aligns with both theoretical models and real world mechanical testing. In this research the tensile behavior of a CCFRAM ASTM D638 standard sample was chosen for simulation. As this research is designed to build further upon research performed in the field of reinforced AM, the simulation parameters were developed in close accordance with existing research published on the topic. A simulation model and method was selected which allowed for comparison and evaluation against results published by Naranjo-Lozada et al. [13]. The simulation set-up was developed in such a way that the simulation results

could be directly compared to previously published research.

2.2. Model Preparation

To develop a tensile specimen for examination, a specimen was modeled according to ASTM D638 Type 1 specifications for tensile testing per guideline 6.1.3 presented in the ASTM Standard Test Method for Tensile Properties of Plastics [15]. The specimen was modeled in SolidWORKS® 2019. The infill pattern was modeled based on the standard rectangular infill generated by Markforged Eiger® slicing software. To accurately model the geometry to reflect a physically printed sample, the test specimen model was imported into Eiger® and prepared for 3D printing. A 10% infill was selected to conform to testing parameters used in prior research [7, 13]. Next, the toolpath was carefully examined, and the solid model was edited based on the generated toolpath and the nozzle deposition diameter to produce a model which precisely copies the geometry of a physical sample.

A separate body was then modeled within the test sample for the reinforcement fiber. Again, the path and location of the reinforcement fiber was determined using the toolpath generated by Eiger® slicing software. Four carbon fiber reinforcement configurations were examined which matched reinforcement fiber configurations examined previously [13]. These reinforcement configurations were then examined in Markforged Eiger® slicing software and their form and infill dimensions were mimicked in the model preparation. The end result was four tensile test specimens which matched the output of the Eiger slicing software for a 3D printed CCFRAM tensile specimen of the configurations shown in Table 2. These tensile models were imported into ANSYS® Workbench 19.1 for simulation. Lastly, a cutting operation was performed on the model so that the gage length alone of the tensile specimen could be examined. The final model on the tensile specimen for use in the ANSYS® simulation is shown in Figure 2, with the translucent material representing the polymer matrix, and the opaque material representing the fiber reinforcement filament.

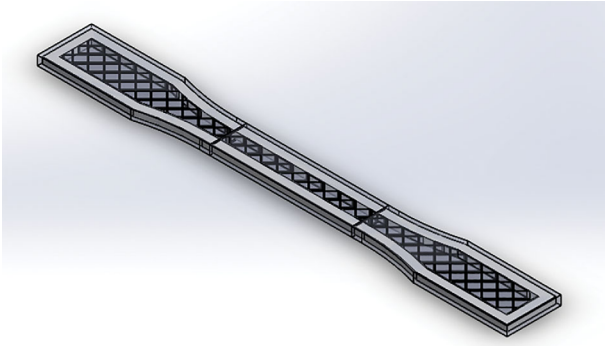


Figure 2. ASTM D638 Type 1 tensile specimen configuration. (a) Translucent material denoting polymer FDM matrix, opaque material denoting continuous fiber reinforcements. (b) Rectangular 10% infill pattern shown. (c) Test specimen split along gage length boundaries for isolated analysis.

2.3. Development of material property datasets

To develop an accurate simulation setup, it was important to develop material property datasets which were consistent with the actual behavior of the AM materials. To do this, material properties from published datasheets from Markforged were compiled within ANSYS [5]. An orthotopically elastic material was created for the continuous carbon fiber material, with directional material properties obtained from research performed by Ghebretinsae et al. [2]. The nylon material was defined from published material properties released by Markforged for their proprietary nylon blend [5].

2.4. Ansys® simulation setup

Static structural analysis was performed within ANSYS® Workbench to simulate the tensile response of the sample. A linear solution was first obtained for initial simulation analysis. Following this, a nonlinear solution was obtained to closer mimic the tensile test process. In ANSYS® Workbench, four static structural analysis systems were created in the project schematic. The SolidWORKS® assembly was imported into the Geometry tab, and material properties were assigned. Within ANSYS® Mechanical, the model was meshed using program defined element order with a medium starting mesh size. A force of 1600 N was applied to one end of the test sample, and a fixed support was applied to the other as shown in Figure 3. This figure specifically indicates the loading conditions of the model as well as delineates the isolated gage length (green) which was selected as the solution area. Resolving through the cross section of an ASTM D638 Type 1 tensile specimen as shown in Eq. (2), a 1600 N force will result in a stress of 38.5 MPa, which

is well below the established yield strength of AM nylon matrix material according to the Markforged® material data sheet [5, 15]. A sample calculation for resulting stress determination is shown.

$$\sigma = \frac{F}{A_c} \quad (2)$$

$$\sigma = \frac{F}{A_c} = \frac{1600.0 \text{ N}}{0.00320 \text{ m} \times 0.0130 \text{ m}} = 38.5 \text{ MPa}$$

A directional deformation solution object was added along the axial direction, with the gage length body selected as the target geometry so that the change in length of the test sample gage length could be determined. A convergence analysis was added to the solution object to determine the converged solution of the simulation. The convergence criteria was set to be a 0.1% difference. This directional deformation solution was used to calculate the strain resulting in the gage length of the sample as shown in Eq. (3). The resulting strain divided by the stress applied to the gauge length of the sample provided the simulated modulus of elasticity of the CCFRAM composite as shown in Eq. (4).

$$\epsilon = \frac{\Delta l}{l_0} \quad (3)$$

$$E = \frac{\sigma}{\epsilon} = \frac{F/A_c}{\Delta l/l_0} = \frac{F \cdot l_0}{A_c \cdot \Delta l} \quad (4)$$

This procedure was followed for the linear static structural analysis first, then the solution parameters were modified to conduct the nonlinear analysis. The nonlinear simulation was time-step driven, solved in increments of 10 μ s. The percent difference between the linear and nonlinear simulation results was calculated to determine the degree to which the model behaved linearly. This simulated modulus of elasticity was then compared to the theoretical modulus proposed by the Rule of Mixtures. The percent error between the simulated results compared to the theoretical and mechanical tensile test results was computed and used to analyze the accuracy of the proposed simulation method.

3. Results

3.1. Ansys® elongation results and data processing

Simulations performed on each tensile specimen resulted in directional elongation values for the sample as shown in Figure 4. As the simulation results were computed by the software relative to the fixed support, the difference between the maximum

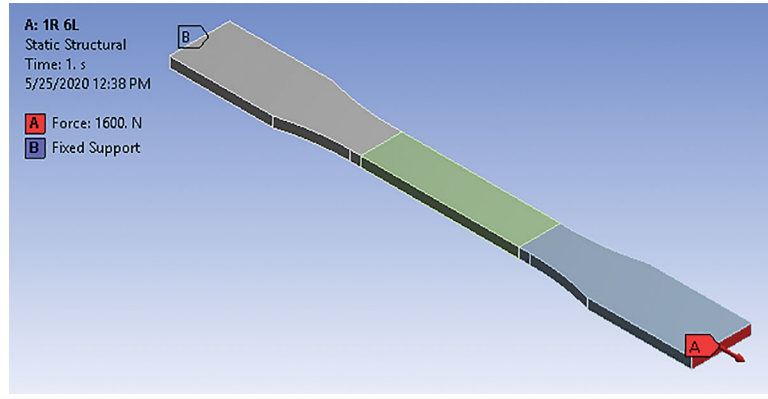


Figure 3. ANSYS® 19.1 simulation loading and support conditions. (a) Fixed support applied to one end of specimen and tensile force applied to opposing end to simulate tensile test conditions. (b) 1600N force resolved through ASTM D638 Type 1 cross section induces 38.5 MPa internal stress. (c) Gage length (green body) defined as the solution area

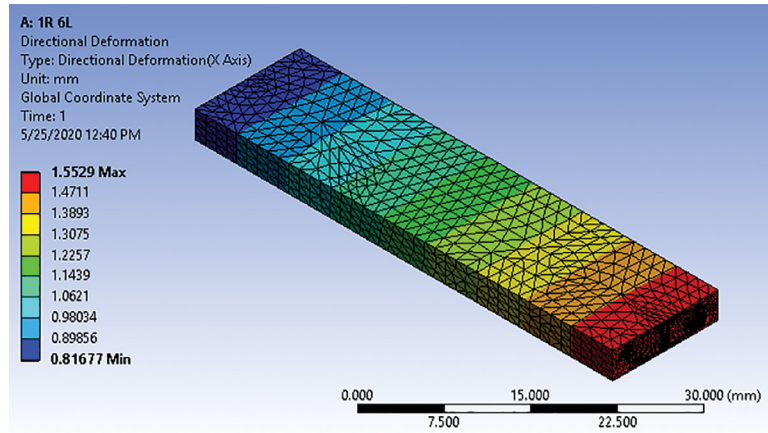


Figure 4. Directional deformation simulation results for the 1R 6L configuration. Test sample configuration featuring 1 ring of continuous fiber reinforcement in 6 layers. (b) ANSYS® 19.1 Simulation directional deformation result evaluated from origin at fixed support. Total Elongation is thus the difference between the maximum and minimum elongation.

directional elongation and the minimum directional elongation was computed to obtain the directional elongation of the gage length alone. The calculated elongation of the sample due to the applied stress was used to determine resulting strain as described in Eq. (2). This resulting strain was then used in conjunction with the applied stress to simulate the modulus of elasticity of the sample as described in Eq. (4). Sample calculations are shown here for the determination of resulting strain and the modulus of elasticity of the first test specimen, featuring 1 ring and 6 layers of CFR (1R 6L).

$$\epsilon = \frac{\Delta l}{l_0} = \frac{1.5529 \text{ mm} - 0.81677 \text{ mm}}{50.0 \text{ mm}} = 0.0147$$

$$E = \frac{\sigma}{\epsilon} = \frac{38.5 \text{ MPa}}{0.0147 \text{ mm/mm}} = 2.58 \text{ GPa}$$

This process was repeated for each sample configuration, for both the linear and nonlinear analysis solutions. In this manner, the strain and the simulated

modulus of elasticity was obtained for each configuration. These are reported for comparison in Table 3, in which the linear and nonlinear results for applied stress, resulting strain, and simulated modulus of elasticity are displayed. Table 4 includes the stiffness modulus for each solution method and the percent difference between them. This allows for a better understanding of the differences in sample behavior between linear and nonlinear simulation methods.

4. Discussion

4.1. Comparison between linear and nonlinear solution methods

The linear simulation analysis was compared with the nonlinear analysis in table. Here, it can be seen how the two methods compare at different fiber reinforcement configurations and volume fractions. From the table, the percent difference between the two solutions was observed to increase with increasing CFR volume

Table 3. Linear and nonlinear analysis tensile simulation results.

	Sample configuration	Applied stress (MPa)	Resulting strain (mm/mm)	E _{Simulated} (GPa)
Linear	1R 6 L	38.5	0.0147	2.62
	1R 18 L		0.00647	5.95
	3R 6 L		0.00606	6.35
	3R 18 L		0.00233	16.5
Nonlinear	1R 6 L	38.5	0.0147	2.63
	1R 18 L		0.00657	5.86
	3R 6 L		0.00613	6.28
	3R 18 L		0.00243	15.9

Table 4. Comparison between linear and nonlinear solution.

Sample configuration	Linear solution E _{Simulated} (GPa)	Nonlinear solution E _{Simulated} (GPa)	% Difference
1R 6 L	2.62	2.63	0.345
1R 18 L	5.95	5.86	1.53
3R 6 L	6.35	6.28	1.15
3R 18 L	16.5	15.9	4.30

fraction. At very low CFR volume fractions, the simulation sample behaved similarly for both the linear and nonlinear scenarios. As the volume fraction increased however, the difference between simulation methods increased, as the nonlinear solution more accurately approximated the behavior of the tensile specimen. Nonetheless, as a whole it can be observed that the solution to the simulation varied only slightly between the two methods, indicating that linear behavior dominated the deformation of the sample. This is to be expected as the specimen was specifically tested within the linear elastic region of the sample deformation.

4.2. FEA simulation results compared to existing research dataset

To validate the ability of the proposed simulation methodology to accurately predict the behavior of the CCFR AM tensile specimen, and to determine whether the model the results obtained from the simulation methodology was compared to theoretically predicted and physically determined results obtained in previous work by Naranjo-Lozada et al. [13]. The percent error between the simulation methodology and experimental and theoretical results was determined to quantify the degree to which the simulation reflected previous experimentation. A comparison between simulated and theoretical results is shown in Table 5, and the comparison between the simulated and mechanical testing results is shown in Table 6. Both the linear and nonlinear solution methods were compared.

4.3. Percent difference comparison between research results and prior research

From the results shown in Table 5, it can be seen that the simulated results closely match those predicted by

Table 5. Simulated modulus of elasticity compared to theoretical results.

	Sample configuration	CFR Vol. fraction	E _{Simulated}	E _{Theoretical}	% Error
Linear	1R 6 L	4%	2.62	2.22	17.9
	1R 18 L	11%	5.95	5.79	2.78
	3R 6 L	11%	6.35	5.83	8.99
	3R 18 L	32%	16.5	16.6	0.35
Nonlinear	1R 6 L	4%	2.63	2.22	18.3
	1R 18 L	11%	5.86	5.79	1.22
	3R 6 L	11%	6.28	5.83	7.75
	3R 18 L	32%	15.86	16.6	4.45

the Rule of Mixtures for higher CFR volume fractions. The simulated modulus of elasticity remains under 9% error for all configurations with a CFR volume fraction at or above 11%. However, for very low CFR volume fractions, such as the 1 R 6 L configuration which contains a volume fraction of 4% CFR, the percent difference is much higher, near 18%. When comparing the linear and nonlinear results with theoretical values, no consistent trend can be observed which indicates which case better reflects the theoretical calculations. The percent error remains quite consistent, with the exception of the higher volume fraction at 32% CFR. In this case, the linear simulation results clearly better reflected the theoretical calculations, with the nonlinear simulation differing by 4.1% more than the linear simulation which very closely matched the theoretical prediction.

In Table 6, a similar trend can be observed between the simulation results and prior research [13]. The simulation results quite closely matched recorded strengths obtained in work done by Naranjo-Lozada et al. for CFR volume fractions near 11% [13]. For both linear and nonlinear solutions, the maximum discrepancy observed between the recorded strengths and the simulation strengths was under 2.5% error at 11% CFR. For very low CFR volume fractions however the comparison very closely resembles the results from the comparison with theoretical strengths. Higher percent error was observed

Table 6. Simulated modulus of elasticity compared to prior mechanical tensile test [13] results.

	Sample configuration	CFR Vol. fraction	E _{Simulated}	E _{Mechanical}	% Error
Linear	1R 6 L	4%	2.62	2.15	21.7
	1R 18 L	11%	5.95	5.83	2.07
	3R 6 L	11%	6.35	6.20	2.49
	3R 18 L	32%	16.5	10.4	59.1
Nonlinear	1R 6 L	4%	2.63	2.15	22.2
	1R 18 L	11%	5.86	5.83	0.53
	3R 6 L	11%	6.28	6.20	1.32
	3R 18 L	32%	15.86	10.4	52.5

in these cases for both linear and nonlinear solutions. Additionally, the percent error between the simulated results and the recorded strengths was significantly larger for the higher volume fraction measured. Percent error up to 60% was observed.

4.4. Observed effects of CFR volume fraction on FEA simulation percent difference

The observed fitment with the existing dataset, as well as the areas where the simulation deviated from the data set, can be understood by further consideration of the materials and simulation methods involved. 3D printed materials are largely dominated by anisotropic material properties, which are directionally dependent due to imperfections in the polymer matrix produced by air entrapment, filament orientation, and even filament color [11]. However, the data sheet for Markforged® proprietary nylon filament composition reports the polymer matrix material as if it were an isotropic material [5]. To qualify the reported isotropic material property, a footnote was included noting that properties reported in the Markforged® data sheet are highly dependent on the printing configuration [5]. Continuous fiber reinforcement material, on the other hand, is highly orthotropic in behavior and is dependent on loading orientation rather than printing conditions [2]. Thus, it is possible to accurately predict the orthotropic behavior of CFR material based on existing physical tensile testing done [2]. At low CFR volume fractions, the material properties of the overall composite are less dependent on the behavior of the reinforcement fiber and more dependent on the less predictable behavior of the 3D printed polymer matrix which by nature is anisotropic. Therefore, it can be inferred that higher CFR volume fractions yield simulation results which more closely align to theoretical predictions made using the Rule of Mixtures.

As predicted, in comparison between the simulation results and both the theoretical and mechanically recorded data sets, very low CFR volume fractions

resulted in high percent difference, while low percent error was seen as the volume fraction increased. However, as an additional aspect to consider, the mechanically recorded tensile test results obtained for the 3R 18L configuration in prior research differed substantially from the simulation results obtained from this research. This extreme percent difference is also seen between the mechanical testing results and the theoretical calculations, as shown by Naranjo-Lozada et al. [13]. As shown in Table 1, mechanical testing results obtained for the 3R 18L sample show a 60% difference when compared with theoretical predictions. In a similar manner, simulation results obtained here corroborate the work done by Naranjo-Lozada et al. in that a 54.6% difference is seen in comparison between simulated and mechanical tensile test results [13].

4.5. Effect of fiber reinforcement start point on discrepancies between physical and simulation results

Naranjo-Lozada et al. found that the location of the fiber reinforcement start point, where the extrusion process begins to embed the fiber reinforcement, highly influenced the strength of the CCFRAM component since the start point produced lower strength localized to that area due to the break in the reinforcement filament [13]. At higher CFR volume fractions, the effects of multiple start points occurring through the reinforcement multiply to yield a significantly weaker component than that which is predicted via theoretical calculations, as theoretical calculations consider the perfect or ideal condition. This conclusion is corroborated by work performed by Van Der Klift et al., where the number of micro voids between the start and end of the reinforcement material rings increase as the number of layers increases [6] and thus more reinforcement layers lead to higher deviation from the ideal condition. As the simulation method developed in this research neither considers the start and end points of the fiber reinforcement nor the existence of micro voids, but rather considered it to be a perfect unified ring of reinforcement, it is very understandable that at high CFR volume fractions the simulation results would fit the theoretical calculations rather than the mechanically recorded behavior.

4.6. Final observations regarding the application of FEA simulations in CCFRAM design

As the simulation results for 11% CFR volume fractions closely match the properties established via

theoretical and physical examination, it can be concluded that this simulation method can be used to approximate the behavior of similar components produced by CCFRAM for end-use applications. When designing components to be produced by CCFRAM methods, these components may be simulated in tensile loading conditions with reasonable confidence for fiber volume fractions around 11%. Simulation of components with low volume fractions near 4% or higher volume fractions near 32%, however, should be further studied to increase the degree to which the simulation solution matches real world tensile data.

Finally, because this simulation method for CCFRAM composite components closely matches the mechanical tensile testing and theoretical behavior of such composites at volume fractions near 11%, it can be applied with confidence to the design and optimization of end-use components intended for tensile loading applications. CCFRAM components offer significant potential for low volume custom production of end use components. However, until now, validation of such components rested solely on either rough simulation estimates or experimental validation during prototyping. Now however, using the method validated in this research, structural simulations can be performed accurately on components within a defined range of continuous fiber reinforcement parameters. Additionally, autonomous optimization methods could use these simulation results to optimize components for even greater weight reduction, although the use of such optimization simulation methods must be examined further. Thus, it is clear that this FEA simulation validation is of great importance to the design and testing of end use CCFRAM components of applicable configurations.

5. Conclusions

A simulation method is proposed in which Finite Element Analysis is applied to Continuous Carbon Fiber Reinforced Additive Manufacturing (CCFRAM). In this research, a tensile test specimen model was prepared which mimics the configuration of a CCFRAM printed component and tensile simulations were performed on the model. The test specimen model was then used in a simulated tensile test experiment to determine the simulated overall modulus of elasticity of the sample. The simulated material properties were compared with those previously determined using the Rule of Mixtures and through existing mechanical tensile testing. It was found that the simulation results closely matched the theoretical

results predicted by the Rule of Mixtures. Except for very low fiber reinforcement volume fractions, very low percent differences were seen to occur in simulation samples. Lower fiber reinforcement volume fractions were seen to match theoretical and physical results to a lesser extent due to the higher influence of the printing configuration-dependent polymer matrix on the overall material property. Additionally, it was seen that both theoretical and simulated material properties differ substantially from the mechanical tensile test results at much higher fiber volume fractions due to micro void multiplication as the number of reinforcement layers increases. Overall, the simulation method proved to be effective for median fiber reinforcement volume fractions near 11%, where the behavior of the sample was primarily driven by the orthotropic fiber reinforcement properties but not significantly affected by micro voids at the reinforcement start locations. Thus, the objective of this research is achieved and a simulation method in which the behavior of CCFRAM components is verified for fiber volume fractions near 11%. This simulation method is able to be reliably used to approximate the behavior of end-use components matching this fiber volume fraction.

Conflict of interest and authorship conformation form

Please check the following as appropriate:

- x All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.
- x This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
- x The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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Abbreviations

AM	Additive Manufacturing
CCFRAM	Continuous Carbon Fiber Reinforced Additive Manufacturing
CFR	Carbon Fiber Reinforced
FDM	Fused Deposition Modeling
FEA	Finite Element Analysis
SLA	Stereolithography

Notes on contributors

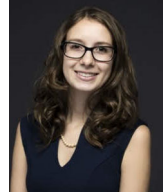


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