Development and Evaluation of Modeling Approaches for Extrusion-based Additive Manufacturing of Thermoplastics

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Development and Evaluation of Modeling Approaches for Extrusion-Based Additive Manufacturing of Thermoplastics

By Christopher Bock

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An Abstract of the Thesis Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science (in Mechanical Engineering) May 2022

This work focuses on evaluating different modeling approaches and model parameters for thermoplastic AM, with the goal of informing more efficient and effective modeling approaches. First, different modeling approaches were tested and compared to experiments. From this it was found that all three of the modeling approaches provide comparable results and provide similar results to experiments. Then one of the modeling approaches was tested on large scale geometries, and it was found that the model results matched experiments closely. Then the effect of different material properties was evaluated, this was done by performing a fractional factorial design of experiments where the factors were ±15% of the baseline material properties. From this it was found that coefficient of thermal expansion (CTE) is by far the most important material property for the simulated warpage. This test was repeated with a simulated desktop printer, simulated commercial printer and a simulated room scaled printer to evaluate if the relevant material properties change as a function of length scale; it was found that as length scale increases, conduction becomes increasingly important, but this effect was still small compared to that of CTE. Finally, the effect of the environment was evaluated by running a Latin hypercube Design of Experiments (DOE) over environmental factors; it was found that the most important effects are the bed and enclosure temperatures. It also pointed to the feasibility of using radiative heating to mitigate warpage, because as length scale increases natural convection becomes less important.
This work is significant because it leverages modeling and simulation to evaluate the effects of the different phenomena in 3D printing and points out some of the gaps in the current state of the art that are not evident from performing simple experiments or simple simulations, namely implementing a model for build plate adhesion.
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CHAPTER 1

INTRODUCTION

1.1. Background

Thermoplastic Extrusion Additive Manufacturing (TEAM) is a type of additive manufacturing that involves extruding polymer in a pattern to create the desired geometry. This process is shown in Figure 1.1 material is being extruded from a nozzle to create a linear spring using glass fiber reinforced PETg.

![Figure 1.1: Thermoplastic Extrusion Additive Manufacturing](image)

1.1.1. Additive Manufacturing

When using traditional manufacturing techniques to manufacture parts, a lot of preparation work needs to be done, which means that one off or prototype parts are costly and time consuming to make. Additive manufacturing allows for manufacturing of low volume parts or prototypes with minimal overhead from needing to manufacture specific tooling.

The lack of specialized tooling for AM means that the process is especially well suited for prototyping, where many one-off parts are created and iterated on. AM has other advantages such as allowing for extremely complex geometries, that cannot even be cast, meaning that one part can replace 50. AM not only reduces tooling costs, but also reduces expenses from assembling the component the AM part replaces. Once parts are in production there are other advantages. Such as the ability to continuously improve the parts with minimal overhead, and to have a more scalable production rate which can be increased or decreased by simply adding or removing printers.
1.1.2. Thermoplastic Extrusion Additive Manufacturing

Thermoplastic Extrusion Additive Manufacturing (TEAM) is a process where hot polymer is extruded in a pattern to create the desired part. The typical workflow from concept to production is short and is shown below in Figure 1.2.

![Figure 1.2: Workflow from design to process for TEAM](image)

This process can be quite fast. For desktop printers generally, much of the time is spent working on the CAD model itself.

1.1.3. Large Format AM

1.2. Motivations

Additive Manufacturing (AM) is a family of manufacturing processes that add material rather than remove material, typical AM processes operate on parts that typically have a build volume of less than one cubic foot. Recently AM has been applied to much larger structures, like a car [1] in a process family called Large Area Additive Manufacturing (LAAM), which is a family of processes that can take place on machines like the BAAM or the Ingersoll Masterprint. An example of LAAM is shown in Figure 1.3.
Some of the advantages of Large Area Additive Manufacturing (LAAM) is that it can be used to produce complicated shapes, has faster turnaround times, and does not rely on design specific tooling and fixtures. Therefore, LAAM is extremely well suited for prototyping, as normally the process for creating a structure would be Design $\rightarrow$ Tooling $\rightarrow$ Assembly $\rightarrow$ Complete, all these steps are labor intensive. While the same structure made with additive would be Design $\rightarrow$ Print $\rightarrow$ Complete, the only process that is labor intensive is the design step. This means that parts can be produced faster and cheaper, with even more savings compared to traditional methods seen when a low volume of parts is needed.

This said, LAAM is not without some issues. One of most prominent issues in LAAM is warpage, or process induced deviation from the intended shape. Warpage is caused by differential thermal contraction in different areas in the part, which causes stresses to develop in the part. This causes the part to deviate from the intended shape. The workflow without simulation is shown in Figure 1.4.
Figure 1.4: Workflow without process model

In this design process the part is printed and iterated on until the part is in spec, meaning that material and printer time are wasted for each unsuccessful iteration. The workflow with a predictive model is shown in Figure 1.5.

Figure 1.5 Workflow with a predictive manufacturing process model.

This predictive model allows for predicting if the part will be in spec before printing, freeing up time on expensive large-scale printers and preventing wasted material. Other advantages to using modeling are that models can be tied to optimization and allow for sensitivity analysis to be done.

1.3. Previous Work

1.3.1. Material Properties

Beads are the shape of the material extruded by the printer, in some literature filament is used instead, but this can be confused with the feedstock for desktop printers.

Duty et al. [2] characterized the properties of ABS and CF ABS on a Big Area Additive Manufacturing (BAAM) machine. It was found that there is significant anisotropy in printed CF ABS. It was also found that failure is most likely to occur at the interfaces between beads.
Duty et al. [3] reported on the mechanical properties of Carbon Fiber (CF) ABS and Glass Fiber (GF) PPS and found that with the current material processing capabilities, CF ABS is likely the best choice. However, if a higher extrusion temperature can be achieved, GF PPS could also be a contender. It was also found that at the extrusion temperature tested (i.e., 357 °C) GF PPS exhibited large amounts of micro voids. A plot of as printed and injection molded tensile strengths can be found in Figure 1.6.

![Figure 1.6: Materials evaluated for BAAM [3]. The dashed bars represent the additively manufactured properties, and the solid bars are for injection molded properties.](image)

The plot shows that there is significant degradation in the material properties of AM material when compared to injection molded properties. The degradation can be attributed to the porosity of the as-printed material.
Tekinalp et al. [4] compared the properties of molded CF ABS parts and TEAM CF ABS parts. One of the quantities of interest in this study is the effects of processing conditions on the orientation distribution of fibers in the finished part. This study found that the TEAM parts tended to have fibers oriented with the toolpath. It was also found that as the amount of fiber increases, the number of macro voids decreases but the number of micro voids increases. Micrographs are shown in Figure 1.8.
Figure 1.8 : Micrographs of injection Molded (a-d) and printed (e-h) 0%CF ABS(a,e), 10%CF ABS (b,f), 20% CF ABS (c-g), and 30% CF ABS (d-h) [4].

Heller et al.[5] used a Newtonian flow simulation to model effects of nozzle geometry and over/under extrusion on the orientation of fibers passing through the nozzle. They found the fiber orientation was mostly aligned with the flow direction in the middle and on the edges of the bead. In Colon-Quintana et al. [6] it was found that there are differences in the material properties between the exterior and interior of the bead, which were attributed to differences in mean fiber orientation between these two locations.

Cattenone et al. [7] indicated the importance of using calibrated temperature-dependent modulus and yield strength for the material model, so that the mechanical response of the material is captured throughout the range of temperatures.
1.3.2. Thermal Modeling

Process modeling of TEAM processes via finite element analysis (FEA) typically utilizes element deactivation-activation schemes to simulate the depositional process, as well as conduction, convection, and radiation heat transfer to estimate thermal evolution [7–10]. Via concurrent (i.e., fully coupled) or sequential analysis, FEA can estimate time- and temperature-dependent processes while explicitly accounting for macro-scale geometry. Figure 1.9 shows the temperature distribution from an FEA analysis during the simulated printing process.

![Temperature distribution during element activation (units: °C)](image)

Armillotta et al. [11] derived an analytical conductive heat-transfer model to describe bead temperature variations during layer deposition. The analytical model was then used to develop an analytical warpage model for 3D printed rectangles. The rectangles were made of ABS plastic and were quantified using flatness error, defined as the range of z coordinates of a point cloud taken of the top surface. This was done with a design of experiments (DOE) technique where the factors were length, width, height and layer height. The results were found to be within around 20% of experimental results.
1.3.3. Structural Modeling

1.3.4. Meshing

The structured mesh method, as shown in Figure 1.10 involves defining an initial mesh of similar (e.g., voxel) elements and then activating elements through which the extruded bead is placed via the toolpath. This method can be used regardless of whether the bead fills the voxel or not. If the bead does not fill an entire voxel, homogenization can be used to account for the un-filled voxel. In short, this method requires some post processing when accounting for partial bead fills. The method used by Cattenone [7] determines if the centroid of an element is within the marching rectangle for the element to be activated.

![Structured mesh method showing element activation.](image)

Figure 1.10: Structured mesh method showing element activation. When the centroid of an element is inside the bead section, the element is activated [7]

This method has been widely used in the literature [7, 12-16]. A potential explanation is that the method is extremely robust because it takes a mesh that has already been made by well-established meshing tools. This is also the method used in Abaqus AM [17] and Genoa [18]. This method, however, does not model the bead geometry. This approach can model a mesh made of discrete beads, by simply having the initial mesh be made of initial beads.

The unstructured meshing approach will be discussed in more detail in Chapter 4.
1.3.5. Warpage

Warpage is defined as being process induced deviation from the final shape. Since warpage results from thermal gradients caused by printing, accurate reproduction of nodal temperature evolution is critical for modeling warpage.

The literature includes multiple warpage studies. Cattenone et al. [7] studied the warpage of a simulated 3D printed linear spring and determined that small element activation steps and calibrated temperature-dependent modulus and yield strength were important to simulate warpage. Cattenone et al. [7] also found that sharp corners increased warpage in finite element modeling and in experimental results as shown in Figure 1.11.

Beyond finite element analysis, the literature includes methods to estimate, measure, and design for warpage. Armilotta et al. [11] presents an analytical theory and empirical data for the warpage of 3D printed ABS plates. Casavola et al. [19] demonstrates a method to measure the residual stresses in the layers of a 3D printed part involving measurement of a printed part, drilling a hole into the printed part’s layers, and then optically measuring the displacement field due to the creation of the hole. Schmutzler et al. [20] introduces an intermediate CAD geometry that accounts for warpage such that the final, as-printed and -warped part embodies the original design intent Figure 1.12. Some of the limitations of this method is that it does not account for residual stress in the part, which can have implications for the service loading of the parts.
Figure 1.12: As-warped geometries to be included in an intermediate CAD geometry. The intermediate CAD geometry accounts for warpage such that the final, as-printed and warped part embodies the original design intent [20].
Zhang and Chou [21] used finite element analysis to attempt to estimate the warpage of a 3D printed part and used the model to look at the effects of print direction on the final part. This model was tested on 40mm x 10 mm x 1.016 mm plate made from ABS. Numerical results from this are shown in Figure 1.13.

![Figure 1.13: Bottom surface of 3D printed specimen printed with (a) [90], (b) [0], (c) [0|90] raster pattern, long axis is 0 [21]](image)

One thing to note is the effect of print pattern, where the 0 print direction part appears to be warping about a different axis than the 90 deg part. Zhang and Chou (2008) [9] used a FEA model to look at the effects of bead width, bead height and print speed on simulated warpage of a part. It was found that print speed is the most important factor, and it is implied that the interaction of bead height and width follows in importance. This mirrors a remark from Compton et al. [22] that if the temperature of the current layer drops below the glass transition, then severe warpage is likely.
Moumen et al. [15] used finite element analysis capabilities in DigiMat AM to look at the development of warpage and residual stress in a 3D printed specimen. It was found that using the activation schemes tested there is little difference in the simulated deformation Figure 1.14.

![Figure 1.14 Warpage of part as predicted by various activation schemes (a) 100% of layer activated at once. (b) 20% of layer activated at once [15]](image-url)
This mirrors the results from [7] in that the time step tends to have a minimal effect on the development of residual stresses in the part. It was also noted that residual stresses in the part increased if the time derivative of temperature was high, and that corners are where the most warpage can be expected.

1.3.6. Bonding between Layers

Layer bonding has been simulated at relatively small length scales. Favaloro et al. [13] and Barocoio et al. [23], [24] used ABAQUS UMATHTs and UMATs to calculate weld time, degree of crystallinity, and degree of bonding at interfaces of polymer beads between polymers. An overview of some of the phenomena handled by the UMAT used is shown in Figure 1.15.

![Figure 1.15: Phenomena affecting extruded material](image)

Bellehumeur [25] performed experiments to gather data on the sintering behavior of filament during the printing process.

Coogan and Cazmer [26] created models for the bond strength between beads based on the model provided by Wool and O’Conner [27]. It was found that the model results loosely correlated with experimental results.

All the bonding models used the idea of reptation time, or the idea that as time progresses more of a polymer chain is subject to diffusion and is eligible to create bonds between filaments.
One gap is modeling the cohesive bonding behavior between filaments. This would physically model the bond surface and measure the diffusion occurring over the bond surface and use a model like Wool and O’Conner [27] to model the development of the bond over time.

1.3.7. Activation

The fused deposition process has been modeled using finite element simulation based on element activation approaches. Given that the evolution of thermally induced strains is of interest, an important question is how many elements should be activated at once? At the smallest discrete temporal step, a single element can be activated. Although mimicking the deposition processes, activation of a single element will doubtlessly increase computational costs, rendering such solutions intractable. At the other temporal boundary, all elements could be simultaneously activated. Simultaneous activation of all elements fails to faithfully replicate the deposition process. Thus, the question: How many elements should be activated simultaneously?

The literature suggests the lack of an accepted number of elements. For example, Talagani et al. [14] simultaneously activated 100% of a layer for the simulation of printing a full-scale car. Grant [16] utilized a layer-by-layer activation scheme within GENOA [18] to simulate the manufacture of tensile dogbone specimens. Instead of arbitrarily choosing the number of elements to activate, Cattenone et al. [7] systematically varied the number of activated elements by varying the activation time step, Δt, from 8 seconds to 0.03125 seconds. As shown in Figure 1.16 results from Cattenone et al. [7] indicate that the time step duration has a minimal effect on residual stresses, but a significant effect on nodal temperatures. This is shown in Figure 1.16.
1.3.8. Nozzle Flow

Xia et al. [28] explicitly modeled the printer nozzle and used a front tracking finite volume approach detailed in Unverdi and Tryggvason [29] to model the flow of polymer exiting the nozzle and the deposition of the polymer as shown in Figure 1.17.

The approach, however, has the disadvantage of being computationally impractical for larger domains. This work provides insight into the development of the bead geometry. This work was expanded in Xia et al. [30] to include solidification of the material.

Comminal et al. [31] also modeled the flow of semi molten material with a focus on final bead geometry. It was found the faster the nozzle the more cylindrical the bead, while slower nozzle speeds produced a more rectangular bead geometry.
There is also a gap in the use of flow models to inform parameters for heat transfer and mechanics models. Flow models could be used to estimate bead geometry, fiber orientation, and micro void content based on process parameters, which can be used to create material definitions for heat transfer and mechanics models.

1.4. Research Scope and Questions

After reviewing what has been done by others, four questions became apparent:

1. How should a Process-Structure-Property-Performance (PSPP) workflow be implemented for modeling macro-scale process induced deformations (warpage) in thermoplastic extrusion additive manufacturing (TEAM)

2. What are the material properties most relevant for modeling warpage?
   a. How does scale affect relevance of material properties

3. What are the environmental factors most relevant for modeling warpage?

4. How should the performance and accuracy of models be quantified?
   a. How should warpage be quantified both experimentally and in models?

Additionally, this work is primarily focused on the modeling aspects of TEAM; however, there will be some experimental work carried out to ensure the models behave correctly. The overarching goal of this thesis is not to create and validate a single model, but instead look at multiple models and modeling approaches and to interrogate how the models respond to different parameters and inputs. The goal is to establish a universal warpage modeling workflow for TEAM that can be validated and deployed into design tools, optimization, and the standard operating procedures for AM to reduce costs from failed prints and improve part quality.
CHAPTER 2

2. MODELING CONSIDERATIONS

2.1. Considerations

The modeling of Thermoplastic Extrusion Additive Manufacturing (TEAM) is a non-trivial task because it involves multiple physical phenomena at different length scales: the part is subject to heat transfer between itself and the surrounding environment, thermal contraction of material as it cools, adhesion to the print bed, and the deposition of material. A diagram showing the macro scale phenomena that a part is subject to on the print bed is shown in Figure 2.1.

Figure 2.1: Macro Scale phenomena

These phenomena can be grouped into four distinct categories: Thermal Environmental, Environmental Mechanical, Thermal Material, and Material Mechanical. These categories group the thermal and mechanical phenomena the part is subject to from the environment and from its constituents. This is shown in Figure 2.2.
These phenomena and their importance are summarized in Table 2.1.
Table 2.1: Summary of Phenomena

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Description</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion to Print Bed</td>
<td>The adhesive force between the print bed and part</td>
<td>Separation can damage the printed part and increase warpage</td>
</tr>
<tr>
<td>Constitutive response</td>
<td>The deformation of the material when subject to stress.</td>
<td>Dictates how the material will deform from thermal/mechanical stress</td>
</tr>
<tr>
<td>Thermal Contraction</td>
<td>The contraction of the material (with positive thermal expansion coefficient) as temperature decreases</td>
<td>Differential shrinkage is the driving factor behind the warpage.</td>
</tr>
<tr>
<td>Radiation</td>
<td>The heat flow from the part to the environment via radiation</td>
<td>Influences the thermal history of the part.</td>
</tr>
<tr>
<td>Convection</td>
<td>The heat lost to the environment via convection</td>
<td>Influences the thermal history of the part.</td>
</tr>
<tr>
<td>Conduction with Print Bed</td>
<td>Heat flow between print bed and part from conduction</td>
<td>Greatly influences the thermal history of the part near the build plate.</td>
</tr>
<tr>
<td>Hygroscopic effects</td>
<td>Effect of taking on moisture to the material.</td>
<td>High moisture content can affect thermal contraction and constitutive response.</td>
</tr>
<tr>
<td>Self-Conduction</td>
<td>Conduction between adjacent material</td>
<td>Influences thermal history of part.</td>
</tr>
<tr>
<td>Material Addition</td>
<td>Deposition of Material</td>
<td>Addition of mass and heat to system</td>
</tr>
</tbody>
</table>

The mathematical relationships between each selected phenomenon and result are shown in Figure 2.3.

![Figure 2.3 Numerical relationships between selected phenomena.](image-url)
The first and most apparent modeling consideration is material addition which is where the geometry is defined over some domain “D” that will change as a function of time. Then radiation, convection, and conduction boundary conditions are used along with the conduction equation to get the thermal history. Thermal history is used to get the thermal contraction of the material. Thermal contraction is used along with the structural boundary condition (print bed reaction) along with the constitutive response to get the warpage and residual stress in the final part. The image above shows that the phenomena that appears to be most connected to the warpage are thermal contraction and material addition. This chapter will focus on the environmental phenomena affecting prints, and later chapters will focus on the other phenomena that made up the bulk of the modeling effort.

2.2. Hygroscopic Effects

Hygroscopic effects are effects on the material as a result of taking on moisture. Or changes to the material properties because of the material taking on moisture, this can often manifest as an increase in specific heat or changes to thermal conductivity. In plastics processing, moisture in the feedstock is undesirable as it can lead to porosity in the finished parts, in hydrophilic materials. Hygroscopic effects are eliminated in this research by ensuring that the feedstock is dried according to the manufacturer’s datasheet, which is standard practice in polymer processing [32].

2.3. Print Bed

When the first layer of the part is being printed, the molten material will adhere to the print bed. As the layers build up and the part cools, the part wants to pull up from the print bed due to contraction and the adhesion resists this force. If the stress at the part-print bed interface exceeds the strength of the adhesion, then this adhesion can break in some locations, and cause more warpage. The stress at the part-print bed interface can be lowered by using a heated bed, the heated bed works by keeping the base of the part warm and lowering the amount of differential thermal contraction at the base, meaning that generally parts printed on a heated bed will be less likely to separate from the build plate [33].

All the experiments and models used a heated bed, and no separation was observed in any of the prints categorized as successful. Meaning the perfect adhesion assumption, where nodes are fixed at the build plate boundary during the printing process held up. Computationally perfect adhesion translates to nodes on the build plate being constrained in the X, Y, and Z directions, meaning there is no displacement at the surface of the build plate during printing.
3D printed parts generally are not used while still on the build plate, meaning the cooldown of the part and removal needs to be simulated. Cooldown is simulated by allowing the part to cool while still subject to the perfect adhesion condition, simulating the part being left to sit while still on the build plate. Then, the nodal constraints in the X, Y, and Z directions are released and subject to an inertia relief load, which simply prevents rigid body motion of the part. The simulated removal assumes the part is being removed from the bed gently, because the loads applied by someone trying to force the part off the plate are very unpredictable, and gentle removal is standard operating procedure when printing.

However, the part bed interface can be treated as an elastic foundation, and analytical solutions [34] can be found for this case if assumptions are made such as perfect elasticity, and from there stresses at the print bed can be found.

Thermally the print bed can be treated two ways, first is by assuming a fixed temperature [35,7]. If the region between where the temperature set point is held and the top surface of the build plate is assumed to be thermally thin. Second is by simulating the build plate using a thermal resistance from the temperature set point to the bottom surface as in Eq. 2.1.

\[ q = (T - T_{setpoint}) \left( \frac{k_{plate}}{t} \right) \]  

(2.1)

Where \( k_{plate} \) is the thermal conductivity of the build plate, \( t \) is the distance from the temperature set point to the bottom surface of the part. \( T_{setpoint} \) is the temperature setpoint of the build plate, or the temperature of the build plate, as specified in G-code. A graphical representation of the two methods for handling the build plate is shown in Figure 2.4.
In the thermally thin case, the build plate is assumed to have a negligible thermal resistance and as such has a constant temperature throughout the thickness of the part. The thermally thick case is where there is a decrease in temperature as a function of $Z$ meaning that the temperature at the surface of the build plate is lower than the temperature of the set point.

2.4. Convection

During the printing process the printed material will cool and lose heat to the surrounding air. The amount of heat flux is dictated by Newton’s law of cooling, expressed in Eq. 2.2

$$\dot{q} = h(T - T_{\infty})$$

Which states that the heat flux $\dot{q}$ away from an object at temperature $T$ will be proportional to the difference between the object’s temperature and far field temperature, $T_{\infty}$. This proportion is given by some uniform, constant coefficient $h$ called the heat transfer coefficient. This reflects what other researchers have done [22]. Convection was assumed to be natural or driven by the buoyancy of warmer air. Forced convection was not considered as it would have been more difficult to simulate, and the larger printers used do not have cooling fans. The natural convection coefficient is estimated for a constant temperature is done like so.
First the Prandtl number, representing the ratio of heat transfer by mass transport (Convection) to conduction, is found using Eq. 2.3

\[ Pr = \mu \frac{c_p}{k} \]  (2.3)

Where \( \mu \) is the viscosity of the working fluid (Air), \( c_p \) is the constant pressure specific heat of the working fluid, and \( k \) is the thermal conductivity of the working fluid, these were calculated at the mean temperature between the surface at temperature \( T \) and the air at temperature \( T_{air} \) using the pyro-mat python module [36].

Then the Grashoff number is found using Eq. 2.4.

\[ Gr = \frac{L_c^3 \rho_{air}^2 g \Delta T \alpha_{air}}{\mu^2} \]  (2.4)

The Grashoff number is a measure of the buoyant to viscous forces driving the fluid flow. \( L_c \) is the characteristic length of the part, defined in this case as the area of the plate to the perimeter of the plate. \( \Delta T \) is the difference in temperature between the working fluid and the surface temperature, \( \alpha_{air} \) is the coefficient of thermal expansion of the working fluid (air).

The Grashoff and Prantl numbers are combined to create the Rayleigh number shown in Eq. 2.5.

\[ Ra = GrPr \]  (2.5)

The Rayleigh number is a measure of the amount of natural convection. This is then looked up in a table to find the Nusselt number (Eq. 2.6). The table used was from Cengel et. al [37].

\[ Nu = \frac{hL_c}{k_{air}} \]  (2.6)

Where \( h \) is the convective heat transfer coefficient that is to be used. Expressions for finding the Nusselt number in relation to the Rayleigh number for various geometries are tabulated in the back of textbooks [37]. The expression for a vertical plate is given by Eq. 2.7.

\[ Nu = 0.59 \; Ra^{\frac{1}{4}} \]  (2.7)

For a horizontal plate Eq. 2.8 is used.

\[ Nu = 0.54 \; Ra^{\frac{1}{4}} \]  (2.8)
The equation(s) of note are the ones for a vertical or horizontal hot plate. These equations give the following values for convection for a flat plate at uniform temperature $T$, in free convection with air at standard laboratory (~296K).

These figures show that as the characteristic length increases, the convection coefficient goes down. Additionally at smaller and smaller length scales the convection coefficient varies more and more as a function of temperature, meaning that the convection becomes less and less linear. For a sense of scale, a typical characteristic length for a desktop printer printing a long thin section would be around 1 mm while for a BAAM a typical value would be around 15 mm. This also points to the need of two different values for vertical and horizontal surfaces which requires a subroutine, another complicating factor for convection is not all geometries are flat, meaning that for realistic geometries, the convection coefficient will be a guess if there is not extensive work to determine the convection coefficient for a specific geometry.

The enclosure temperature was also assumed constant, this is generally assumed to be standard laboratory conditions [38] except for small-scale printers, where a K type thermocouple was placed in the print volume while printing and allowed to reach equilibrium. This accounts for any heating in the enclosure. An image of this setup is shown in Figure 2.6.
2.5. Radiation

Radiation generally has been assumed to be negligible in literature and ignored [10,35]. If the convection coefficient is small; the radiation flux can exceed the convective flux. Both the incident and emitted radiation were assumed to be diffusive and self-irradiation was ignored. This assumption eliminates the need to recalculate all the view factors each time material is deposited. This means that the effective view factor from a surface to the far field is 1 [39]. The radiation field was also assumed to be gray; this was done because of solver and material characterization limitations. This means that the radiative flux from a surface of the part to the environment is given by [40] in Eq. 2.10

$$\dot{q}_{rad} = \varepsilon \sigma (T^4 - T_{inf}^4)$$ (2.10)

Where the radiative flux $\dot{q}_{rad}$ is proportional to the difference in the object and far field temperatures taken to the fourth power. $\sigma$ is the Stefan Boltzmann constant, and $\varepsilon$ is the total hemispherical emissivity, which is a value from 0 to 1. The ratio of radiative flux of a perfect blackbody to the sum of radiative and convective flux as a function of temperature for various convection coefficients and emissivities is plotted in Figure 2.7.
Figure 2.7 Proportion of radiative flux to total surface heat flux for an object at \( T \) to environment at standard laboratory. (296K) showing common print temperature for PETg and Polycarbonate (PC).

The plot in Figure 2.6 shows that for low convection coefficients, the radiation represents a significant proportion of the total heat transfer to the far field. So, radiation could play a large part in the thermal history of the parts and should be considered. One thing to note is that for most of the work conducted, the convection coefficient was below 10 W/sq. m K, meaning that radiation made up a significant portion of the heat transfer at the boundaries. A ratio of expected radiation to expected convection can be created by linearizing the radiation \([41]\) as Eq. 2.11.

\[
q_{rad} = \sigma 4 T_{char}^3 \epsilon (T - T_\infty)
\]  
(2.11)

This also allows for a number to express the ratio of radiation to convection (Eq. 2.12).

\[
Rh = \frac{\sigma 4 T_{char}^3 \epsilon}{h}
\]  
(2.12)

The dimensionless Rh number corresponds to the contours showing the percentage on Figure 2.7 and is meant to be a measure of the surface heat transfer regime of a given object.

The linearized radiation can also allow for a modified Biot number to be defined as Eq. 2.13.
\[ B_0 = \frac{(\sigma 4T_{\text{char}}^3 \epsilon + h) L_{\text{char}}}{k} \]  

(2.13)

This is a measure of the surface heat transfer to internal heat transfer for an object subject to both radiation and convection.

2.6. Summary of phenomena

A summary of the phenomena occurring during the printing process is shown in Figure 2.8.

![Figure 2.8: Phenomena during printing.](image)

There are many phenomena occurring during the printing process and simulating and evaluating the effect of each phenomenon is important when creating efficient and scalable modeling approaches and workflows. Simulating the environmental conditions is important because they feed into the thermal and stress history of the part. Because these phenomena lie “upstream” of the material and constitutive response, getting something at least close to reality is arguably more important than the material model. A compiled list of environmental phenomena and assumptions is shown in Table 2.2.
Table 2.2: Complied list of phenomena and associated assumptions.

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>Gray, Diffuse, No Self irradiation</td>
</tr>
<tr>
<td>Convection</td>
<td>Uniform, constant free convection</td>
</tr>
<tr>
<td>Build Plate Adhesion</td>
<td>Perfect adhesion</td>
</tr>
<tr>
<td>Build plate Conduction</td>
<td>Fixed Temperature, Resistance</td>
</tr>
<tr>
<td>Hygroscopic Effects</td>
<td>Ignored</td>
</tr>
</tbody>
</table>
3. MODELING OF PROCESS AND PERFORMANCE

3.1. Modeling Workflows

The overall workflow and how the different tools fit into one another is shown in Figure 3.1. All the components in green are material properties and will be dealt with later. This figure shows the different methods to take the geometry and G-code of the part and be used to create input decks for Abaqus to simulate the warpage of the final part.

Figure 3.1 Overall workflow, showing different components.
The flowchart shows the overall process map containing all components and data that are available in the framework for creating a workflow. This chapter will focus on the components and workflows highlighted. With the goal of creating a functional workflow for general use on the selected materials.

3.1.1. CLOSAMS Approach

CLOSAMS is a software tool that stands for CLOsed Source Additive Manufacturing Simulator that can take G-code and directly use it to create the input deck for Abaqus to run a simulation of the printing process. A visual representation of this workflow is shown in Figure 3.2.

Figure 3.2: Pure CLOSAMS.
This approach starts with the slicer which will produce G-code, the G-code and bead dimensions are passed to CLOSAMS standard, which meshes the part and creates an activation schedule inside of the .inp files for Abaqus Thermal and Structural. Then Abaqus Thermal is run, and the results are used to inform the thermal contraction in the structural model, where the displacements at the end of the cool down step are the predicted warpages. The activation schedule is known before the simulation is run meaning more control over activation can be exercised.

This workflow handles boundary conditions by explicitly defining the element surfaces that are subject to convection and radiation. The convection is handled by *SFILM and radiation is handled by *SRAD in Abaqus. One of the unique features of this workflow is that it allows for different convection and radiation properties to be specified on a per location basis without requiring the use of a user subroutine.

**Advantages:** This workflow is not reliant on meshing the part manually, and a model can be created with minimal human intervention. This method is also able to explicitly represent the bead geometry, and explicitly tracks and activates the interfaces between the beads. The main advantage of this method is that because the *MODEL CHANGE keyword is used to handle the activation instead of *ELEMENT PROGRESSIVE ACTIVATION, a quasi-static analysis can be used for the displacement simulation instead of a fully static analysis, which allows for viscoelastic material behavior to be modeled. Additionally, the activation schedule is known before runtime, meaning extensive control over element activation can be exercised. Although not leveraged in this work, the explicit interface identification capabilities can be leveraged to allow local failure methods at the regions between interfaces to be implemented.

**Disadvantages:** This method is limited to very simple geometries; care needs to be taken to ensure that the element boundaries on adjacent beads line up so the surfaces merge correctly. Additionally using the *MODEL CHANGE keyword requires a new step to be created for each discrete instance of simulated material deposition, which means the solution time increases significantly with problem size.

### 3.1.2. Abaqus AM Approach

This approach involves using the new AM specific features in Abaqus to model the part. This involves creating a mesh with some meshing tool like Hypermesh or Abaqus CAE, then using G-code to create an event series which is used by UEPActivationVol inside of the solvers themselves to simulate the bead and handle element activation. The Abaqus AM Workflow is shown in Figure 3.3.
Figure 3.3: Abaqus AM Workflow

The Abaqus AM workflow is how a model would be created to use the UEPActivationVol with an existing FEA mesh. This workflow is based on how the AMModeler in Abaqus is used. The mesh is created in LS Prepost, Hyperworks, or Abaqus CAE, and then imported into the model. The user subroutine uses the simulated bead geometry to handle element activation. Additionally, this workflow differs in the implementation of boundary conditions. The *FILM and *RAD keywords are used to automatically apply uniform convection and radiation conditions to the free surfaces of the part. Thus, this method is restricted to simulating uniform convection and radiation.
Advantages: Geometry is only limited by what can be meshed with commercial codes. *ELEMENT PROGRESSIVE ACTIVATION is much faster than *MODEL change. The activation times of elements is only known during runtime meaning that less control can be exercised over element activation.

Disadvantages: Bead geometry is made to conform with the mesh. Element and bead boundaries are not coincident with each other, meaning that failure modeling of parts using local methods cannot be done.

3.1.3. Hybrid Approach

Figure 3.4: Hybrid Workflow
The hybrid workflow is meant to combine the two best things about each approach, where the bead-based meshing from CLOSAMS is used with the progressive element activation of the Abaqus AM approach.

**Advantages:** Compared to using pure CLOSAMS, the hybrid approach uses the *ELEMENT PROGRESSIVE ACTIVATION* keyword which does not require a new analysis step for each discrete activation of elements. Meaning it runs faster.

**Disadvantages:** The hybrid approach is constrained to simple geometries, and one needs to pay special attention to ensure that the element boundaries on adjacent beads are properly aligned, so the surfaces merge correctly.
CHAPTER 4

4. COMPUTATIONAL FRAMEWORKS

This chapter will primarily focus on the technical implementation of the tools that make the modeling methods discussed in Chapter 3 possible. This chapter will go over the implementation of the bead-based meshing approach, G-code parsing, event series, and user subroutine UEPActivationVol. The objectives of this chapter are to provide insight into how the approaches work on a very technical level, and to provide a low-level overview of some of the challenges of simulating TEAM at multiple length scales.

4.1. CLOSAMS Meshing and Event Scheduling

The tool CLOSAMS is a suite of two different tools that are used to create models to simulate the process of thermoplastic extrusion additive manufacturing (TEAM). CLOSAMS Standard (Std.) is the module that takes the toolpath data and uses it to create a mesh and an activation schedule. While CLOSAMS Events is another executable built onto the G-code interpreter in CLOSAMS Std that creates the event series needed for using the Hybrid and Abaqus AM workflow. A flowchart highlighting the data flowing through each of the tools is shown in Figure 4.1.
First the toolpath is partitioned into discrete segments, separated by non-extrusion travel moves. These moves are then split into deposition steps, which correlates 1:1 with element sets activated in each analysis step. This is shown in Figure 4.2.
4.1.1. Mesh Extrusion

The first part of CLOSAMS developed was the module responsible for taking the toolpath and extruding a mesh along it.

This module takes the toolpath to inform when and how to extrude the mesh. This module also takes the bead geometry as a mesh template in the form of a spreadsheet that describes the elements making up a bead cross section. This module outputs an unmerged mesh. A graphical representation of this is shown in Figure 4.3.
The next step is tracking the surfaces as discussed below.

### 4.1.2. Surface Tracking and Merging

The second part of CLOSAMS developed was the module responsible for merging and tracking surfaces subject to bonding. This module takes the mesh extruded from the previous step and checks the distance between surfaces. If the surfaces are within a given tolerance, the higher numbered surface is replaced by a pointer to the lower numbered surface; hence, if the higher numbered surface is queried, data for the lower numbered surface is given. This merge along with the associated step where bonding occurs is recorded in a table, so in the analysis a change in boundary condition is applied to the bond region. This is shown in Figure 4.5.
The nodes are then merged to make the mesh region continuous, again by making the higher numbered node be a pointer to the lower numbered node. Using pointers instead of simply deleting the higher numbered node simplifies a lot of the bookkeeping. After this is done for all nodes, the instances where merged nodes occur in element definitions are replaced by the node number at the base of the pointer chain. This is shown in Figure 4.6.
The node merging and element node replacement allows for two bonded surfaces to act like a continuous region.

### 4.1.3. Activation Schedule

During the actual analysis procedure, changes are made using a construct called an Activation Schedule. This is a collection of two tables that are treated like queues when writing the output for a given analysis. The first table contains information on which surfaces are to be activated during a given analysis step. The second table contains information on which elements should be activated for a given deposition step. The process inside of the solver is shown in Figure 4.7.

![Figure 4.7: Domain change handling during analysis.](image)

Activations of element sets as well as boundary and surface conditions are specified explicitly according to this activation schedule. This is meant to facilitate precise control over which boundary conditions are applied to what surface at a given instant in time. Another advantage of using the activation schedule is that it allows for convection and radiation conditions that vary as a function of spatial coordinate without requiring the use of user subroutines.

### 4.2. G-code

G-code is the formatted instructions for Computer Numerical Control (CNC) tools that are stored and passed to the printer. Interpreting G-code is important because it allows for a numerical process model to take the print instructions directly. G-code is a vital part of the process because an ideal model would only take the geometry as implied by the G-code and not use the CAD geometry. G-code is generated by a slicer program.
An example of G-code given to an Ultimaker is given below in Figure 4.8: Example G, where. G1 tells the printer to move to X Y coordinates specified, E corresponds to the position of the extruder axis or how much to advance the filament, and F tells the printer how fast to move.

```plaintext
;TYPE:WALL-INNER
G1 F1200 X207.5 Y128.5 E4.21356
G1 X207.5 Y129.5 E4.26373
G1 X122.5 Y129.5 E8.52745
G1 X122.5 Y122.5 E8.87858
G1 X206.5 Y122.5 E13.09215
G1 X206.5 Y117.5 E13.34295
G1 X122.5 Y117.5 E17.55652
G1 X122.5 Y110.5 E17.90765
G1 X207.5 Y110.5 E22.17138
G1 X207.5 Y111.5 E22.22154
G1 X123.5 Y111.5 E26.4351
```

Figure 4.8: Example G-code

Any positions or values not specified in a line of G-code are propagated from previous lines.

### 4.2.1. G-code Flavors

Generally, G-codes for two printers look similar. However, there are some slight, but key differences. The most apparent of these differences is in how the extruder is turned on or off. This is best shown by comparing the G-code for the same print movement in the different flavors as given in Table 4.1.

<table>
<thead>
<tr>
<th>G-code Flavor</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Language</td>
<td>Go to $X = 0$, $Y = 0$, $Z = 0$ and print a 100mm line in the $+X$ direction.</td>
</tr>
<tr>
<td>BAAM (Cincinnati)</td>
<td>G0 X0 Y0 W0 Z0; M3 S100; M10; G1 X100 Y0 W0</td>
</tr>
<tr>
<td>Masterprint (Ingersoll)</td>
<td>G0 X0 Y0 Z0; EXTRUDER(100); M100; G1 X100 Y0 Z0; TRAVEL MOVE TO (0,0,0)</td>
</tr>
<tr>
<td>Ultimaker (Modified Marlin)</td>
<td>G0 X0 Y0 Z0; G1 X100 Y0 Z0 E10; MOVE TO 100 0 0 WHILE MOVING FILAMENT 10 INCREMENTS AHEAD</td>
</tr>
<tr>
<td>Gigabot (Marlin Screw)</td>
<td>G0 X0 Y0 Z0; G1 X100 Y0 Z0 E10; TRAVEL MOVE TO (0,0,0)</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of G-code Flavors
Table 4.1 shows that there are differences. Like the BAAM moving the bed to print layers, and because the bed axis is addressed as W, changing the z coordinate of the material being extruded is done with W. Cincinnati uses parentheses for comments while the others use semicolons. Of course, the quantity associated with the screw speed and filament axis will depend on the bead size, material, and other parameters. The most glaring difference is the two extra lines for the BAAM and Masterprint because they use screw type extruders that are not controlled like an extra axis as in the Gigabot.

4.2.2. Differences between Screw and Filament Machines

The BAAM, Masterprint and Gigabot are screw machines meaning a screw pushes the material out of the nozzle. While filament fed machines push the filament into a heated die and out the nozzle. The biggest operational difference is the mass flow rate in filament fed machines is roughly linearly proportional to the move rate of filament axis. However, the mass flow rate of screw machines is significantly more complicated. Additionally, in screw machines, there can sometimes be significant heating in the screw because of friction.

But, as far as macro scale warpage modeling is concerned, the only thing needed is whether the extruder is extruding material and the nominal bead dimensions. Additionally, the numerical process model assumed constant bead dimensions, as trying to extract the bead dimensions from G-code is exceedingly difficult in a screw type extruder. All of the geometries presented were printed with a constant bead geometry.

4.2.3. Development of a Modular G-code Reader

One of the concerns when moving from 3D printer to 3D printer is the lack of a universal G-code flavor for all machines to use. The G-code will often vary by manufacturer, so an interpreter for modeling efforts needs to be able to handle the multiple flavors of G-code. CLOSAMS fixes this problem by using a dictionary file, or a file that tells the interpreter how to read the G-code. This is stored in the form of a JSON file, which contains regular expressions (regex) to define the G-code syntax of a given printer. This process allows for all of the different syntaxes to be interpreted without needing to write a new G-code interpreter for each and every flavor of G-code. This process is shown in Figure 4.9.
The other advantage to using this approach, where the machine specific commands are stored in a separate file, is that extending the interpreter for other machines is extremely simple, and generally only requires editing a few lines of regex. Since differences in G-code flavors are often small, this procedure is often very quick.

4.3. **UEPActivationVol**

4.3.1. **Stock Subroutine**

Newer versions of Abaqus include a version of UEPActivationVol with the AM Modeler. This subroutine was deemed inadequate because the version packaged with Abaqus 2019 did not orient elements with the bead direction, and the material exhibits severe anisotropy, especially when fibers are added to the base polymer (matrix) material.

The stock subroutine differed from the one used for the models in the element activation criteria. The stock subroutine activates elements based on volume fraction of the simulated bead area inside of a given element. The subroutine also differed in the activation shape, where the simulated bead in this subroutine is a rectangle the one used for the models was a cutoff circle.

4.3.2. **In House Subroutine**

To work around the limitations of the stock subroutine, a custom subroutine UEPActivationVol was written in FORTRAN 77 and compiled using the Intel FORTRAN Complier Classic 2021 [42] for Abaqus Standard 2019 and 2021. [10] Importantly, the user subroutine was developed to orient the elements in the print direction which was not possible via Abaqus AM 2019’s stock UEPActivationVol subroutine.
Simulated Bead

The simulated bead, in the form of a sliced circle, in the developed subroutine is as shown in Figure 4.9. This geometry was selected for computational efficiency reasons because algorithmically checking whether an element’s centroid intersects the bead only consists of two operations.

Additionally, a value known as stack offset is passed to the subroutine to account for the offset in the direction parallel to the extruder bore between the bead centroid and the printer tip. The simulated bead geometry is shown in Figure 4.10.

![Figure 4.10 Simulated bead geometry.](image)

This subroutine will also unconditionally activate an element if the centroid is within the simulated bead. This was done for computational and algorithmic simplicity.

The overall process of this subroutine is as follows:

1. Toolpath segments that intersect the current time increment are found
2. Toolpath segments that are within a given distance from the element centroid are found
3. Toolpath segments are checked to ensure they fall on the same layer as the element
4. If there are segments that satisfy all the above conditions, the segment that occurs first is selected and the element is activated
5. The 11 direction of the element is set to be parallel to the selected toolpath segment
6. The 33 direction is set to be parallel to the global z axis
7. The 22 direction is set to be equal to the cross product of the 11 and 33 directions
4.3.3. Differences between Stock and In-House Subroutines

The differences between the stock and in-house subroutine are as follows. First, the stock subroutine activates elements based on volume fraction that the simulated bead geometry intersects, while the in-house subroutine activates elements if the centroid is inside of the simulated bead geometry. Second, the stock simulated bead is a rectangle, while the in-house bead geometry is a sliced circle. Finally, the stock subroutine with Abaqus 2019 does not orient elements with the bead direction, while the in-house one does. These differences are best shown in two models showing the elements activated with the 11 (Blue) and 22 (Green) material directions overlaid in Figure 4.11.

Figure 4.11 Material orientation and activation comparison on a representative section for (a) custom-developed UEPActivationVol user subroutine, and (b) Abaqus AM’s stock subroutine.

One thing to note is the orientations in (a) align with the beads. While those in (b) are all aligned. More elements are activated in (b), this is because the volume fraction threshold for activation was set to 1% in the stock subroutine, and because the only condition for (a) is that the element centroid is inside of the bead.
CHAPTER 5

5. MODELING OF MATERIALS

5.1. Motivation and Objectives

As seen in Figure 2.2 most of the phenomena occurring during the printing process are associated with the material, making material modeling one of the most important components in TEAM simulation.

One of the limiting factors in creating a robust material model is the time and labor costs of performing material testing. When combined with the knowledge that the material is anisotropic because of the aligned inter bead voids and will need to be simulated over a wide range of temperatures, exhaustive testing would be needed to fully capture the material behavior. Some assumptions can be used to drastically cut down on the amount of characterization required, so an objective is to create a workflow that lowers the amount of material testing required.

Material properties are defined in the material coordinate system, shown in Figure 5.1.

![Figure 5.1: Material directions on representative bead.](image)

The 11 direction is along the bead, this will often be the strong axis of the material, as the beads are parallel to the loading direction. The 33 direction is in the build direction.

5.2. Material Limitations

There are some limitations in using UEPActivationVol to handle element activation, the most glaring being that mechanical analysis is restricted to a static analysis step. This means that if a material response with time or rate dependence is used, the analysis will find the steady state response of the material, which is problematic because at elevated temperatures plastic acts viscoelastic and flows, meaning that the steady state response is vastly different from the transient response.
There is also the option of writing a UMAT; however, because the UMAT is being used to simulate time
dependent behavior in an analysis type not meant to simulate time dependent behavior, an extremely
rigorous validation exercise would be needed to first ensure that the UMAT is behaving correctly, and
second to establish an envelope where the UMAT behaves correctly. As a result of these limitations,
writing a UMAT was discounted, and instead some assumptions were made to work around this
obstacle.

5.3. Constitutive Behavior

The material is assumed to have a linear elastic orthotropic response because the intra-bead voids
(meso voids) shown in Figure 5.2 decrease stiffness in directions transverse to the bead direction.

![Intra bead voids on PLA](image)

Because the material has well defined directions, the material is assumed to be orthotropic, or have
elastic symmetry along 3 orthonormal planes. The material’s elastic moduli were defined based on the
bead directions shown in Figure 5.1.

The bead direction is the direction of printing, the stack direction is parallel to the bore axis of the
extruder during printing, and the across direction is the cross product of the other two directions. The
stress-strain response for a linear elastic orthotropic material is given in Eq. 5.1

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$ (5.1)
Where $\sigma_{ij}$ is the Cauchy stress tensor, $C_{ijkl}$ is the stiffness tensor, and $\epsilon_{ij}$ is the infinitesimal strain tensor.

Plasticity generally was not used in the models, this is because it can cause convergence issues most notably when there is perfect plasticity, and for most geometries it is not expected. Viscoplasticity was also ignored because of solver limitations in using the *STATIC analysis step in Abaqus.

Also as seen in section 7.3 the material exhibits ductile failure in the 11 direction, and brittle failure in the 33 direction. The inbuilt Abaqus processes were deemed inadequate for modeling a material with different failure modes in different directions.

5.4. Thermal Behavior

Thermal conduction in an anisotropic medium is given by Eq. 5.2.

$$\frac{\partial T}{\partial t} \rho C_p = -\nabla \cdot k \nabla T \quad (5.2)$$

where $T$ is the temperature in K, $t$ is time in seconds, $\rho$ is the density in kg/m$^3$, $C_p$ is the specific heat at constant pressure in J / kg K, $\nabla$ is the gradient operator defined as $\nabla = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k$, $\cdot$ is the inner product operator, and $k$ is the conductivity tensor describing the relationship between temperature gradient and heat flow.

The material was assumed to have a temperature-independent orthotropic or isotropic conductivity tensor $k$, having values consistent with those found in literature [35]. As shown in section 8 thermal conductivities have less of an effect on warpage than other parameters, at least for the parameters and parameter values considered.

5.5. Effect of Temperature

Thermoplastics exhibit a reduction in stiffness when the temperature is increased [43], and because the material needs to be modeled over a wide range of temperatures, this behavior needs to be considered.

To account for the effect of temperature on the elastic properties, the multifactor technique is used [43], which allows for the temperature dependence of a known property to be used to estimate the temperature dependence of unknown properties.

By assuming properties degrade at the same rate, the multifactor technique estimates material properties at temperatures other than the reference temperature. Mathematically, the multifactor technique is expressed as Eq. 5.3.
\[ P_{T_1} = P_{T_0} \left( \frac{T_g - T_i}{T_g - T_0} \right)^{\beta_i} \]  \hspace{1cm} (5.3)

where \( P \) is the material property, \( T_1 \) is the temperature at some discrete point, \( T_0 \) is the reference temperature, \( T_g \) is the glass transition temperature, \( T_i \) is the temperature at point \( i \), and \( \beta_i \) is the multifactor exponent for a given temperature point given by Eq. 5.4.

\[ \beta_i = \frac{\log \left( \frac{P_i(T_i)}{P_i(T_0)} \right)}{\log \left( \frac{T_g - T_i}{T_g - T_0} \right)} \]  \hspace{1cm} (5.4)

where \( P_i \) is the reference property for which temperature dependent data exists. This technique is powerful in that it allows for modeling the constitutive response of the material with minimal experimental data.

5.6. Accounting for Relaxation

Relaxation is a time dependent phenomenon that cannot be effectively modeled within the restrictions imposed by UEPActivationVol. So, a workaround is needed which is inspired by the work of Armillotta et. al [44], which assumed warpage of the final part is insensitive to thermal expansion and contraction above \( T_g \). This is elaborated in the section on thermal expansion.

5.7. Thermal Expansion

A temperature-dependent orthotropic CTE was assumed to represent the thermal expansion of 3D-printed CF-PETg. This was informed by experimental results given in Section 7.3 and the CTEs at 23 ℃ shown in Table 5.1 were assumed. In Table 5.1 and throughout this work, material direction refers to the direction with respect to the as-printed beads, not a global coordinate system.

<table>
<thead>
<tr>
<th>Material Direction</th>
<th>( \alpha ) (( \mu \epsilon/\text{℃} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>33</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5.1: Room temperature CTEs for Techmer CF-PETg
The temperature-dependent properties of the polymer are represented via the polymer equation of state proposed by Hartman and Haque [45] of the form of Eq. 5.5:

\[
P \frac{B_{0s}}{v_{0s}} \left( \frac{v}{v_{0s}} \right)^5 = \left( \frac{T}{T_{0s}} \right)^\frac{3}{2} - \ln \left( \frac{v}{v_{0s}} \right) \tag{5.5}
\]

where \( B_{0s}, T_{0s}, \) and \( v_{0s} \) are fit parameters related to bulk modulus, temperature, and specific volume, respectively, \( v \) is specific volume, \( P \) is the current pressure, and \( T \) is temperature. When absolute pressure is low, the left side of Eq. 5.5 can be assumed equal to zero, \( i.e. \), (Eq. 5.6)

\[
0 \approx \left( \frac{T}{T_{0s}} \right)^\frac{3}{2} - \ln \left( \frac{v}{v_{0s}} \right) . \tag{5.6}
\]

Solving for \( v \) results in a closed-form expression for the specific volume as a function of temperature for a polymer at low pressure of the form of Eq. 5.7.

\[
v = v_{0s} \exp \left( \left( \frac{T}{T_{0s}} \right)^\frac{3}{2} \right) \tag{5.7}
\]

Equation (5.7) requires only two fitting parameters. Using the large strain formulation, the change in specific volume can be related to thermal strain using the large strain assumption relating thermal strain to change in specific volume (Eq. 5.8.)

\[
\frac{v(T) - v(T_0)}{v(T_0)} = 3\epsilon_{th} + 3\epsilon_{th}^2 + \epsilon_{th}^3 \tag{5.8}
\]

where \( T_0 \) is the reference temperature, and \( \epsilon_{th} \) is the thermal strain. The above process of calculating fit parameters, finding the specific volume as a function of temperature at atmospheric pressure, then using change in specific volume with the large strain assumption to get thermal strain can be used to find the temperature dependent CTEs of the polymer. This workaround is not needed for many polymers, as often the fit parameters are tabulated [46] but values were not readily available for PETg.

At temperatures greater than the glass transition temperature, thermal contraction was assumed to have a negligible effect on part warpage [11]. Accordingly, the thermal stress was assumed to be of the form of eq. 5.8.
\[
\sigma_{ij}^{th} = (T_g - T) \alpha_{kl} C_{ijkl}
\] 

(5.8)

where \(\sigma_{ij}^{th}\) is the thermal stress component of the Cauchy stress tensor, \(T_g\) and \(T\) are the glass transition and current temperatures, respectively, \(\alpha_{kl}\) is a second rank diagonal coefficient of thermal expansion tensor where the diagonal terms are the coefficients of thermal expansion in the material directions, and \(C_{ijkl}\) is the stiffness tensor. This assumption was made because above \(T_g\) the polymer undergoes viscous relaxation after enough time. For temperatures less than \(T_g\), this relationship can be extended to determine the effective strain at a given point of time for a material where the thermal strain is defined as a function of temperature eq. 5.9.

\[
\epsilon_{th}(t) = \left( \epsilon_{th}(T_g) - \epsilon_{th}(T(t)) \right) \quad \forall \ T(t) < T_g
\]

(5.9)

where \(\epsilon_{th}\) is thermal strain, and \(t\) is the time. Numerically this assumption can be enforced by setting the thermal strain for all temperatures greater than the glass transition to be equal to the thermal strain at the glass transition temperature. A plot of the thermal strain according to this assumption versus temperature is shown in Figure 5.3.

Figure 5.3: Thermal strain as a function of temperature with (dashed green) and without (blue) the viscous relaxation assumption. This work assumed a viscous relaxation assumption as shown in the dashed green curve.
Note that the standard thermal strain curve has a different slope before and after the glass transition temperature. This is because another set of fit parameters were calculated for neat PETg’s rubbery phase between $T_g$ and the melt temperature $T_m$.

Implementation of thermal expansion within the commercial numerical solver Abaqus [17] required the total CTE given by eq. 5.10.

$$\alpha(T) = \left( \frac{\varepsilon_{th}}{T - T_{ref}} \right)$$

(5.10)

where $T_{ref}$ is the reference temperature at which the thermal strain equals zero. If CTE is constant within a temperature range, the total CTE given in Eqn. (11) is equivalent to the differential form of CTE given by eq. 5.11.

$$\alpha'(T) = \frac{d\varepsilon_{th}(T)}{dT}.$$  

(5.11)

The temperature-dependent CTE in all three directions used in the simulations are shown in Figure 5.4.
Note that the increase in CTE from room temperature to the glass transition is very small. The difference in some sample CTE values passed to the model with and without the thermal strain assumption is best shown in Figure 5.5.

![Figure 5.5](image_url)

**Figure 5.5:** Sample CTEs passed to the model with and without viscous relaxation assumption.

An alternate approach would be to simulate the relaxation of the part. However, such an alternate approach is unsupported in Abaqus AM’s *STATIC analysis step [17].

The limitation to handling the relaxation of the part in this way is that this method can only really be used in materials that exhibit a sharp change in the relaxation behavior at the glass transition, like PETg [43]. For a material having a more gradual shift from viscous to elastic behavior, an alternative numerical approach would likely be required.

For CF-PETg thermal conductivity was assumed to be isotropic, temperature-independent, and equal to $k = 0.3 \text{ W/(m}^2 \text{ K)}$. The CF-PETg was assumed to have a temperature-independent, isotropic specific heat of $1120 \text{ J/(kg K)}$ and a temperature-independent, uniform density of $1500 \text{ kg/m}^3$ [47].
CHAPTER 6

6. COMPARISON AND VALIDATION OF MODELING METHODS USING SMALL CIRCLES

6.1. Introduction

This chapter evaluates and compares the three different modeling approaches in a material agnostic fashion and compares numerical and experimental warpage results. Results from this chapter will inform modeling choices at larger length scales.

6.1.1. Objectives

The high-level objectives of this exercise are as follows: First, use simple geometries to compare the warpage results for three different modeling approaches. Second, compare the numerical model results to experiments. Third, compare and evaluate the runtimes. The overarching goal is to evaluate and compare the efficiencies of the different modeling approaches before selecting one for future modeling work.

6.1.2. Modeling approaches

6.2. Geometry

The part to be analyzed is the closed tubular geometry shown in Figure 6.1.

Figure 6.1: Circle geometry

The part is two beads thick in the radial direction, with each bead 0.48-mm wide. This geometry was selected because it is relatively simple to analyze and is more stable on the print bed than a wall.
6.3. Methodology

The extruder temperature range of 190 ℃ to 230 ℃ was selected by taking the range for printing PLA [48] and shrinking it to try and ensure a linear response for warpage. The 0.1 mm and 0.2 mm layer heights were selected based on prior experience printing PLA, where at these levels a stable print geometry is achieved. Finally, the layer time range was chosen as 88.8 s to 44.4 s by taking the initial value of then changing the values to try and keep a linear response.

This takes the form of a three-factor, two-level resolution III fractional factorial DOE, i.e., a $2^{3-1}$ DOE. Within a resolution III fractional factorial DOE, main effects are mathematically inseparable, or aliased, with two-way effects. The purpose of the DOE was to create a diverse data set for model validation. Meaning a higher resolution DOE would not have benefited the objectives of this experiment much. The DOE resulted in a total of six parts: four vertices and two center points.

Meshes showing the three modeling approaches are shown in Figure 6.2.

Figure 6.2: Image showing mesh cross section for (a) Abaqus AM (b) Hybrid (c) CLOSAMS Std. models

The CLOSAMS Std. models activated entire rasters of elements at a time per the activation schedule, while the hybrid and Abaqus AM models activated elements based on toolpath element intersection. To show the difference between the three modeling approaches for element activation, images of the models before and after an instance of element activation are shown in Figure 6.3.
The CLOSAMS Std. model activates entire beads of elements at a time. While the other two activate elements based on the simulated bead. The differences in the different modeling approaches are summarized in Table 6.1.

Table 6.1: Differences in modeling approaches.

<table>
<thead>
<tr>
<th></th>
<th>CLOSAMS Std.</th>
<th>Hybrid</th>
<th>Abaqus AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements / Bead</td>
<td>9</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Element Type</td>
<td>[DC</td>
<td>C]3D20 (2nd Order)</td>
<td>[DC</td>
</tr>
<tr>
<td>Activation Type</td>
<td>Activation Schedule (Step)</td>
<td>Progressive Element Activation</td>
<td></td>
</tr>
<tr>
<td>Activation Amount</td>
<td>Beads</td>
<td>Depends on Time Step and Feed Rate</td>
<td></td>
</tr>
</tbody>
</table>

The hybrid and Abaqus AM approaches both used 2nd order elements this is to allow for smoother curvature. The main purpose is to determine the accuracy of warpage predictions and run times of each workflow and compare results between workflows.
The environmental properties of the part are as follows. The build plate was simulated as being thermally thick and had an equivalent thermal resistance of $\frac{1}{210} \frac{m^2K}{W}$. Radiation was ignored for this batch of models. The environment temperature was set to 35 °C and a convection coefficient of 30 W/m$^2$ K was specified.

6.4. Material

The parts were printed using Mattterhackers Pro Series Clear 2.85mm PLA [48]. This material was selected because of prior experience in printing this material. An image of the material is shown in Figure 6.4.

![Matterhackers clear PLA filament](image)

Figure 6.4: Matterhackers clear PLA filament

A temperature-dependent orthotropic elastic constitutive model was assumed using the temperature-dependent elastic constants shown in Figure 6.5. This validated material model was extracted from Grant [44] who used neat Matterhackers Pro Series Clear PLA. Room temperature elastic constants were measured via ASTM D638 [49]. The utilized temperature-dependent elastic constants are shown in Figure 6.5.
Figure 6.5: Elastic constants as a function of temperature, Abaqus will interpolate between the points.

The CTE as a function of temperature from [44] is given in Figure 6.6.

Figure 6.6: Temperature dependent CTE for PLA, Abaqus will interpolate between the points.
The sharp increase at 150 °C is because this is around where the polymer starts melting. The conductivity, specific heat, and density as a function of temperature were found by Grant using MCQ Chopped, nominal room temperature values for these are given in Table 6.2. One thing to note is that PLA is a semi-crystalline polymer meaning that it will behave differently from amorphous polymers like PETg.

Table 6.2: Nominal properties for PLA

<table>
<thead>
<tr>
<th>Property</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1266</td>
</tr>
<tr>
<td>Specific Heat (J/kg K)</td>
<td>1483</td>
</tr>
<tr>
<td>Conductivity (W/m K)</td>
<td>0.18</td>
</tr>
</tbody>
</table>

6.5. Experimental Validation

The factors for each of the model runs are shown in Table 6.3.

Table 6.3: Factors for circles

<table>
<thead>
<tr>
<th>Treatment #</th>
<th>Nozzle Temperature (°C)</th>
<th>Layer Height (mm)</th>
<th>Layer Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>230</td>
<td>0.2</td>
<td>88.8</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>0.1</td>
<td>44.4</td>
</tr>
<tr>
<td>3</td>
<td>190</td>
<td>0.2</td>
<td>44.4</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>0.1</td>
<td>88.8</td>
</tr>
<tr>
<td>5</td>
<td>210</td>
<td>0.15</td>
<td>66.6</td>
</tr>
<tr>
<td>6</td>
<td>210</td>
<td>0.15</td>
<td>66.6</td>
</tr>
</tbody>
</table>
The parts were manufactured on an Ultimaker 2+. Using a thermocouple, the steady state temperature of the interior of print chamber was found to be 35 °C. An image of a realized circle is shown in Figure 6.7.

![Figure 6.7: Realized circle for treatment 6](image)

Each realized circle was removed from the build plate before being scanned.

### 6.5.1. Quantification

Results from the three numerical workflows and the experiments were compared via waist displacement, defined as the minima of nominal diameter compared to the outer diameter of the part. Outer diameter was selected because it is a fixed reference. This was done on a per z-coordinate basis.

The as-manufactured six parts were individually measured via a 4-step process. Before anything happened, the parts were allowed to cool until the build plate reached ambient temperature. First, each part was sprayed with Dynaflux DNF crack developer. A part before and after spraying is shown in Figure 6.8.

![Figure 6.8: Part before and after spraying with Dynaflux DNF crack developer](image)

In the second step, each part was scanned with a FARO quantum arm shown in Figure 6.9.
Third, the point cloud was de-noised in the PolyWorks [50] software. The point cloud after scanning and de-noising is shown in Figure 6.10.

In the fourth and final step, the de-noised data is analyzed by: (a) splitting into clusters based on the global z-coordinate (i.e., the build direction), (b) selecting points on the outer diameter (OD), (c) selecting points on the inner diameter (ID) after turning the point cloud inside out, (d) fitting circles to the interior and exterior points per the Newton Pratt method [51], and (e) comparing ID and ODs, as shown in Figure 6.11.
The location of the waist was found manually, as there can be some noise in data, specifically near the build plate of the part.

6.6. Results

The plot of waist displacement with respect to layer height is shown in Figure 6.12.

The model results are all within around 10% of each other because the modeling problem is not particularly sensitive to the modeling workflow. One likely reason for the difference in the results could be that there are some relaxation effects occurring, where if material is reheated, it reverts to a semi-molten state. A plot of waist displacement with respect to nozzle temperature is shown in Figure 6.13.
Figure 6.13: Waist displacement as a function of nozzle temperature.

The plot above shows that apart from the runs at 190 °C, the experimental and model results matched up quite nicely. A likely reason for this is that the melt temperature of PLA is around 180 °C and the nozzle temperature used was only causing partial melting of the polymer. A plot of waist displacement with respect to layer time is shown in Figure 6.14.

Figure 6.14: Effect of layer time.
From the above plots it is apparent that the models and experiments in general match up, where they differ is mainly due to nozzle temperature. A summary showing the average percent difference between the models and experiments is shown in Figure 6.15.

![Percent Difference Chart]

Figure 6.15: Average percent difference between modeling methods and experimental.

The plot above shows that the difference in results between the three methods is small. When compared to the experimental results all three approaches were on average within 10% of the experimental results meaning that as far as warpage is concerned, all three approaches work just as fine for this case.

The average runtimes for the different modeling approaches are shown in Figure 6.16.

![Average Runtime Chart]

Figure 6.16: Average runtime of modeling approaches.
The increase in runtimes between the different modeling methods can be attributed to two reasons. First, the CLOSAMS and Hybrid workflows had ~40 times the degrees of freedom than the Abaqus AM workflow. The effect of increasing the DOFs is shown by the increase in runtime between the Abaqus AM and Hybrid approaches which comes out to be an around 1000% increase in runtime. Second, the effect of the activation method is seen by going from the Hybrid to the CLOSAMS approach which gives an approximately 600% increase in runtime. The increase in runtime combined with no apparent increase in accuracy means that the most efficient method for modeling warpage appears to be the Abaqus AM workflow.

6.7. Concluding remarks

The Hybrid and CLOSAMS workflows are limited to simple geometries, such as hollow right cylinders discussed in this chapter and other simple shapes. Additionally, the Hybrid and CLOSAMS workflows’ increased number of degrees of freedom causes simulations of simple geometries to require 1000% to 6000% longer than Abaqus AM. Hence, the Abaqus AM workflow is preferred for most real-world geometries.
CHAPTER 7

7. VALIDATING ABAQUS AM WORKFLOW ON LARGE SCALE GEOMETRIES IN CF-PETG

7.1. Introduction

To validate the Abaqus AM workflow with fiber-reinforced materials, different geometries were printed in CF-PETg on a BAAM. This work also involved material testing and characterization of the as-printed material to create a material model that will be plugged into the process model. The warpage of the printed geometries will be compared to the warpage as predicted by the process model.

7.1.1. Objectives

The objectives are:

- Create and validate a material model for CF-PETg
- Validate the numerical process model for large geometries

7.2. Geometries

7.2.1. T Section

To provide a more thorough validation the model will be validated on two different geometries. The first validation geometry was a T section as shown in Figure 7.1. Layers will be stacked along the Z direction.

Figure 7.1: T section showing global coordinate system (units: mm)
7.2.2. Corrugated Wall

The second validation geometry was a corrugated wall having dimensions shown in Figure 7.2 and Figure 7.3, the part was printed with the layer being stacked in the Z direction.

![Figure 7.2: Isometric view of corrugated wall (units: mm).](image)

![Figure 7.3: Top view of corrugated wall (units: mm).](image)

7.3. Carbon Fiber Reinforced PETg

The material used for printing the part is Techmer PM Elecrafil 1711 3DP carbon fiber reinforced Polyethylene terephthalate glycol (CF-PETg), which contains 30% by volume of carbon fibers in a PETg matrix. An image of the material in pelletized form is shown in Figure 7.4.
Additionally, PETg is a relatively amorphous polymer [52] meaning in general it can be assumed to have a low crystallinity, so crystallization effects may be ignored.

Techmer PM Elecrafil 1711 3DP carbon fiber reinforced Polyethylene terephthalate glycol (CF-PETg) materials were characterized via quasi-static tensile testing and coefficient of thermal expansion testing whose results are shown in Table 7.1. Parts were printed on a Cincinnati BAAM machine and then CNC machined out to create the appropriate specimen shape per the ASTM standard. The drying and printing steps for the specimens were performed on the same equipment and utilized similar processing settings as the corrugated wall.

7.3.1. Static Testing

Quasi-static testing of six specimens – three in the 11 material direction parallel with the bead, and three in the 33 material direction along with three in shear in the 13 direction– was performed in accordance with ASTM D638 [49] and ASTM 7078 [53]. Each specimen was tested within 26 days of printing and was stored at room temperature at ambient humidity. Representative results in the 11, 33, and 13 directions are summarized in Figure 7.5, Figure 7.6, and Figure 7.7, respectively.
Figure 7.5: Representative stress-strain curves for Techmer PM Elecrasil 1711 3DP carbon fiber reinforced Polyethylene terephthalate glycol (CF-PETg) in the 11 direction.

Figure 7.6: Representative stress-strain curve for Techmer PM Elecrasil 1711 3DP carbon fiber reinforced Polyethylene terephthalate glycol (CF-PETg) in the 33 direction.
Elastic moduli from static testing are summarized in Table 7.1.

Table 7.1: Summarized elastic constants from static testing.

<table>
<thead>
<tr>
<th>Modulus</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$</td>
<td>12.2 GPa</td>
</tr>
<tr>
<td>$E_{33}$</td>
<td>2.70 GPa</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>1120 MPa</td>
</tr>
</tbody>
</table>

This contrasts with the same material printed on a Masterprint [54]. Where the tensile moduli in the 11 and 33 direction were 5.4 GPa and 2.67 GPa, respectively.

7.3.2. Thermal Expansion Parameters

Coefficient of thermal expansion (CTE) measurements were evaluated per ASTM E831-19 [55]. Testing included a total of nine nominally 7 x 5 x 5 mm specimen. three in the 11 direction along the printed bead direction, three in the 22 direction perpendicular to the 11 direction in the build plane, and three in the 33 direction out of the build plane. Specimens were excised via a subtractive CNC mill. The CF-PETg specimen were manufactured on a Big Area Additive Manufacturing (BAAM) using Techmer CF-PETg using the settings in Table 7.2 on the 7th of October 2021.
Figure 7.8 shows the overall 3D-printed part (left) and the CTE specimens (right).

Table 7.2: Printing parameters for CTE specimen

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer Thickness</td>
<td>5.08 mm (0.2”)</td>
</tr>
<tr>
<td>Bead Width</td>
<td>15.9 mm (0.65”)</td>
</tr>
<tr>
<td>Nozzle Temperature</td>
<td>190 ℃</td>
</tr>
<tr>
<td>Feed rate</td>
<td>100%</td>
</tr>
<tr>
<td>Infill</td>
<td>100%</td>
</tr>
<tr>
<td>Screw Speed</td>
<td>300 RPM</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>0.066%</td>
</tr>
</tbody>
</table>
Figure 7.8: Orientation of specimens in relation to original panel. (b) Specimens that were tested and the orientation in which they were tested. From top to bottom: 11 direction, 22 direction, 33 direction.

The sample ID and dimensions of each CTE specimen are shown in Table 7.2.

**Table 7.3 Dimensions of CTE Specimen**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>X dimension (mm)</th>
<th>Y dimension (mm)</th>
<th>Z dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X2</td>
<td>8.45</td>
<td>5.07</td>
<td>5.02</td>
</tr>
<tr>
<td>X4</td>
<td>8.54</td>
<td>5.01</td>
<td>5.01</td>
</tr>
<tr>
<td>X6</td>
<td>8.53</td>
<td>5.01</td>
<td>5.00</td>
</tr>
<tr>
<td>Y1</td>
<td>10.05</td>
<td>5.02</td>
<td>5.02</td>
</tr>
<tr>
<td>Y2</td>
<td>10.06</td>
<td>5.02</td>
<td>5.02</td>
</tr>
<tr>
<td>Y4</td>
<td>10.02</td>
<td>5.03</td>
<td>5.04</td>
</tr>
<tr>
<td>Z1</td>
<td>5.05</td>
<td>5.01</td>
<td>7.01</td>
</tr>
<tr>
<td>Z2</td>
<td>5.09</td>
<td>5.00</td>
<td>6.99</td>
</tr>
<tr>
<td>Z3</td>
<td>5.09</td>
<td>5.00</td>
<td>7.01</td>
</tr>
</tbody>
</table>

CTE measurements were performed on a TA instruments Q400 thermomechanical analyzer (TMA). Technical specifications for the TMA are shown in Table 7.4.
Table 7.4: TA instruments Q400 TMA specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Range</td>
<td>150 to 1,000 °C</td>
</tr>
<tr>
<td>Temperature Precision</td>
<td>± 1 °C</td>
</tr>
<tr>
<td>Maximum Sample Size - solid</td>
<td>26 mm (L) x 10 mm (D)</td>
</tr>
<tr>
<td>Maximum Sample Size – film/fiber</td>
<td>26 mm (L) x 0.5 mm (T) x 4.7 mm (W)</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>15 nm</td>
</tr>
<tr>
<td>Force Range</td>
<td>0.001 to 1 N</td>
</tr>
</tbody>
</table>

7.3.3. Temperature dependent properties

The elastic constants of the material are assumed to decrease with respect to temperature at the same rate as the storage modulus per the multifactor approach. The storage modulus (G’) is the value in Dynamic Mechanical Analysis (DMA) that is used to indicate the amount of elastic energy stored. In this case, G’ is assumed to be analogous to the elastic modulus at room temperature [56]. This allows for the elastic constants to be given as a function of temperature. The storage modulus for neat PETg at room temperature was assumed to be 6.2 GPa (cf. Bhandari et al. [43]). The temperature-dependent storage modulus for neat PETg used from [43] is shown in Figure 7.9.
This can be used as the reference property in the multifactor technique, to estimate the temperature dependent elastic properties for the material. This curve was also used to estimate the glass transition temperature $T_g = 88 \, ^\circ C$, at which the material transitions from elastic response at temperatures less than $T_g$ to a viscous response for temperature greater than $T_g$. The temperature dependent elastic properties passed to the model are shown in Figure 7.10.
Lacking empirical data in the 12 direction, the material was assumed to be transversely isotropic, meaning parameters for the 13 direction were assumed for the 12 direction.

7.4. Mesh and Time Step Validation

A mesh convergence study was conducted using the T section geometry (cf. Figure 7.1) and the mesh densities shown in Figure 7.11. In Figure 7.11, subfigures (a), (b), and (c) show meshes having a single element, four elements, and 16 elements, respectively, per bead cross section, the element density out of the page also doubled in each refinement, leading to the number of elements increasing by a factor of 8 from subfigure (a) to subfigure (b), and from subfigure (b) to subfigure (c). The meshes shown in Figure 7.11(a), (b), and (c) resulted in 2,565, 16,720, and 132,924 elements, respectively, for the T section geometry (cf. Figure 7.11).
For each of the three meshes, the displacements in the Z direction of each of the four corner nodes on the T section’s bottom surface were averaged. The percent difference of the average Z displacements for the meshes shown in Figure 7.11 (a), (b), and (c) were calculated. Similarly, a percent difference of the average Z displacements for the meshes shown in Figure 7.11 (a), (b), and (c) were calculated. Figure 7.12 shows the % difference in the average Z displacement of the meshes shown in Figure 7.11 (a) and (b) using the Z displacement of the mesh shown in subfigure 7.11(c) as a reference. Figure 7.12 also shows an exponential equation fit to the percent differences.
Mesh convergence was assumed to occur for meshes having an average Z displacement within 5% of the average Z displacement of the mesh shown in Figure 7.11 c. Based upon this criterion, the meshes shown in Figure 7.11 (a) and Figure 7.11 (b) are converged. The results presented here agree with results found in Cattenone et al. [7], which found that converged meshes may contain elements spanning multiple beads. Based upon these results, simulations of T sections will utilize four elements per bead, and simulations of the subcomponent geometry will utilize one element per bead to facilitate tractable numerical problems.

7.5. Experimental Validation

7.5.1. Manufacturing

Parts were manufactured on a Cincinnati Incorporated Big Area Additive Manufacturing (BAAM) Print parameters for the T section are shown in Table 7.5.

<table>
<thead>
<tr>
<th>T section Serial Number</th>
<th>Nozzle Temp (°C)</th>
<th>Layer Time (s)</th>
<th>Screw Speed (RPM)</th>
<th>Layer Height (mm)</th>
<th>Bead Width (mm)</th>
<th>Batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>205</td>
<td>270</td>
<td>80</td>
<td>5.08</td>
<td>15.9</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>205</td>
<td>270</td>
<td>80</td>
<td>5.08</td>
<td>15.9</td>
<td>1</td>
</tr>
<tr>
<td>2.1</td>
<td>195</td>
<td>270</td>
<td>50</td>
<td>5.08</td>
<td>15.9</td>
<td>2</td>
</tr>
<tr>
<td>2.2</td>
<td>195</td>
<td>270</td>
<td>50</td>
<td>5.08</td>
<td>15.9</td>
<td>2</td>
</tr>
</tbody>
</table>

A batch is a group of parts that were printed at the same time. The screw speed was changed to prevent over extruding. Additionally, a minimum layer time was enforced to allow for the polymer to cool down and solidify before printing over it. A slicer rendering of the G-code for the T section is shown in Figure 7.13 the grey lines correspond to travel movements, and the green lines correspond to extrusion movements.
Images for the four realized T sections are shown in Figure 7.14.

The corrugated wall was printed on a BAAM and sliced with ORNL Slicer 1 [57]. A rendering of the first 50 layers of the wall in G-code is shown in Figure 7.15. The brown lines are build plate partitions, and the volume boundaries are shown in black.
Figure 7.15: Rendering showing the first 50 layers of the corrugated wall’s 200 total G-code layers. The brown lines indicate separations in the build plates making up the build surface area.

Print parameters for the wall are given in Table 7.6.

Table 7.6: Print parameters for corrugated wall.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Temperature</td>
<td>215 °C</td>
</tr>
<tr>
<td>Layer Time</td>
<td>300 s</td>
</tr>
<tr>
<td>Screw Speed</td>
<td>300 rpm</td>
</tr>
<tr>
<td>Bead Height</td>
<td>5.08 mm (0.2&quot;)</td>
</tr>
<tr>
<td>Bead Width</td>
<td>15.9 mm (0.65&quot;)</td>
</tr>
</tbody>
</table>
The realized corrugated wall is shown in Figure 7.15.

![Figure 7.16: Realized wall of 200 layers.](image)

7.5.2. Quantification

The warpage of the parts was quantified by scanning the bottom surface of the parts with a Faro arm.

7.6. T Section Results

Warpage for each realized T section was defined as the deviation of the bottom surface \((Z = 0)\) from a flat plane. The deviation map Figure 7.17 shows two major features. The first feature is the yellow vertical line, which has a positive deviation compared to the nearby region. This is likely a break in the build plate. The second feature is in the upper right corner of Figure 7.17 and has an upper-left-to-lower-right diagonal region having a positive deviation compared to the nearby region. Both the first and second features were likely formed due to geometric features on the build sheet. The lack of additional features (e.g., an observable surface roughness or other features caused by the build plate) indicates that global warpage was less than approximately 0.3 mm.
Except for the end-of-bead 180° turns shown at the far left and right, the T section beads were generally aligned. Although this alignment could allow local material directions to be defined globally for T section simulations, the desire to simulate components having non-aligned beads motivates the search for a more general definition of local material directions.
Deviation maps of the bottom surfaces of the four realized T sections are shown in Figure 7.18

![Figure 7.18: Experimental bottom surfaces.](image)

Based upon visual inspection, the bottom surface of the T sections are very rough and there appears to be negligible warpage when compared to the surface roughness on the top surfaces of the part. Additionally, the surface roughness of the part will add uncertainty to the warpage measurements of the corrugated wall [58]. To get a measure of this, a histogram of the Z coordinates of a 3 cm × 3 cm square at the center of the bottom surface of T section 1.2 was made Figure 7.19.
Figure 7.19: Histogram of $Z$ coordinates for a $3 \text{ cm} \times 3 \text{ cm}$ region of T section 1.2. The long tail going in the negative direction can be attributed to inter bead grooves.

From this plot it is apparent that inter-bead grooves and other small scale surface features contribute to warpage uncertainty.
7.6.1. Comparison

Deviation maps for the bottom surfaces of the T section models and experiments are shown in Figure 7.20.

Figure 7.20 Simulated and experimental bottom surfaces of T sections. Simulated results are for Model (Batch 1) and Model (Batch 2); experimental results are for T sections 1.1, 1.2, 2.1, and 2.2.

These maps show that the deviations on the bottom surfaces of the T sections appear to be dominated by the roughness of the build substrate and other build substrate features. If there is warpage it is likely on a length scale on the order of 0.1 mm. Because 1.2 and 2.2 were printed at the same locale on the print bed, ridges and other prominent features likely exist on the build surface that are leaving impressions on the part.
7.7. Corrugated Wall

7.7.1. Experimental

A contour plot of the deviation from planarity of the bottom surface of the wall is shown in Figure 7.21.

Figure 7.21: Deviation map showing the bottom surface of the 3D-printed corrugated wall. Negative deviations indicate a deviation into the part; positive deviations indicate a deviation away from the part.

The wall bottom surface is mostly warping along the long axis of the part. The raw warpage of the bottom surface is found by taking the range of $Z$ displacements of the bottom surface, which in this case is 2.62 mm. The three vertical regions, or ridges, in the contour plot resulted from discontinuities in the build plate (cf. Figure 7.15). Note the ridge approximately 0.3 mm high, which is a feature that is picked up in a max $Z$ displacement in the middle of the part. This means true warpage when accounting for this build plate discontinuities was 2.32 mm, meaning that measuring the warpage of this part is hampered by the low ratio relative to roughness.
7.7.2. Simulated

Process model results for the wall are shown in Figure 7.22.

Figure 7.22: Simulated displacement magnitude of corrugated wall

Note that some of the contours appear to line up with where the skin meets the infill. As shown by the blue-colored displacement contours on the vertical wall section of the wall, some of the simulated displacement contours appear to coincide and be caused by the infill.
7.7.3. Comparison

Deviation from flat of the bottom surface of the wall are shown alongside scan data from the realized part in Figure 7.23.

Figure 7.23: Deviation maps in the Z direction for (a) a simulated and (b) the realized corrugated wall. The three vertical lines in (b) correspond to breaks in the build plate.

The deviation maps for the simulated and realized corrugated walls are similar. The total warpage was defined as the maximum minus the minimum deviation from flat of the bottom surface of the part. The realized wall warped 2.32 mm excluding the 0.3-mm center ridge resulting from the build plate discontinuity, while the model predicted a warpage of 2.33 mm, resulting in an <1% difference between the simulated and experimental results. The 0.01 mm difference in max warpage between simulated and experimental results was less than the 0.5-mm surface roughness estimated via the T sections.
7.8. Final Remarks

Models for the printing process of large-scale geometries were created. These models were then used to predict the warpage of the large-scale geometries of the parts. Results from these models were validated against scans of the realized parts created using Faro Arms. This exercise also validates the modeling approach used, meaning that it can be used for future warpage models. This also highlights that for smaller parts, the warpage will be overshadowed by the surface roughness of the part. This approach shows the effectiveness of using correlations to minimize the amount of characterization work.
8. SENSITIVITY OF SIMULATED WARPAGE AS A FUNCTION OF MATERIAL PARAMETERS

8.1. Motivations

Looking at the effect of material parameters on simulated warpage in the form of a sensitivity analysis provides important insights. First, a sensitivity analysis can reduce labor and resource requirements during material characterization efforts, by informing which properties are most important. Second, a sensitivity analysis can identify the most consequential material properties, thus informing material selection efforts.

8.2. Methodology

8.2.1. Development of Neat PETg material model

Neat PETg has a room-temperature elastic modulus of 2 GPa [59], and a Poisson’s ratio of 0.36. The curve used to extrapolate the high temperature elastic properties is from [43]. The extrapolated elastic modulus is shown in Figure 8.1.

![Figure 8.1: Elastic modulus of neat PETg as a function of temperature](image)

Although a temperature-dependent orthotropic constitutive model is included in the workflow, directionally dependent moduli for neat PETg were unavailable. Hence, the temperature-dependent isotropic parameters shown in Figure 8.1 were assumed. One thing to note is that Abaqus will linearly interpolate between the points.
The values for CTE for PETg are from [6] and were evaluated using the same process for the CF-PETg model from Chapter 5. The room temperature value used was 60 μm/K. The thermal conductivity was assumed to be isotropic and have values of 0.3 W/m K.

8.2.2. Geometry

The linear spring geometry is shown in Figure 8.11.

![Linear spring geometry](image)

**Figure 8.2: Linear spring geometry for material parameter sensitivity study (units: mm).**

Inspired by Cattenone et. al [7], the linear spring geometry amplifies warpage via large in-plane dimensions and small out-of-plane dimensions. The linear spring’s warpage amplification contrasts with the T sections described in Chapter 8.

8.2.3. Boundary Conditions

The thermal boundary conditions for all the model runs associated with this model are shown in Figure 8.3. The environmental temperature is based on values obtained by placing a thermocouple in the enclosure which was connected to a Fluke 116 multimeter. The nozzle temperature corresponds to the temperature of the nozzle heat band that is set in the slicer.
Figure 8.3: Thermal boundary conditions.

The build plate was simulated as thermally thin meaning the nodes @ z = 0 were fixed at 80 °C. This reflects that the build plate on the Gigabot is made from a thermally conductive material (aluminum). The convection coefficient was applied globally to all free surfaces of the part.

8.2.4. **DOE**

To show the effects of material on a model for the geometry will have the material properties varied according to a fractional factorial DOE. The nominal material properties for this geometry are the CF-PETg material model developed in section 7.3.

An 11-factor, 2-level resolution IV fractional factorial DOE was conducted using the factors and levels shown in Table 8.1. The high and low levels for the factors are based on ± 15% of the nominal, or “mid,” values to normalize the range of the factor levels. A resolution IV fractional factorial DOE is appropriate because 3rd order effects were expected to be negligible.
Table 8.1: DOE 1 (CF-PETg)

<table>
<thead>
<tr>
<th>Coded Factor</th>
<th>Definition</th>
<th>Factor</th>
<th>LOW</th>
<th>MID</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A Thermal Conductivity (W/m K)</td>
<td></td>
<td>0.255</td>
<td>0.300</td>
<td>0.345</td>
</tr>
<tr>
<td>B</td>
<td>B E11 (GPa)</td>
<td></td>
<td>9.52</td>
<td>11.2</td>
<td>12.9</td>
</tr>
<tr>
<td>C</td>
<td>C E22 (GPa)</td>
<td></td>
<td>1.87</td>
<td>2.20</td>
<td>2.53</td>
</tr>
<tr>
<td>D</td>
<td>D E33 (GPa)</td>
<td></td>
<td>1.87</td>
<td>2.20</td>
<td>2.53</td>
</tr>
<tr>
<td>E</td>
<td>E E12 (GPa)</td>
<td></td>
<td>1.04</td>
<td>1.22</td>
<td>1.40</td>
</tr>
<tr>
<td>F</td>
<td>ABC E23 (GPa)</td>
<td></td>
<td>1.04</td>
<td>1.22</td>
<td>1.40</td>
</tr>
<tr>
<td>G</td>
<td>BCD E13 (GPa)</td>
<td></td>
<td>.748</td>
<td>.8.80</td>
<td>1.01</td>
</tr>
<tr>
<td>I</td>
<td>CDE α-11 (1/K)</td>
<td></td>
<td>6.80E-06</td>
<td>8.00E-06</td>
<td>9.20E-06</td>
</tr>
<tr>
<td>J</td>
<td>ACD α-22 (1/K)</td>
<td></td>
<td>2.13E-05</td>
<td>2.50E-05</td>
<td>2.88E-05</td>
</tr>
<tr>
<td>K</td>
<td>ADE α-33 (1/K)</td>
<td></td>
<td>8.50E-05</td>
<td>1.00E-04</td>
<td>1.15E-04</td>
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<tr>
<td>L</td>
<td>CDE ρ (kg/m^3)</td>
<td></td>
<td>1.02E+03</td>
<td>1.20E+03</td>
<td>1.38E+03</td>
</tr>
</tbody>
</table>

The goal of this DOE is to screen for the most important factors for simulating process-induced warpage within TEAM. This DOE is also meant for looking at linear effects because of the number of factors. Additionally, one center point where all the factors are set to their midpoint value called run 0 will be run which corresponds to the baseline material model and will be the run compared to experimental results. Additionally, another DOE with properties of neat PETg was run; the factors are shown in Table 8.2.
### Table 8.2: Neat PETg Properties

<table>
<thead>
<tr>
<th>Coded Factor</th>
<th>Definition</th>
<th>Parameter</th>
<th>LOW</th>
<th>MID</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>Thermal Conductivity (W/m K)</td>
<td>0.255</td>
<td>0.3</td>
<td>0.345</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>E11 (GPa)</td>
<td>1.70</td>
<td>2.00</td>
<td>2.30</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>E22 (GPa)</td>
<td>1.70</td>
<td>2.00</td>
<td>2.30</td>
</tr>
<tr>
<td>D</td>
<td>D</td>
<td>E33 (GPa)</td>
<td>1.70</td>
<td>2.00</td>
<td>2.30</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>E12 (GPa)</td>
<td>0.723</td>
<td>0.850</td>
<td>0.978</td>
</tr>
<tr>
<td>F</td>
<td>ABC</td>
<td>E23 (GPa)</td>
<td>0.723</td>
<td>0.850</td>
<td>0.978</td>
</tr>
<tr>
<td>G</td>
<td>BCD</td>
<td>E13 (GPa)</td>
<td>0.723</td>
<td>0.850</td>
<td>0.978</td>
</tr>
<tr>
<td>I</td>
<td>CDE</td>
<td>α-11 (1/K)</td>
<td>0.000051</td>
<td>0.00006</td>
<td>0.000069</td>
</tr>
<tr>
<td>J</td>
<td>ACD</td>
<td>α-22 (1/K)</td>
<td>0.000051</td>
<td>0.00006</td>
<td>0.000069</td>
</tr>
<tr>
<td>K</td>
<td>ADE</td>
<td>α-33 (1/K)</td>
<td>0.000051</td>
<td>0.00006</td>
<td>0.000069</td>
</tr>
<tr>
<td>L</td>
<td>CDE</td>
<td>ρ (kg/m^3)</td>
<td>1020</td>
<td>1200</td>
<td>1380</td>
</tr>
</tbody>
</table>

#### 8.2.5. Warpage Measurement

For this geometry, the quantity of interest will be the change in length of the top and bottom sides of the part, which are referred to as TL and BL, respectively. This is shown onto contours showing the X displacement (U1) in meters of the top surface Figure 8.4.
For validation, top and bottom length is difficult to measure because of beads, and the flexible geometry of the part. So, the $z$ displacements of the bottom surface will be used for validation purposes. Additionally, the maximum stresses in the material’s 11, 22, and 33 directions will be evaluated and are referenced in the results as S1, S2, and S3, respectively.

8.3. Experimental Validation and Digital Twin

To increase the applicability of the results produced, a real-life counterpart to this experiment will be done. This will be done with CF-PETg and neat PETg and will investigate the effects of warpage on the realized parts. Part will be printed on Gigabot X with a 2.8 mm diameter nozzle and an 0.6 x 0.6 x .45 m build volume using the two different PETgs shown in Table 8.3.
Table 8.3: PETg varieties

<table>
<thead>
<tr>
<th>Material</th>
<th>CF-PETg</th>
<th>Neat PETg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade Name</td>
<td>Electrafil</td>
<td>Hifill</td>
</tr>
<tr>
<td>Vendor</td>
<td>Techmer</td>
<td>Techmer</td>
</tr>
<tr>
<td>Filler &amp; VF</td>
<td>20% Carbon Fiber</td>
<td>Neat</td>
</tr>
</tbody>
</table>

An image of the setup is shown in Figure 8.5.

Figure 8.5: Gigabot X with instrumentation

The Gigabot is fitted with a pellet extruder. An image showing the components of the extrusion portion of the Gigabot is shown in Figure 8.6.
A couple of days before printing, pellets are dried in an oven per the datasheets to make sure the pellets are dry. Then, pellets are placed in the hopper, which accumulates, and feeds pellets to the extruder. The agitator prevents clogging and ensures a consistent flow of pellets to the extruder. Then the pellets are heated – by shear stresses applied by the extruder and by three heat bands external to the extruder barrel – before being extruded out the nozzle.

8.3.1. Neat PETg

The print parameters are shown in Table 8.4
Table 8.4 Print Parameters for Neat PETg

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>10 mm/s</td>
</tr>
<tr>
<td>Zone 1 Temperature</td>
<td>240 °C</td>
</tr>
<tr>
<td>Zone 2 Temperature</td>
<td>230 °C</td>
</tr>
<tr>
<td>Zone 3 Temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Measured enclosure temperature</td>
<td>32.1</td>
</tr>
</tbody>
</table>

An image of the part being printed is shown in Figure 8.7

Figure 8.7: Neat PETg linear spring being printed

The part was printed on blue painter’s tape oriented along the part’s long axis of the part. The part was scanned after spraying with Dynaflux DNF crack developer. The developed part is shown in Figure 8.8.
Figure 8.8: Neat PETg part after spraying with developer.

The developer makes the surface of the part scan better by providing a matte surface.

8.3.2. Carbon Fiber PETg

The print parameters for the realization in this material are shown in Table 8.5.

Table 8.5: Print Parameters for CF-PETg

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>10 mm/s</td>
</tr>
<tr>
<td>Zone 1 Temperature</td>
<td>240 °C</td>
</tr>
<tr>
<td>Zone 2 Temperature</td>
<td>230 °C</td>
</tr>
<tr>
<td>Zone 3 Temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Measured enclosure temperature</td>
<td>32.1 °C</td>
</tr>
</tbody>
</table>

An image of the realized part is shown in Figure 8.9.
8.4. Model Validation and Results

Images of the bottom surfaces of the realized parts are shown with the simulated out-of-plane warpages are shown in Figure 8.10.

The CF-PETg model and experiment match up in that both have very little warpage. While the neat PETg model does not match, the most likely case for this is the part deforming as a result of handling, as the part is quite flexible and deforms visibly under its own weight. The simulated results for neat and filled models appear to match up because both results lie in the middle of the scale because the warpage magnitude of the models is small relative to the experiments, but upon closer inspection, the neat PETg has some regions that lie in a different contour zone, and these regions appear to superficially match the some of the regions in the experimental PETg bottom surface.
8.4.1. CF – PETg

The overall effect of the different material properties can best be seen using a sensitivity index, which is defined here as the ratio of the sum of squares of a given factor to the total sum of squares. This is meant to be a method of ranking the relative importance of different factors. The sensitivity index for the top and bottom lengths (TL, BL) shown in Figure 8.4 and the maximum stress in the 11 22 and 33 directions (S1,S2,S3) are shown in Figure 8.11.

![Figure 8.11: Sensitivity indices for material factors of CF-PETg](image)

This shows the most important factors for warpage are the αs or the coefficient of thermal expansions (CTEs); for stress the most important factors are both moduli of elasticity and CTEs. Which makes sense given the expression from Armillota [11], where the expression for thermal stress can be written as (Eq. 8.1).

\[ \sigma_{ij}^{th} = C_{ijkl} \alpha_{kl}(T - T_0) \]  

(8.1)
Where $\sigma^{th}$ is the thermal stress component of the stress tensor, $C$ is the stiffness tensor, and $\alpha$ is the thermal contraction tensor. Defined as a tensor relating the change in temperature $\Delta T$ to the thermal strain tensor $\epsilon^{th}$. The thermal contraction tensor is often a diagonal tensor, and in isotropic materials can be represented as $\delta_{kl}\alpha$ where $\alpha$ is the isotropic coefficient of thermal expansion and $\delta$ is the Kronecker delta. This shows that the primary straining mode is normal.

8.4.2. Neat PETg

The sensitivity index for the top and bottom lengths (TL, BL) and the maximum stress in the 11 22 and 33 directions ($S_1, S_2, S_3$) are shown in Figure 8.12.

![Figure 8.12: Sensitivity Index for neat PETg.](image)

Again, it is shown that CTE is the most important factor as far as warpage is concerned. Additionally, there appears to be less coupling between directions, as the effect of $\alpha_{11}$ on max stress in the 22 direction is less for the unfilled PETg. The results otherwise match up with the results from CF-PETg.
8.5. Findings

The results make sense because thermal expansion is one of the phenomena that drives everything else. Additionally, stiffness having a minuscule effect on warpage is consistent with Armillotta [11], which finds that the modulus of elasticity cancels out of analytical expressions for warpage. Additionally, the CTE in the 33 direction being relatively insignificant is also expected because it does not induce a bending and is not restrained as the top surface of the part is free.

One of the reasons for the difference in the effects between the neat and filled model is the spans between the high and low levels are based on ±15% of the baseline value meaning that because the baseline value of the CTE in the 11 direction for the neat PETg is much greater than that of the CF-PETg.

If looking for a polymer that will warp more look for a polymer with a higher coefficient of thermal expansion. Something like CF-PC or similar is recommended which has a higher $T_g$ and a much higher CTE, this is shown in Figure 8.13.

8.6. Concluding Remarks

The effect of material properties on the warpage and residual stresses in 3D-printed parts was calculated for two linear springs simulating the printing of CF-PETg and neat PETg on a Gigabot X. Results from the numerical models were then compared to experimental data, which was inconclusive because of the compliance of the as-printed parts.
The findings presented in this chapter are limited by several assumptions. First, the findings are limited in that the assumptions used to model the material need to still hold. Second, a comparison of as-simulated and as-measured temperatures was precluded by an inability of the thermography camera to measure temperatures through a Plexiglas door and the requirement to keep the door closed to maintain build envelope temperature. Third, the findings are limited by a lack of proper simulation of the relaxation of the print, which is implicitly handled in the no thermal contraction above $T_g$ assumption. Finally, the linear spring parts were compliant and could be plastically deformed when removing the part from the print bed. Future research may benefit from less compliant geometries. Additionally different polymers could be used to get a wider coverage of materials.
CHAPTER 9

9. SCALING EFFECTS

9.1. Motivations

Additive manufacturing occurs at many different length scales, and if a scaling correlation is created, then small scale results can be used to inform large scale printing. Meaning that a workflow to predict the warpage of large-scale objects could look like Figure 9.1.

![Figure 9.1: Workflow incorporating using scale parts to limit large scale iterations.](image)

This is where once a model that can take the warpage of a scale part and predict the warpage of the total part is found, scale models can be used to evaluate the warpage of the full-scale part, which can save material and machine time for the large-scale printers.

9.2. Geometries

Three different length scales were selected, the geometry was dimensioned in terms of bead widths and height. A table summarizing the three different length scales is shown in Figure 9.1.

Table 9.1: Table showing bead dimensions for the different printer.

<table>
<thead>
<tr>
<th>Printer</th>
<th>Bead Height (mm)</th>
<th>Bead Width (mm)</th>
<th>Bead Aspect Ratio</th>
<th>Scale to BAAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimaker S5</td>
<td>0.32</td>
<td>1</td>
<td>3.125</td>
<td>15.875</td>
</tr>
<tr>
<td>Gigabot</td>
<td>1.28</td>
<td>4</td>
<td>3.125</td>
<td>3.96875</td>
</tr>
<tr>
<td>BAAM</td>
<td>5.08</td>
<td>15.875</td>
<td>3.125</td>
<td>1</td>
</tr>
</tbody>
</table>

The geometry to be printed for the BAAM is shown in Figure 9.2.
Figure 9.2: BAAM Geometry (Inches shown because sliced in IPS)

The geometry and the G-code for the Gigabot is shown in Figure 9.3.

Figure 9.3: G-code and dimensions for Gigabot (units: mm)
An image of the toolpath and geometry for the Ultimaker is shown in Figure 9.4.

Figure 9.4: G-code and dimensions for Ultimaker (units mm).

All of the parts are scale models of each other, the Ultimaker part is a 1:4 scale of the Gigabot part, which in turn is a 1:4 scale of the BAAM part.

9.3. Printing

The print parameters for the CF-PETg printed on the Gigabot are shown in Table 9.2.

Table 9.2: Print parameters for CF-PETg on the Gigabot.

<table>
<thead>
<tr>
<th>Print Speed</th>
<th>10 mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 Temperature</td>
<td>240 °C</td>
</tr>
<tr>
<td>Zone 2 Temperature</td>
<td>230 °C</td>
</tr>
<tr>
<td>Zone 3 Temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Measured enclosure temperature</td>
<td>32.1 °C</td>
</tr>
</tbody>
</table>

An image of the part being printed is shown in Figure 9.5.
The print parameters for the neat PETg printed on the Gigabot are shown in Table 9.3.

Table 9.3: Neat PETg print parameters for the Gigabot.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>10 mm/s</td>
</tr>
<tr>
<td>Zone 1 Temperature</td>
<td>240 °C</td>
</tr>
<tr>
<td>Zone 2 Temperature</td>
<td>230 °C</td>
</tr>
<tr>
<td>Zone 3 Temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Measured enclosure temperature</td>
<td>32.1 °C</td>
</tr>
</tbody>
</table>

An image of the part being printed is shown in Figure 9.6.
The part was also printed on an Ultimaker the completed part is shown Figure 9.7.

The print parameters for the part on the Ultimaker S5 are given in Table 2.1. The part was printed in Ultimaker black PETg which was dried and kept in an airtight cabinet with desiccant.
Table 9.4: Print Parameters for the Ultimaker

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>10 mm/s</td>
</tr>
<tr>
<td>Nozzle Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Measured enclosure temperature</td>
<td>N/A</td>
</tr>
</tbody>
</table>

After printing the part was scanned with a FARO arm to get the bottom surface deviation.

9.4. Environmental Phenomena

The environmental phenomena take the form of boundary conditions. The boundary conditions applied to the BAAM numerical models differed from those applied to the Gigabot and Ultimaker numerical model. The boundary conditions applied to the Gigabot and Ultimaker models are shown in Figure 9.8.

Figure 9.8 Gigabot and Ultimaker Boundary Conditions

The difference is that for the BAAM scale prints the bed temperature was set to 60 °C and the nozzle temperature was set to 205 °C to reflect the print parameters from Chapter 7. The BAAM environmental conditions are given in Figure 9.9.
9.5. Materials

Both parts will be printed out of Carbon Fiber reinforced PETg using the same material model as in section 8. The source (Techmer) is the same as the one from section 8. Additionally, the materials were dried for per the datasheets [60]. in accordance with the material datasheet to ensure no degradation of the material properties. The filament used on the Ultimaker is Ultimaker black PETg. The same PETg material model was used for both PETg varieties, which because of the different additives and colorants added by the compounder [61] likely have different properties.
9.6. Validation

Plots of the convergence with respect to time step for the three length scales are shown in Figure 9.10.

The models for all three length scales have converged.

Images of the scanned bottom surfaces of the printed parts next to the bottom surface of the corresponding model are shown in Figure 9.11.
One of the possible reasons for the realized parts on the Gigabot differing from the model is because a higher bed temperature was used which is in the regime where the part starts acting rubbery, meaning that the material model out of the envelope defined by the assumptions. Additionally measuring the top and bottom length of the parts was infeasible because the part is so flexible that the PETg parts deform on the order of millimeters when measuring with calipers.
9.7. Results

The sensitivity indices for the six linear spring DOE for each length scale and material are shown in Figure 9.12.
Some overall trends observed are that as the length scale increases the effect of thermal conductivity increases, which makes sense when considering the Biot number of the part, which is ~0.01 at the Ultimaker scale and around ~0.1 for the BAAM scale. Additionally, it appears that as length scale increases the effect of elastic moduli on the residual stress of the part decreases. One curious feature is that density appears to have a large effect on the residual stress in three of the six runs, one reason could be gravity loads, which will resist warpage another possible reason is the general inconsistency in the boundary conditions. This comparison is complicated by the fact that at different length scales different print parameters were used to reflect some of the print conditions of different printers. Ignoring this, the relative importance of the material factors appears to remain the same at different length scales, meaning that material modeling considerations roughly stay constant with respect to length scale, as far as warpage is concerned.

9.8. Concluding Remarks

As for the model accuracy, it was found that the model can predict the general shape of the out of plane warpage, however because the geometry is quite compliant a quantitative comparison, especially with the in-plane warpage is mostly futile.

It was also found that the dominant material property at all length scales is the coefficient of thermal expansion, which reflects what is shown in Figure 2.3. It was also found that conduction becomes increasingly important as length scale increases which makes sense given that the Biot number will increase as a function of length.
CHAPTER 10

10. EFFECT OF ENVIRONMENT

10.1. Introduction

This chapter represents exercising the linear spring geometry to evaluate the effects of environmental phenomena on the part. With the goal of comparing the results of simulations to that of what others have found.

10.1.1. Objectives

The primary objective of this study is to qualitatively evaluate the effects of different thermal conditions on the simulated warpage of the part, over a wide range of values. To inform which environmental phenomena need to be modeled the most accurately. This is to shorten the time it takes to create a simulated printer by allowing for decisions to be made as to which phenomena to focus the most on.

10.2. Methods

10.2.1. Geometry and Mesh

The geometry and mesh were reused from Chapter 8.

10.2.2. Material

The material is the CF-PETg material model developed in Chapter 8.

10.2.3. Simulated Printer

The print conditions simulate using the Gigabot and unless otherwise stated reflect the settings used in Chapter 8.

10.2.4. Quantities of Interest

The quantities of interest of this study are the same as those in Chapters 8 and 9.
### 10.2.5. Experiment Design

The sink temperature for the convection and radiation conditions are different because of two reasons, first is because it presents an interesting opportunity to evaluate the effectiveness of using radiant heating methods to decrease the warpage of the parts, which could be more feasible to use on printers like the Ingersoll™ Masterprint© where the build volume is so large that enclosing and heating the entire print volume is unfeasible, and radiant heating can be used to emulate the effects of a heated enclosure without needing to have the printer in its own building that is heated to high temperatures. Additionally, because radiant heat can be focused and directed from a farther distance, it could be used to selectively heat only areas that need heat. Second, a heated bed could increase the effective radiation temperature.

The experiment took the form of a Latin hypercube with maxi-min sampling which means that sample sites were selected to maximize the minimum distance between sites. This design was picked to account for any non-linearity in a response and to get adequate coverage of the design space. The factors are shown in Figure 10.1

![Figure 10.1: Image showing factor ranges.](image)

The factors are also shown in Table 10.1.
Table 10.1: Factor ranges for environment study.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Units</th>
<th>Min Value</th>
<th>Max Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissivity ($\epsilon$)</td>
<td>Unitless</td>
<td>0</td>
<td>0.99999</td>
</tr>
<tr>
<td>Bed Temperature ($T_{bed}$)</td>
<td>°C</td>
<td>23</td>
<td>100</td>
</tr>
<tr>
<td>Nozzle Temperature ($T_n$)</td>
<td>°C</td>
<td>190</td>
<td>250</td>
</tr>
<tr>
<td>Convection Coefficient ($h$)</td>
<td>W/m² °C</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Far Field Radiation Temperature ($T_{rad}$)</td>
<td>°C</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>Far Field Convection Temperature ($T_{conv}$)</td>
<td>°C</td>
<td>20</td>
<td>90</td>
</tr>
</tbody>
</table>

10.3. Results

Plots of the change top length in relation to some normalized factors are shown in Figure 10.2.

Figure 10.2: Plot showing response of change in top surface length with respect to normalized factors.
It is interesting that the print bed has the greatest effect on the part. This does make sense considering that the part is quite low to the plate. In contrast Compton et al. [35] found that environmental temperature had a greater effect on the thermal history, but the geometry was a wall that rose much higher above the build plate. Additionally, the fact that the sign is different compared to the other temperatures is interesting but makes sense, as heat from the build plate is flowing orthogonally to the warpage direction being measured. Overall, the three temperatures associated with boundary conditions had the greatest effects on the warpage of the part.

Additionally, the effect of radiation for low convection coefficients can be seen in Figure 10.3. Which shows the plot of normalized radiation temperature vs. change in top length (ΔTL) and splits the data into two subsets based on the quotient of the convection coefficient and emissivity to show that for low convection coefficients like those for natural convection, radiation becomes more important.

![Figure 10.3](image)

**Figure 10.3:** Effect of convection and emissivity on the effect of far field radiation temperature.

It is seen that for low convection coefficient/emissivity ratios the effect of far field radiation temperature increases, and as shown in Figure 2.5 characteristic length increases the convection coefficient decreases, meaning that for larger and larger printers using radiant heat to control the warpage becomes more efficient.
One of the most striking things found is that for the bed, radiation and convection temperatures, the change in sign of the top length change in length appears to be right around the glass transition temperature, which makes sense as this is where the greatest change in constitutive behavior as a function of temperature is.

10.4. Remark about bed adhesion

When evaluating proper settings to print the linear springs for the material study in Chapter 8. Two things were noticed, first is that when printing on painters’ tape in the 90-degree orientation the part separated from the build plate, but when printed on tape in the 0-degree orientation the part did not separate from the build plate but did separate from the painter's tape. This means that the physics behind the tape separation is likely driven by the distance to the free edge of the tape, and that particular care needs to be taken to ensure proper tape placement. Both prints were at a bed temperature of 60 °C. When the part was printed again with the bed at 80 °C the part did not separate from the print bed. The warpage difference between the parts with substrate separation and the one that stayed adhered to the build plate is an order of magnitude, meaning that one of the major factors when looking at the warpage of parts is the adhesion to the build plate. Implying that print bed temperature in addition to directly influencing the thermal history and warpage, can indirectly have a much greater influence on the warpage of the part by influencing bed adhesion. An image of PETg prints after the printing process that did and did not separate from the build plate is shown in Figure 10.4.

Figure 10.4: (A,B) Prints at bed temperature of 60 C showing separation from build plate (A) and substrate (B) (C) Print at 80 C showing no separation.
What was observed shows that there will be significant warpage if the part does separate from the build plate. There were also plans to print GF PETg but there were some issues which eventually led to printing on a GF PETg substrate. The part did not separate from the build plate at all. The adhesion to the build plate was so great the part would have been impossible to remove from the build plate without machining the plate off or severely damaging the part. This is shown in Figure 10.5.

![Figure 10.5: Attempted print of GF-PETg](image)

The above indicates build plate adhesion is likely a function of the build plate material, build material, and time temperature history. Material dependence echoes the findings of [62]. Where they found that printing on the same polymer can lead to the part being inseparable the build plate.

This reflects the results from the model where perfect adhesion was assumed, where that warpage was imperceptible to the naked eye. This means that when simulating a process where there is a significant risk of separation from the print bed, adhesion should be simulated. Two ways adhesion can be simulated is by defining a traction separation law or a user defined boundary condition. Additionally, the fact that much of the strain during the printing process is concentrated at the ends, which is where the part separates during the printing process shows that adhesion could be simulated with the current model with little effort.
10.5. Next Steps

One possible next step is to evaluate having some sort of radiant heater pointed at the part, such that the equivalent far field temperature for radiation is higher. This is more feasible than increasing the enclosure temperature because many printers do not have temperature control for the enclosure. Additionally implementing some “in between” model for the bed adhesion using a traction separation law, which can simulate imperfect bed adhesion should be done as shown with the experience with the neat PETg parts. However, there is the issue of quantifying the constitutive response of the print bed interface and the evolution of the print bed interface.
CHAPTER 11

11. CONCLUDING REMARKS

11.1. Summary of Work

In summary, three different material agnostic modeling workflows were created for thermoplastic extrusion additive manufacturing. Then six 3d printed PLA hollow right cylinders were printed and scanned. The scan data was then used to evaluate the warpage predictions of the three workflows utilizing validated material parameters. It was found that warpage was insensitive to the modeling workflow if a proper material model is used. This informed the decision to use a part-based meshing approach with progressive element activation, as this is the most computationally efficient.

Then a user subroutine was developed to handle orienting the elements in the bead direction, to allow for modeling of anisotropic materials. This subroutine had some key differences to the subroutine included with Abaqus, namely, orienting the material and activation criterion.

Then a material model for 3D printed CF-PETg was created and tested on large scale geometries printed on a BAAM. Where it was found that the material model was able to predict warpage to within ~10% for an approximately 2 m x 0.1 m x 0.1 m corrugated wall geometry and even less if accounting for the feature imposed by the build plate boundary. For smaller scale geometries the warpage was of so little magnitude that the surface roughness of the part made a model comparison infeasible without significant uncertainty.

Finally, a linear spring geometry was created, this was used to evaluate the effect of material on warpage for a medium scale Gigabot X 3D printer. Then the part was printed in CF-PETg and neat PETg and scanned, which correspond to two DOEs evaluating the effects of changing material parameters. Both prints were compared to the models, and it was found that the neat PETg model created using “datasheet” properties was inadequate to model the warpage. The study found that the most crucial factor for warpage is the coefficient of thermal expansion.

Then the printing of three linear springs at three different length scales was simulated. To go along with this a part was printed on an Ultimaker with neat PETg. These results for neat and CF-PETg were compared. Where it was found that the important material properties roughly stay constant as a function of length scale.
11.2. Printer

As shown in the prints with the Gigabot and BAAM there are significant effects from the build plate, specifically from the adhesion to the build plate. There are also significant effects as a result of bead irregularities. Meaning that for warpage modeling the printer needs to go through a rigorous characterization process, and that ensuring the printer maintains controlled conditions is important. The effort for this process can be mitigated by using polymer systems that do not separate from the print bed, and as such are much less sensitive leading to more consistent prints.

11.3. Thermoplastic material

If the material is assumed amorphous and assumed to have a sharp decrease in tensile modulus after glass transition. Then the thermal strain assumption is an adequate assumption and can be used to simulate relaxation within the bounds of the tool used. Additionally, as far as materials for 3D printing are concerned CF-PETg has proven to be a phenomenal material if dimensional stability is required. It was also found that for modelling the most important quantity is the CTE.

Compounders will often add additives and change the chemistry of polymers to best suit an application. Changing the chemistry of the material means that it is often risky to use material properties from the same polymer from literature unless it is the exact same product. Additionally, the difference in material properties of CF-PETg printed on the Ingersoll [54] and BAAM from section 7.3 means different material parameters need to be created for different processes. Where the tensile moduli of material printed on the BAAM in the 11 direction was around twice that of the same material printed on the MasterPrint, such a significant difference in material properties points to the need for a computational material modeling toolkit for AM material as needing to perform all the tests for each material on each machine will get expensive quite quickly.

Overall, the results point to the fact that the issue of modeling warpage primarily lies in material modeling, specifically that of the thermal contraction of the material. The results from chapter 6 show that agnostic to the material model different modeling approaches produce the same results, which are close to experimental when used with a proper material model. But, as shown with the neat PETg where the baseline material model was created with datasheet properties, not the as printed properties, which were unavailable means that the process-structure-property relation is of immense importance for evaluating the warpage of the part. This indicates that much of the important work for modeling the TEAM process lies in the material modeling and bridging the gap between process and property.
Additionally, as shown by [6] there are significant effects from the orientation of the fibers in the material, the fiber orientation is affected by the processing conditions. This means that in the future a purely predictive model for the material properties would look something like that in Figure 1.11.

Figure 11.1: Example multiscale material modeling workflow.

First the printer and toolpath data are passed to a model of the printer that will capture the deposition conditions of the material extruded. This data is used along with materials data to model the micro and meso scale geometry. The geometry and materials data are then used by micro and meso mechanics modules to get the material properties at different length scales. An alternative to the physics-based workflow shown above is using a surrogate model for the macro scale material properties.
The material modeling workflow reflects the fact that there are structures at multiple length scales all effected by the processing conditions that effect the final material properties and the final warpage of the part, and it reflects the importance of the PSPP relations for additive manufacturing.

11.4. Geometry

Of the geometries tested there are two major findings. The first finding is that there are two warpage modes – in-plane and out-of-plane – for each part. Key differences in the two types are summarized in Figure 11.2.

![Figure 11.2 Differences in warpage types](image)

The in-plane warpage component is more time step sensitive because the difference in thermal strain in each layer is dependent on the deposition pattern meaning that changing the toolpath will change the in-plane warpage mode. This is backed up by the fact that the models that were looking at the change in the top length required a smaller time step than the models looking at bottom surface deviation.
Additionally, the linear spring geometry was a poor geometry for evaluating realized parts, as it is so flexible that there is significant deformation imposed by self-weight that makes experimental validation infeasible. Meaning that for further work creating light and rigid structures should be done, and a balance should be struck between the compliance of the part and self-weight, so a geometry like the T section but longer is recommended.

Then for evaluating height effects, a geometry like the one from chapter 6 which is also light and rigid is recommended. The advantages of these two geometries are they are rigid and light meaning that the deformation imposed by self-weight is low, and the warpage of these two geometries is well defined and simple which avoids some of the issues encountered with the linear spring.

11.5. Overall Recommendations and future work

For producing robust predictable prints for AM on most length scales, CF-PETg is recommended, as it has favorable mechanical properties, and keeps warpage to a minimum which in turn mitigates any tendency to separate from the build plate. The reasoning for this is that it has a low CTE and a low T_g meaning the part will not warp, and the associated thermal stress and strain per Armillotta et al. [11] is low.

In terms of improving the process. As shown in Chapter 10, a heated bed can decrease the warpage and make parts more consistent, especially in terms of increasing adhesion. Additionally, as shown by Chapter 10 using radiant heaters increases in efficiency as the length scale increases and as such using radiant heating could be used as a more efficient method of minimizing the temperature difference between deposited layers. Something similar has been done before with thermoplastic composite tapes [63].

Most of the future work for effective thermo-mechanical modeling likely lies in material characterization as the material exhibits significant process dependence and as shown by Chapter 8 using “datasheet” properties is inadequate for modeling warpage. Additionally, work should be put into characterizing and modeling the process dependence of the material such that in the future materials and processes can be tailored for a specific application, or requirements.

In short, the important findings of the work can be summarized as:

1. Most of the challenging work for modeling macro scale warpage for AM is likely in modeling the material
a. The most important quantity for material modeling is that of the thermal contraction Chapter 8
b. As shown by the difference in the material properties between Chapter 7 and [54] is process dependence in material properties which will need to be modeled.

2. As length scale increases, the natural convection coefficient gets lower and as a result radiation becomes the dominant mechanism of surface heat transfer.
   a. Radiative heating can be used to decrease the amount of warpage (Chapter 10)
      i. As the print volume increases the energy required for heating the air inside increases
      ii. Radiation can be focused and directed onto specific regions of the part
      iii. Because the print volume is not heated directly there is a lower occupational hazard if an operator must enter the print volume
   b. This effect increases when using materials with high emissivity

3. Warpage can be separated into two categories
   a. In plane – path dependent
      i. Can be mitigated using tool pathing
   b. Out of plane – layer dependent
      i. Less mitigatable
      ii. Influences separation from the build plate

4. Build plate adhesion is a phenomenon that needs to be considered for warpage
   a. Assume perfect adhesion, then validate
   b. Build plate adhesion can be improved by increasing the bed temperature.
   c. Model interface directly using constitutive law
      i. Influenced by time temperature history of the part
      ii. Likely influenced by substrate material and print material
      iii. Lack of standard testing procedure for interface strength limits model validation capabilities
REFERENCES


[48] TECHNICAL DATA SHEET - PRO Series PLA.


[51] Chernov, N. 1.0.0.0. Circle Fit (Pratt Method).


[54] Large Scale Additive Manufacturing Datasheet Techmer PETG-CF.


APPENDIX

CODES

Codes will be uploaded to https://github.com/CBock879
BIOGRAPHY OF THE AUTHOR

Christopher Bock was born in Waldoboro, Maine on the 24th of June, 1998. He was raised in Waldoboro until the age of 12 then in Yarmouth and graduated from Yarmouth High School in 2016. He attended The University of Maine and Graduated Magna Cum Laude in 2020. He continued on and entered the Mechanical Engineering graduate program at The University of Maine in the summer of 2020. After receiving his degree he will be staying at the University of Maine to pursue a PhD. in mechanical engineering, with a focus on uncertainty quantification, and multilevel optimization of large scale additive manufacturing. He is a candidate for the Master’s of Science degree in Mechanical Engineering from the University of Maine in May 2022.