ALTEN TECHNOLOGY

COMPUTATIONAL ANALYSIS OF FDM-PRODUCED COMPONENTS AND IMPORTANCE OF PRINT ORIENTATION

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INTRODUCTION

Additive manufacturing (AM) encompasses a growing range of technologies for producing a wide variety of components, ranging from single-use prototype parts to end-use components for the aerospace industry. Although AM technologies offer various benefits, they can also induce additional difficulties in the computational analyses many engineers use during a design cycle. For example, performing part manufacturing with AM technologies, such as Fused Deposition Modeling™ (FDM), introduces additional variables beyond those in traditional subtractive manufacturing techniques. In this white paper, we examine the nature of material properties in FDM components and the difficulties in applying rigorous analysis. We also construct a demonstrative component to explore the comparative effects of the manufacturing build orientation variable on the mechanical response.

BACKGROUND

Within the engineering sector, AM is of particular interest for several reasons. One of the primary factors driving use of AM is that it allows developers to design geometry that would otherwise be challenging or impossible to manufacture, such as creating more optimized shapes with intricate or hollow features, and combining multipart assemblies into a single component. AM can also provide cost savings for parts that traditionally require expensive tooling or machining, whether used for prototyping or low-volume production.

Fused Deposition Modeling™ (FDM) is an AM technology developed in the late 1980s and patented in 1992 [1]. FDM builds three-dimensional objects using a moveable dispensing head to extrude a thermoformable material into shaped layers. Since the technology's patent expiration in 2009, FDM has seen growth significantly surpassing any other AM process and has been vital in bringing the concept of AM into the common lexicon, where it is more commonly referred to as "3D printing."

The most common materials used in the FDM process, including in the large hobbyist sector, are acrylonitrile butadiene styrene (ABS) and polylactide (PLA). Other commercially available polymers include nylon, polycarbonate, and acrylonitrile styrene acrylate (ASA) [2]. Of the polymers more recently made available for FDM, ULTEM 9085 holds particular importance for engineers given its very favorable mechanical and thermal properties [3] and approval for use in aerospace applications [4, 5].

Although FDM materials like ULTEM 9085 show promise for engineering applications, as we demand more from our designs, the components and materials in those designs are often pushed closer to their physical limits. To better understand a design and its limits, we can use finite element analysis (FEA) software packages to simulate components with well-defined load cases, allowing the close approximation of the resultant stresses, strains, and displacements. The material properties of the component are critical inputs to these analyses. Metal components can generally be treated as linear-elastic isotropic, implying that they have an elastic region with a linear modulus of elasticity and that the material properties are the same regardless of the direction in which it is loaded [6]. In contrast, plastic components have more complicated material properties in that they are generally nonlinear- elastic, where the modulus of elasticity changes as the material experiences strain [7]. Some plastics and most as-printed AM plastics are even more complicated, behaving in a nonlinear-elastic anisotropic manner. These materials experience variation in the modulus of elasticity when strained and exhibit different material properties depending on which direction the material is loaded. Due to their complicated properties, a significant amount of material characterization can be required to analyze plastic and AM parts.

Given the additional material characterization that AM parts demand, it is crucial that the properties are determined appropriately. Many standard test methodologies provide guidance in the collection of material properties to ensure consistent and appropriate data. Of these, ASTM D638 and ASTM D3039 are both commonly applied standards. ASTM D638 is a "Standard Test Method for Tensile Properties of Plastics," specifically covering "the determination of the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens" [8]. ASTM D3039 is a "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials" that determines "the in-plane tensile properties of polymer matrix composite materials reinforced by high-modulus fibers" [9]. Various research has applied one or both of these standards in establishing the material properties of as-printed FDM materials. We are specifically interested in the characterization of ULTEM 9085, given its recent approval for aerospace applications in FDM components. Furthermore, we have found that much of the current literature on ULTEM 9085 characterization makes use of the D638 standard [10–15], including manufacturers [16], while some choose to apply the D3039 standard [17].

Neither the D638 nor D3039 standards are explicitly appropriate for FDM components. D638 is intended for solid injection-molded parts, and D3039 is designed for use with plastic/non-plastic composites, both utilizing fabrication techniques far different from the FDM process. There are committees currently developing standards specifically around AM parts [18–20], but those standards are not yet fully matured and not finalized for use in characterizing material properties for FDM components.

DIFFICULTIES OF FDM ANALYSIS

ANISOTROPIC NATURE OF FDM

Much of the research focused on the material properties of ULTEM 9085 FDM components presents the material as being orthotropic, a subset of anisotropic materials in which the various properties and strengths are in directions perpendicular to each other. This is similar to how Stratasys and others interpret ASTM D638 to develop their datasheet for ULTEM 9085, often printing the test samples in three different orientations to capture the properties for each Cartesian build orientation possibility.

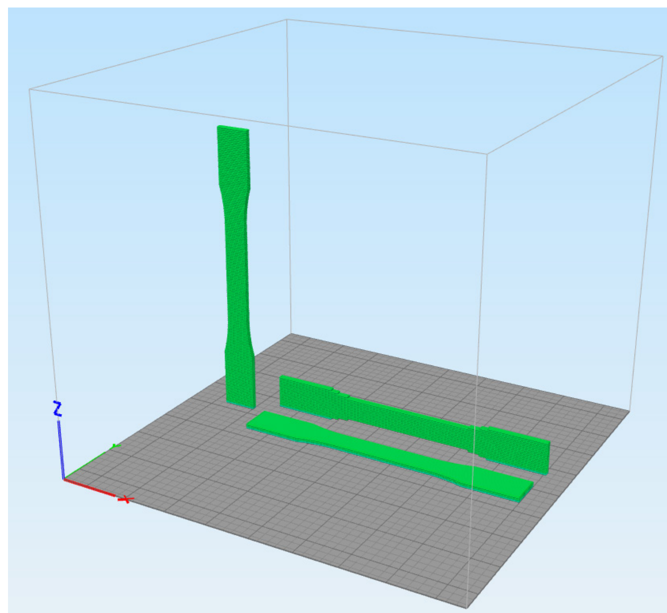


FIGURE 1: STRATASYS PRINT ORIENTATIONS FOR ASTM D638
Layer Thickness Exaggerated. XY (Front), XZ (Rear), ZX (Left)

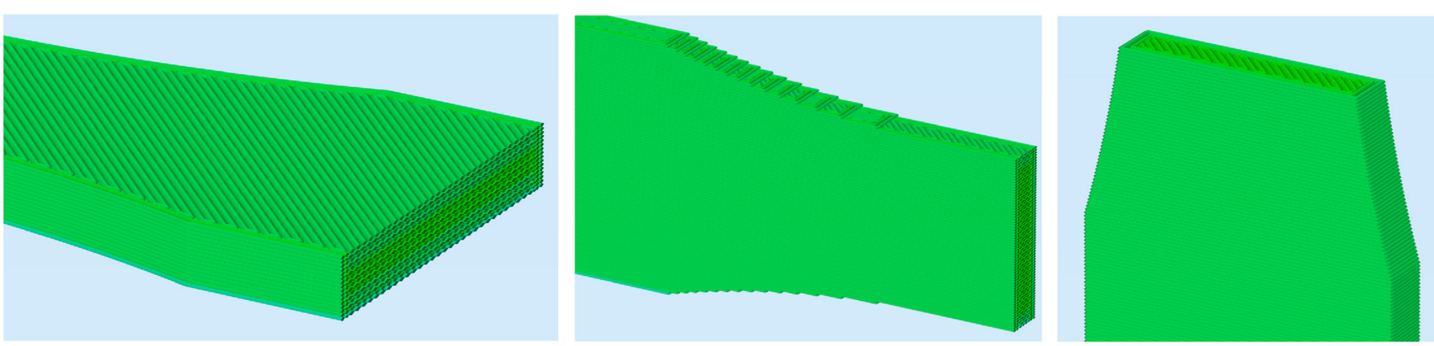


FIGURE 2: CROSS-SECTION OF EACH BUILD ORIENTATION
XY (Left), XZ (Center), ZX (Right)

Figure 1 displays the three printing orientations as defined by Stratasys. The XY sample is layered across the 3.2 mm thickness, the XZ sample is layered across the 19.0 mm width, and the ZX sample is layered across the 165 mm length. Depending on the software used to generate these layers from the solid model, commonly called a "slicer," removable material may be added to the print to support the gap under the necked section on the XZ sample or added to support the high aspect ratio of the ZX sample [10]. Additionally, Figure 2 shows a cross-section of each orientation, detailing how the layers are commonly produced. Each layer is comprised of both a "contour" and an "infill." The contour of each layer is a solid loop that circumscribes any outer and inner edges. In this case, each layer has two outer contour loops. The infill is the material rastered to fill the remainder of the layer, commonly produced at a 45° or 135° angle to the contour, alternating between the angles for each layer. Discussion of other layer variables and terminology not mentioned here can be found in [21].

Inspection of the theoretical layers within the necked region on the XY and XZ samples shows that the primary difference between the two build orientations is the percentage of infill that comprises the layer, as shown in Figure 3. The XY layer comprises 88% infill against 50% of the XZ sample, assuming a 0.4 mm standard nozzle diameter and a dual-loop contour.

The difference in build structure between the two build orientations can explain the greater strength that XZ samples exhibit over XY samples [11, 15]. Contour loops on the XY and XZ build orientations align parallel to the pull force when tested per ASTM D638, allowing them to resist the tension directly and rely primarily on the strength of the ULTEM polymer. The infill is at a less advantageous angle to the pull force and considerably depends on the bond strength between the rastered lines of the infill to resist the tension [4]. This bond strength is significantly weaker than the resin itself [22], resulting in an overall lower bulk tensile strength of the infill and a weaker overall cross-section.

Given the observation that infill bond strength plays a substantial role in the bulk tensile strength of printed components, we theorize that there is additional material behavior that the direct application of ASTM D638 does not capture. For this discussion, assume a component with a simple rectangular layer. If we print a rectangular block using rectangular layers that have the same width as the XZ samples, we expect it to behave with the same properties as the XZ data when loaded in the same tensile direction as the samples. Similarly, we expect a block printed with layers as wide as the XY samples to follow the response of the XY data. However, the infill percentage is the primary contributor to the variance of as-printed material properties. Thus, if we print a rectangular block with rectangular layers that have a width between the XZ and XY samples, we know that the infill percentage is between 50% and 88% dependent on the block width. This results in the material properties of this in-between layer width falling in between the XZ and XY data. All three components are illustrated in Figure 4 on the next page.

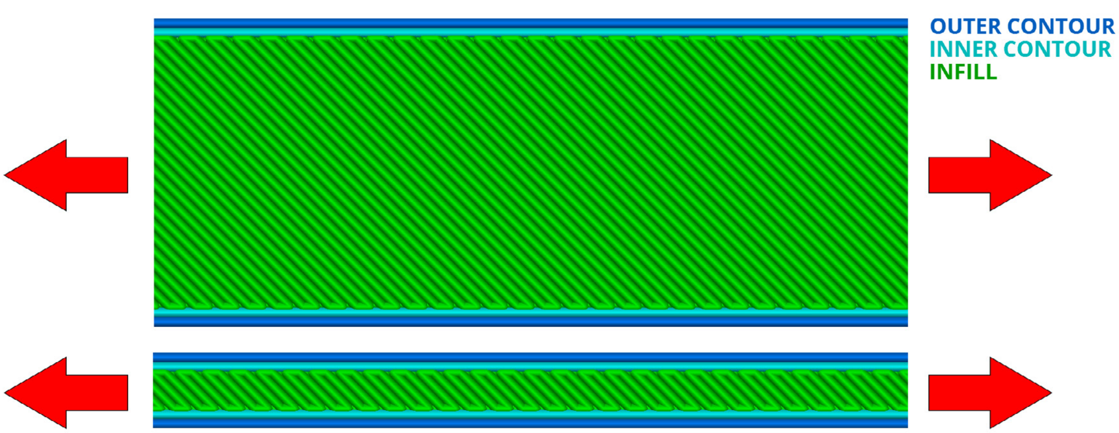


FIGURE 3: LOAD BEARING LAYER-CROSS-SECTION
For XY (Top) and XZ (Bottom)

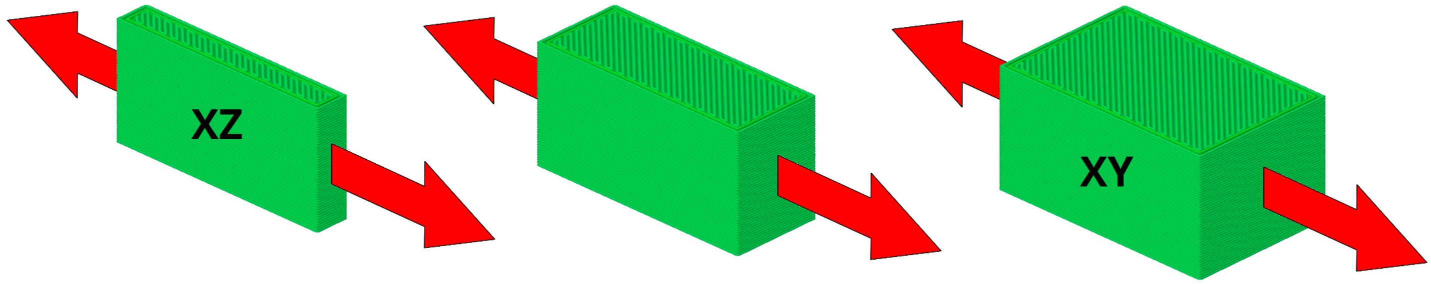


FIGURE 4: RECTANGULAR BLOCK GEOMETRY WITH VARYING PROPERTIES

Ultimately, the layer width is defined only by the component's geometry, and can be anything from a single nozzle diameter up to the maximum dimension the printer can produce. As a result, differing material property datasets exist below, in-between, and above the captured D638 XY and XZ data. We assert that the material data collected from the XY and XZ samples represent only two discrete points along a continuous curve; layer width vs. material performance. This curve describes a geometry-dependent anisotropic material with properties that vary with the load's direction and the size of the feature where the load is applied. Thorough characterization of such a material is complex but could theoretically produce a curve for each varying material property against layer width.

Thermodynamics also influences the FDM component strength. The layer-to-layer bond in FDM depends on the temperature between the print layers. The heat from the newly printed layer diffuses into the previous layer underneath it, partially remelting the plastic of the preceding layer and creating a bond. The closer the temperatures are between the current and prior layers, the stronger the bond [15]. Assuming a constant print speed, layers with a larger overall area will result in greater temperature differences because there is more time for the previous layer to cool, leading to a weaker layer-to-layer bond. This interaction is nearly impossible to universally characterize given the infinitely variable geometry, layer size, and component layer shape, as well as ambient conditions that could affect the rate at which the lower layers cool.

APPLICATION OF FEA TO FDM

FEA software packages can only provide outputs as good as their inputs. FDM parts pose a particular challenge when trying to deliver high-quality solid model inputs because the solid model that is analyzed may be quite different from the as-printed component that is generated by the slicer. The slicing software has to approximate the solid geometry under the constraints of a defined layer thickness and a fixed extrusion nozzle diameter such that it can be fabricated on the FDM machine. This approximation step [5] induces voids and an internal structure to the as-printed part that a solid model does not capture [13, 15, 23]. Simulating the FDM build process to generate an as-printed part model which is then fed into an analysis could yield a significantly more accurate result. Research has been conducted utilizing this approach with promising results [22, 24], but such methods are highly computationally expensive and time-consuming. Commercial packages that can perform analyses on as-printed models have only recently become available [25] and are not yet widely adopted.

The anisotropic nature of the FDM material causes additional problems in providing high-quality inputs to any FEA solver when directly simulating the solid model. It is possible to assign different orthotropic properties to distinct portions of a solid model to account for how the behavior of a single material may differ depending on the geometry [26]. In the referenced example shown in

Figure 5, a composite material could be used to fabricate the component, but would result in a portion of the component with a Cartesian anisotropy and a portion with a radial anisotropy.

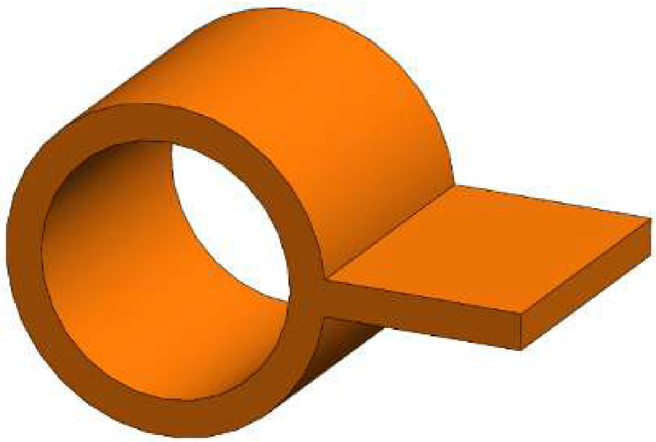


FIGURE 5: COMPONENT EXAMPLE WITH MULTIPLE FORMS OF ANISOTROPY

Similarly, an FDM component could be designed with a discrete number of wall thicknesses separated into multiple distinct portions and matched with layer widths in geometry-dependent anisotropic data collected for the as-printed material. However, in practice, components are rarely so simple that they can be realistically split into a few distinct portions. In fact, one of the advantages of AM components is that their geometry can be considerably more fluid and irregular, lacking any distinct separable portions.

ROUGH FDM FEA APPROXIMATION

With rigorous analysis of FDM components requiring either a simple component that is separable into bodies with known distinct anisotropic properties, or a computationally expensive solution methodology, accurate simulation results cannot yet be expected in a current practical engineering environment. Extensive empirical testing on a collection of agreed-upon reference components may allow a set of material properties or other analysis tool inputs to be developed that roughly approximate the behavior of FDM-produced components. Although final component testing would still be required to determine actual behavior and performance, a rough approximation may allow for initial design iteration and reduced nonlabor costs. Homogenization theory for periodic media has been studied successfully for other types of composite materials [27], which lends credence to the idea that either an analytical or empirical approximation for FDM materials may be possible.

EXAMINATION OF PRINT ORIENTATION

Due to the inherent difficulty of rigorous FEA on FDM components and the lack of a set of proven inputs, we turned our focus onto what we can easily control (excluding part geometry) as designers that will influence component performance. If we assume that the FDM machine and slicing process is in our control, many FDM process variables can be altered to adjust the print. However, most professional machines already have tuned parameters to produce components to the best of the machine's ability, and are commonly heuristically adjusted to achieve the desired result rather than rigorously defined, making further adjustment time-consuming and iterative. Furthermore, given that the commercial equipment capable of producing FDM components from ULTEM 9085 starts around $185k [28], designers are more likely to work with outside vendors, making it less likely that they would be able to exert control over the process parameters.

The one printing variable that a designer can easily specify is the printing orientation. The print orientation governs which side of the part is placed against the print bed and the direction in which the component is layered. Under an assumed set of working loads the part is expected to experience during use, many components have an optimal print orientation that provides better overall performance. As reported in [15], changing the print orientation has effects on the modulus of elasticity, strain to failure, and the ultimate tensile strength for the same ASTM D638 coupon geometry. Similarly, orienting the part to be sliced and printed optimally can help achieve superior performance from the same geometry.

Here we present a constructed example demonstrating the potential comparative variance among three print orientations. For this exercise, we make several assumptions to reveal an analytical difference:

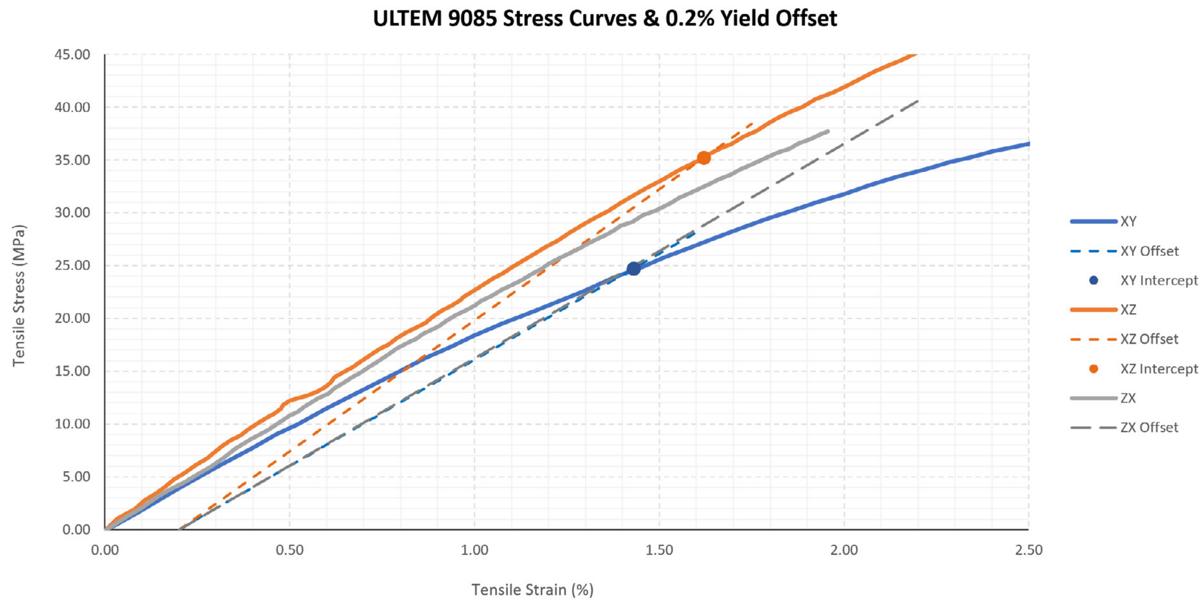


FIGURE 6: OFFSET YIELD PLOT

- We assume that the as-printed material is orthotropic, bearing the material properties of the A, C, and D build orientations as defined in [15]. Mapped to the Stratasys nomenclature, the A, C, and D build orientations match Stratasys' XY, XZ, and ZX orientations, respectively.
- We assume that the material behaves linearly, and there is a consistent framework for applying the XY and XZ material datasets for each print orientation layer. The ZX dataset is unambiguous and applied along the layered direction.

With the lack of available and consistent shear or compressive data, we focus exclusively on the tensile performance of the material. Additionally, we examine the analytical outputs on a strictly comparative basis since we do not have empirical data to support or contradict the absolute values of the component performance under these assumptions.

PROCEDURE

The material data presented in [15] provides the ultimate tensile strength, modulus of elasticity, strain to failure, and a combined stress-strain plot for all build orientations. As most design engineering is concerned primarily with material yield and not failure, we calculated the 0.2% offset yield strength for the XY, XZ, and ZX build orientations utilizing the provided plot and moduli. While successful for the XY and XZ orientations, the ZX orientation experienced low-strain failure and did not intersect with the 0.2% offset line, as shown in Figure 6. The yield-to-ultimate-strength ratio was calculated for the XY and XZ orientations and used to equivalently derate the ultimate strength of the ZX orientation to obtain the yield strength.

For our example, we designed a small right-angle mounting bracket, shown in Figure 7, which includes a hollow gusset and three mounting points—two on one flange and the third on the opposite flange. This bracket was designed specifically for FDM manufacture, keeping the walls of the gusset feature at 45° or less from vertical in all intended print orientations to prevent the need for supports during printing [29]. A partially dimensioned drawing, including general size and overhang angles, is shown in Figure 8.

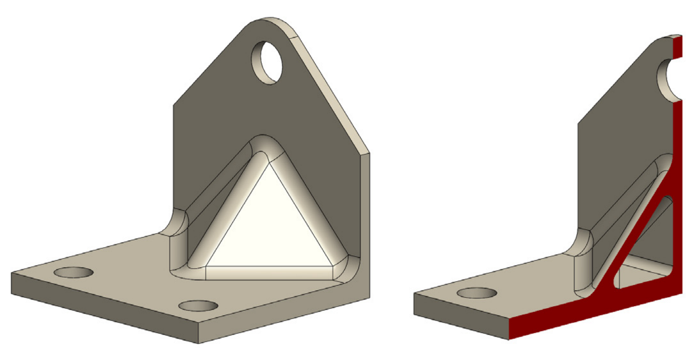


FIGURE 7: EXAMPLE BRACKET AND CROSS-SECTION SHOWING HOLLOW GUSSET FEATURE

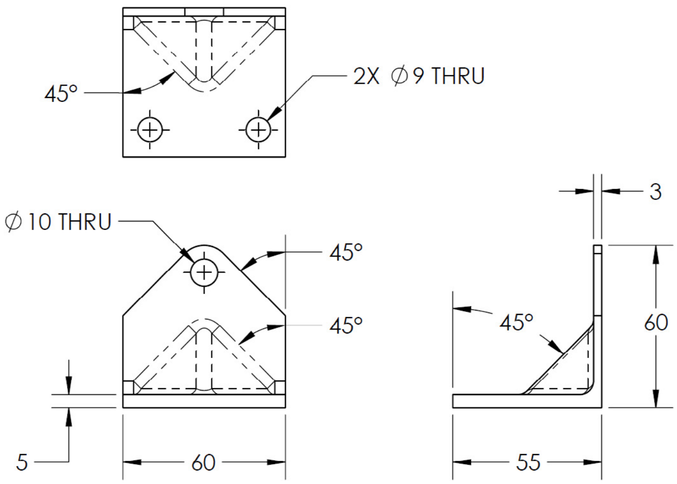
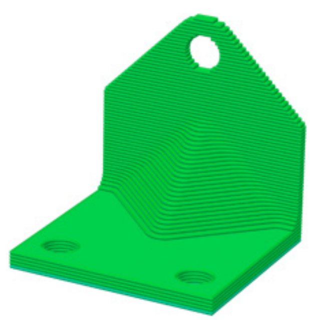
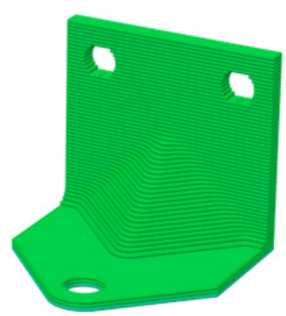
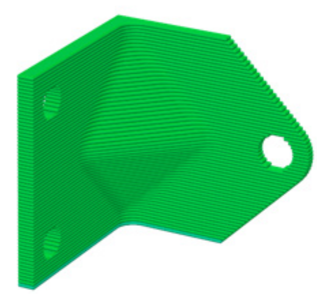
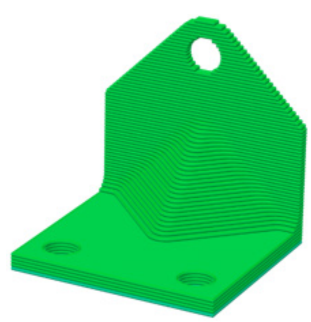
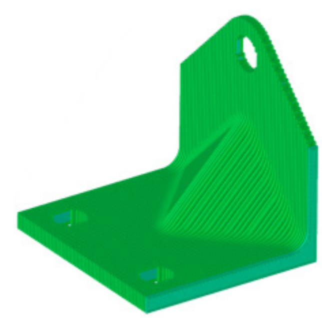


FIGURE 8: PARTIALLY DIMENSIONED BRACKET FOR SCALE
Units in mm

Using both Simplify3D and SolidWorks 2016, we then developed the material properties' framework that defines how the part orientation on the print bed corresponds to the orthogonal directions of the material property. This was done based on the primary print style of the wall that contains the single 10 mm diameter hole, the feature to which the loading will be applied. Our first print orientation slices that wall such that, in tension, the wall is best represented by the ZX dataset. Similarly, our second orientation slicing is best represented by the XY dataset, and our third by the XZ. This framework is shown in Table 1.

TABLE 1: MATERIAL PROPERTY AND BUILD ORIENTATION FRAMEWORK
Layer thickness exaggerated

	1	2	3
Build Orientation			
Build Orthotropy Material Reference Frame	ZX, XZ, XY	ZX, XZ, XY	ZX, XZ, XY
Loading Orientation			
Loading Orthotropy Material Reference Frame	ZX, XZ, XY	XY, XZ, ZX	XZ, ZX, XY
Global Coordinate System Solid Model and FEA	Y, X, Z	Y, X, Z	Y, X, Z

With the material framework in place, the simulation was set up to mimic two bolts affixing the lower flange, and a single bolt through the 10 mm diameter hole in the vertical flange. This single bolt is loaded with a 115 N force in the +Y global direction. Once an appropriate mesh was determined, the simulation was performed three times, adjusting only the orientation of the orthotropic material properties in relation to the body to signify the various build orientations.

RESULTS

We calculated the tensile factor of safety (FOS) for each build orientation simulated in each orthotropic direction. This was accomplished by projecting the local stress components into the material frame of reference and dividing the appropriate yield stress by this value. The FEA software was used to handle the projection since the orthotropic frame of reference aligned with the global coordinate system for this setup, allowing the stresses to be calculated normal to any Cartesian system direction. The minimum FOS for a given build orientation was taken as the FOS for the component. We also recorded the maximum vertical displacement for each build orientation. The values used in the calculations and the results are presented in Table 2.

The stress results are not very visually different between the build orientations. Thus, we only present the normal stress projections for the first build orientation in Figure 9.

TABLE 2: FOS AND DISPLACEMENT RESULTS

115 N Applied Load	Orientation 1			Orientation 2			Orientation 3		
	XZ	XY	ZX	XZ	XY	ZX	XZ	XY	ZX
Modulus of Elasticity (MPa)	2480	2010	2030	2480	2010	2030	2480	2010	2030
Yield Strength (MPa)	35.3	24.7	19.7	35.3	24.7	19.7	35.3	24.7	19.7
Max. Projected Stress (MPa)	8.2	19.0	19.7	8.9	21.0	19.0	22.2	19.0	6.5
Directional FOS to Yield	4.3	1.3	0.9	4.0	1.2	1.0	1.6	1.3	3.0
Minimum FOS to Yield		0.9			1.0			1.3	
Max. Vertical Deflection (mm)		0.57			0.57			0.54	

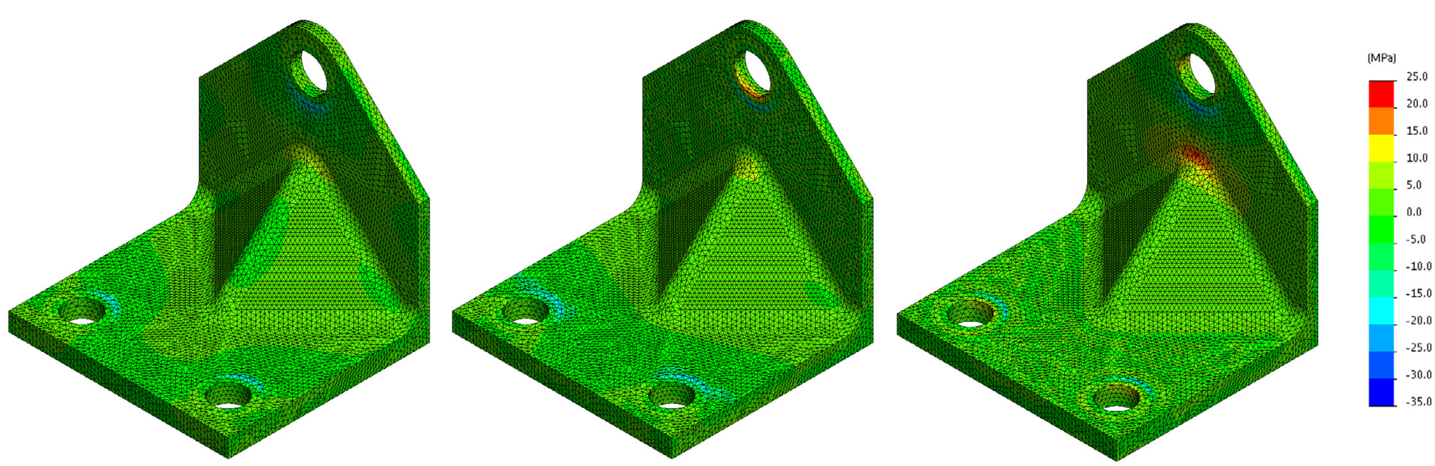


FIGURE 9: NORMAL STRESS PROJECTIONS FOR ORIENTATION 1
XZ (Left), XY (Center), ZX (Right)

DISCUSSION

Though conducted under a set of assumptions that do not explicitly capture the complete behavior of the material, the analysis shows that altering the build orientation affects overall part performance and potentially improves the FOS for a given loading scenario. With the first orientation as the baseline, the results show an 11% increase in minimum FOS for the second orientation and a 44% increase for the third orientation. These improvements could be the difference between a part failing under load and surviving with a safety margin left to spare. The component deflection is effectively equivalent between all build orientations, as is expected with the various orthotropic directions bearing similar moduli of elasticity. Other FDM materials may have a larger spread of moduli, in which case this process could also be used to choose the appropriate build orientation to tune part deflection.

This study focused on three build orientations, based on which side of the part was parallel to the print bed. Provided the use of support material to allow high-angle overhangs is acceptable, it is possible to print the part in any orientation within the build volume of an FDM printer. If we assume that one of the flat sides of the component must lie on the print bed, we could rotate the part about the vertical axis and generate a curve relating the rotation angle to the minimum FOS. The maximum point on this curve corresponds to the most advantageous rotation angle to print the component, potentially improving the minimum FOS in loading. Theoretically, this approach could be extended to multiple orientations and curves if a few sides of the component can be aligned with the print bed. This method can be extended to any print orientation if the part sides cannot be suitably placed on the print bed or if additional support material is acceptable. While it might be possible to manually iterate or use an iterative simulation tool such as SolidWorks Optimization for a known set of orientations and rotation axes, more advanced software with robust optimization algorithms is required to optimally place a component at any orientation in the build volume.

Inspection of the material properties and the potential layering options for a given component design, especially simple components and loading scenarios like the one presented here, may be sufficient to determine the best orientation for printing and not require any analysis.

More complicated geometry or loading cases may benefit from comparative studies as performed on the bracket example, especially in cases where the expected internal stresses are less obvious. For either approach, these methods only seek to reduce the iterative prototype cycles, not replace them. FDM components must still be empirically tested for performance with a statistically significant sampling set before a design is finalized.

SUMMARY

FDM materials offer several benefits for designers but also incur major challenges when computationally predicting their behavior. Rigorous material characterization involves many variables and does not yet have any directly applicable testing standard. Furthermore, because material properties of the FDM component can vary across the geometry, accurately creating a representative model in traditional FEA software can be challenging. It is possible to generate accurate models by simulating the print and then running static analysis on that output. However, this technique is still being researched and has only recently become commercially available.

With rigorous analysis proving to be currently impractical, we examined the impact of the build orientation on the mechanical response of a constructed component to tensile loading. Using calculated yield strengths and an assumed orthotropic material framework, our results revealed up to a 44% difference in minimum FOS simply by adjusting the part's print orientation, demonstrating the importance of this manufacturing variable.

ACKNOWLEDGMENTS

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