

A VALIDATED METHODOLOGY FOR PREDICTING THE MECHANICAL BEHAVIOR OF ULTEM-9085 HONEYCOMB STRUCTURES MANUFACTURED BY FUSED DEPOSITION MODELING

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Abstract

ULTEM-9085 has established itself as the Additive Manufacturing (AM) polymer of choice for end-use applications such as ducts, housings, brackets and shrouds. The design freedom enabled by AM processes has allowed us to build structures with complex internal lattice structures to enhance part performance. While solutions exist for designing and manufacturing cellular structures, there are no reliable ways to predict their behavior that account for both the geometric and process complexity of these structures. In this work, we first show how the use of published values of elastic modulus for ULTEM-9085 honeycomb structures in FE simulation results in 40-60% error in the predicted elastic response. We then develop a methodology that combines experimental, analytical and numerical techniques to predict elastic response within a 5% error. We believe our methodology is extendable to other processes, materials and geometries and discuss future work in this regard.

Introduction

Lattice structure design and manufacturing is one of the most promising areas of research in Additive Manufacturing (AM). This is primarily on account of the ability of lattice structures to elevate performance of the structure at reduced material utilization – and the fact that AM now makes it possible to manufacture these complex structures. While there are several efforts ongoing in developing design and optimization software for lattice structures, there has been little progress in developing a robust, validated material model that accurately describes how they behave. This matters because all design optimization and simulation tools require accurate material models, and also since certification of lattice structures requires a combination of analytical and numerical methods to ensure every part manufactured does not have to be tested. At the present moment, many organizations are not leveraging lattice designs due to the large uncertainties in performance. The complex geometric nature of these structures makes them particularly sensitive to process variables such as build orientation, layer thickness, deposition or fusion width etc.

This paper represents our first attempt to fundamentally develop non-empirical material models that describe the behavior of cellular structures. Broadly speaking, cellular structures are either honeycombs or foams (1). Further, foams can either be closed- or open-cell. There is an interest in a range of properties for these structures in the structural, thermal and fluid flow domains. Just within the structural domain, there is a need to predict their stress-strain response and failure. In this work we focus on honeycomb structures since they represent the simplest formulation of a cellular structure from an analytical standpoint, and as we will show, the use of

closed-form analytical equations is critical to our ability to model their behavior for our work. Further, we focus our work on the quasistatic stress-strain response at low strains.

From a meso-structure standpoint, FDM represents one of the more complex AM processes with strong anisotropy resulting from its internal structure (2). This process complexity greatly amplifies the challenge of developing predictive models for structures with complex cellular geometries. This is demonstrated in Figure 1, in which we show data from tensile testing of identical honeycomb specimen geometries but with different FDM toolpaths during the printing process (details to be discussed in future sections). As expected, the varying FDM toolpath strategies have a strong effect on both the stiffness and the failure of the specimen. The question we seek to answer in our work is: can we predict cellular structure response with the minimum required information? Our approach is to answer this in two steps: first is to develop a methodology that enables this prediction, and the second is to identify the information that is required to make the prediction accurate. We believe the former to be process independent, but the amount and nature of information needed will likely depend on the specific process involved.

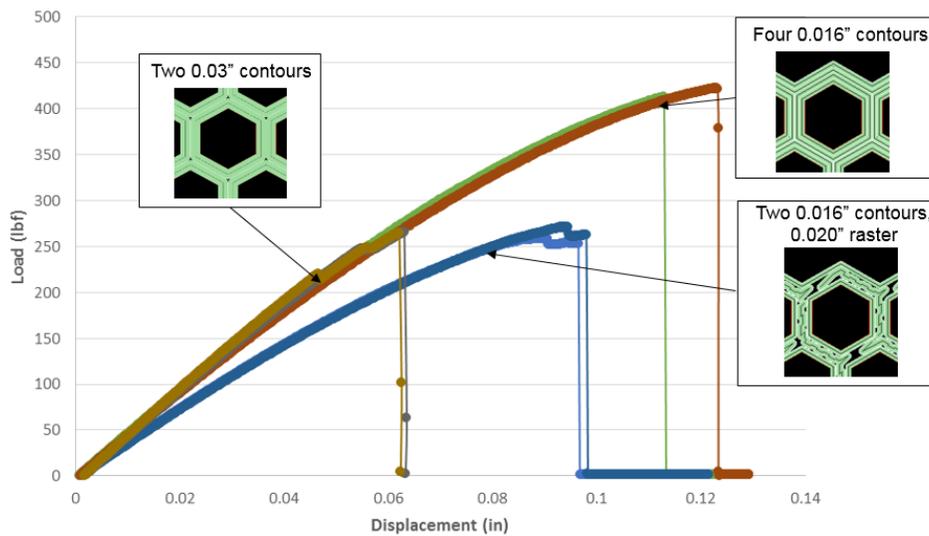


Figure 1. Process parameters in the FDM process have a significant effect on load-displacement response as well as fracture load of identically designed geometries – current models are unable to account for these effects

Given such large process dependencies, it is not surprising that using datasheet values for predicting the response of an FDM structure yields poor results. Using a transversely isotropic material model assumption and associated properties from the supplier (3) and from published work (4), we performed a finite element analysis to simulate the tension test and found we were under-predicting the effective quasi-static stiffness by approximately 50% relative to what we measured experimentally, as shown in Figure 2.

So the question is: how can we improve this prediction? In the subsequent sections, we first develop our methodology to addressing this problem and why we believe it is material and process independent. We then explore our methodology in the context of the previously mentioned scope: FDM ULTEM-9085 honeycomb structures using analytical, experimental and numerical techniques. We conclude with discussing the next steps in this work, some of which are ongoing at the time of writing this paper that we are undertaking to take this research further.

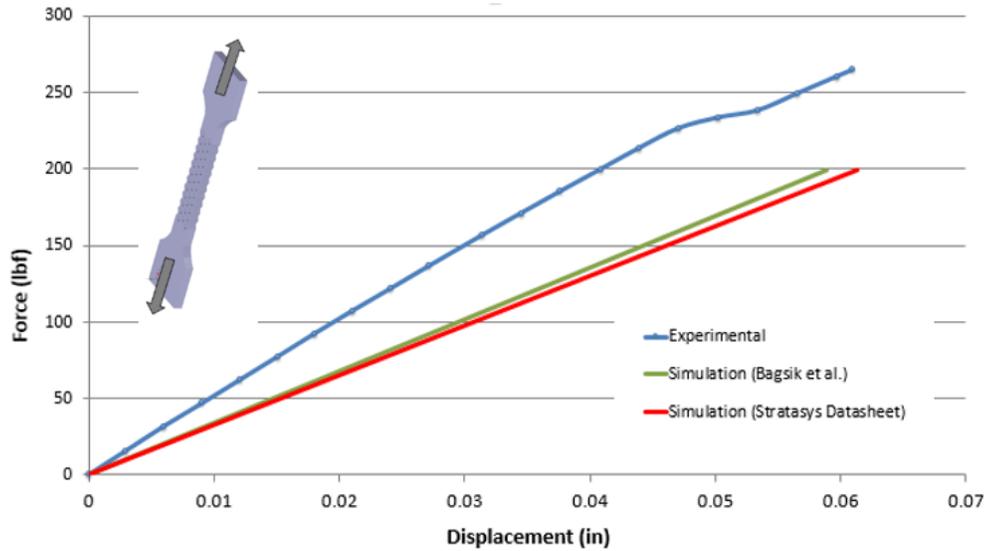


Figure 2. Published continuum values of ULTEM-9085 modulus are not able to accurately predict elastic response of a honeycomb structure, with approximately 50% error in predicted displacement for a given load even at very low strains 0.02 to 0.04

Methodology

At the core of our approach is the notion that we must define *point-wise* material properties and NOT unit cell level properties if we are to exploit true lattice design freedom in end part manufacturing and implementation for structurally critical parts. Previous work in modeling additively manufactured cellular structures has defined properties typically at the cellular level, in terms of a volume fraction or density (5; 6). The limitation with this approach is that it only applies to the specific cell geometry (shape and size) used to develop the model. In this work we seek to relax this constraint by developing non-empirical methods that can be extended to different geometries and loading conditions – and identify the associated regimes over which the model is valid.

Figure 3 below summarizes the methodology we have developed and present in this paper. The methodology consists of six steps: The first 3 steps are experimental, step 4 is analytical, steps 5-6 involve simulation and step 7 brings all the data together to validate the model’s accuracy. In the experimental steps, we replicate work done in most characterization work to design, manufacture and test compression test samples to extract an effective modulus. We then use these experimentally obtained effective properties in closed-form analytical equations for these honeycomb structures to extract a point-wise material properties – this, we believe, is the key novel aspect of our work. We validate these material properties using simulation on a different test condition (tensile test selected here) to, in the last step, compare its performance against the experiment to validate our model. Our goal is to reduce the error in predicted stiffness to less than 10% using this methodology. In the following sections, we deal with the experimental, analytical and numerical parts of our work in more detail and provide the results we obtain at each step along the way.

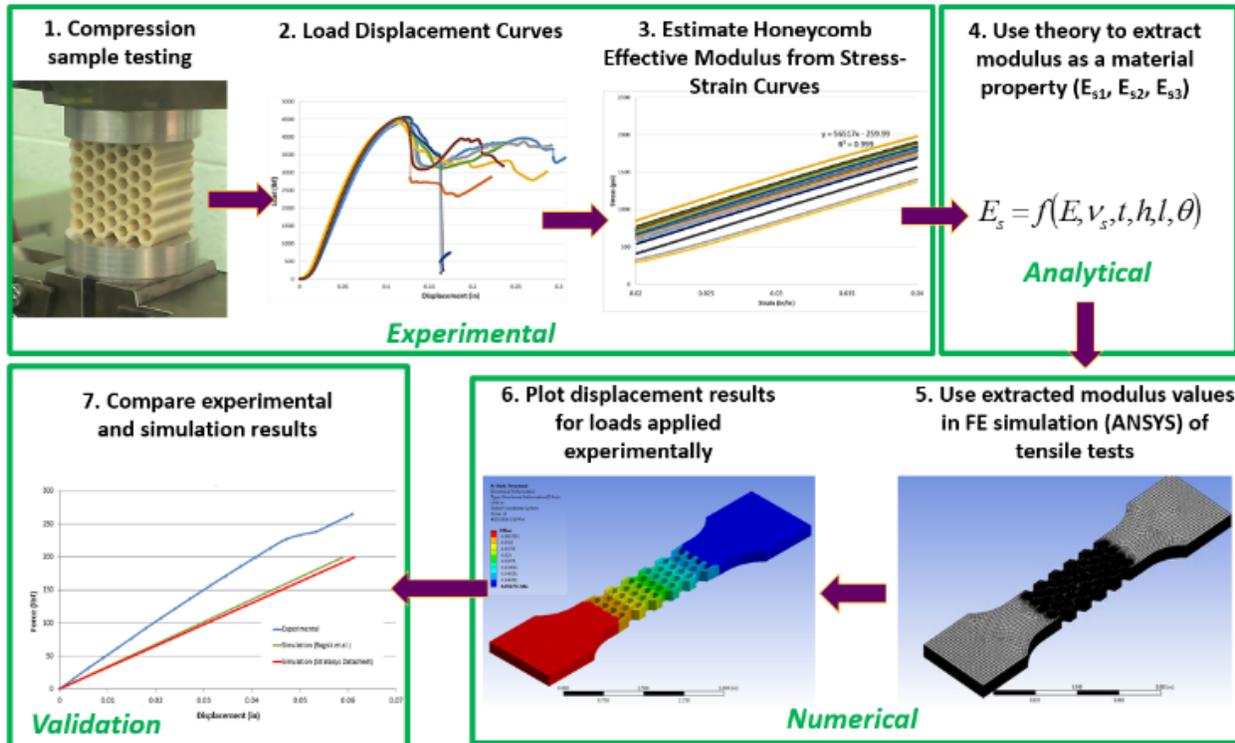


Figure 3. Methodology to extract and validate accurate lattice mechanical properties using a combination of experimental, analytical and numerical methods

Experimental Approach: Compression & Tension Testing

We designed a total of four specimens as shown in Figure 4. The specimens are labeled T1, T2, C1, C2 and C3 by the loading method (Tension or Compression) and the direction the load was applied relative the cell as shown in Figure 4 (C1 and C2 are the same specimen as printed – the only difference lies in the loading direction).

The external geometry for the tensile test specimens followed from the designs used by Barner (7), who modeled them after dimensions prescribed in the ASTM D638 standard. However, standard tensile tests do not lend themselves well to extracting or studying honeycomb behavior – this is because of the limited number of cells that bear the load, causing the possibility of edge effects influencing the behavior. For this reason, we chose to only use compression samples for our characterization efforts and use the tensile test results to validate our model. This will be discussed in more detail in a following section.

For the cell dimensions, we selected a thickness t of 0.060 inch and a regular hexagonal shape with a length of 0.132 inch. The former was selected based on process parameters, the latter based on commonly used volume fractions in the literature (5; 6; 7).

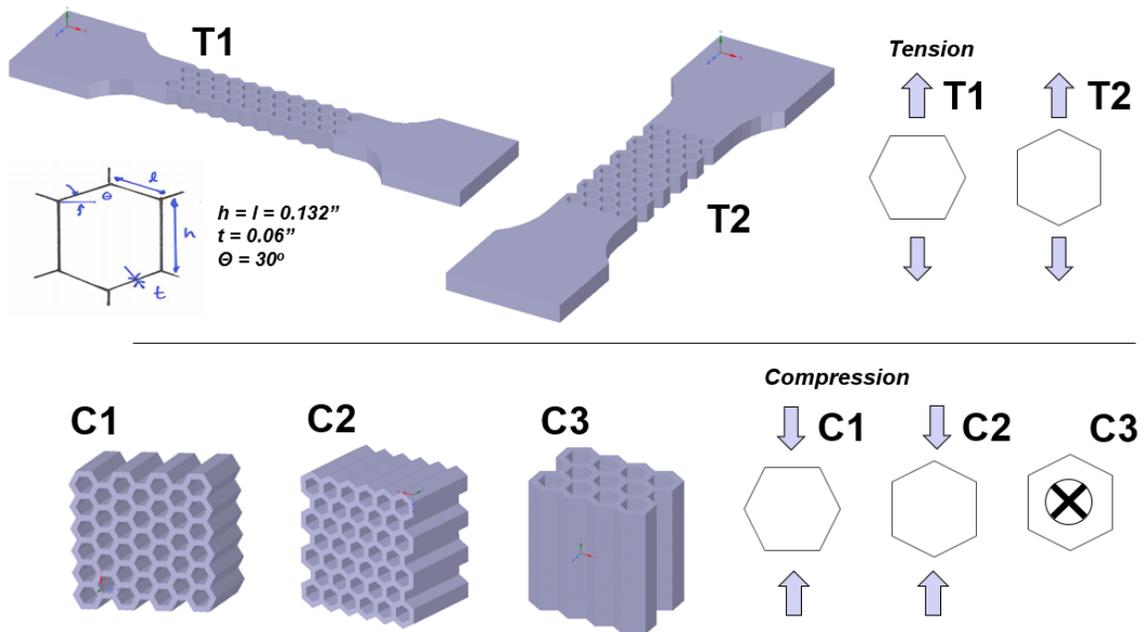


Figure 4. Sample designs and dimensions used for tension (above) and compression (below) for three different loading directions (1, 2 and 3), with T and C indicating Tension and Compression, respectively. Only 1 and 2 were designed for tension testing due to the difficulty in printing in the 3 directions without supports.

The designed specimens were manufactured on a Stratasys Fortus 400mc, a leading industrial FDM machine, using the ULTEM-9085 material. Build parameters are described in Figure 5 and will be familiar to a user of these machines and hence reproduced here. The key parameters used were a layer thickness of 0.010 inch and a contour width of 0.030 inch. Importantly, we chose to do a contour-only cell wall and have as a result 2-contours wide thicknesses for all cells ($t = 0.060$ inch). This is because small width walls in hexagonal cells tend to have large void areas if filled with rasters (as shown in Figure 1) and is not a realistic process users would implement as a result.

All specimens were laid out on the build sheet as shown in Figure 5 and the build was repeated once more to get to a total sample size of 8 for each leg (T1, T2, C1, C2 and C3). We did not study effects of location or build-to-build variation, leveraging published data from the supplier (8) as well as our own experience to deem this an important, but second-order source of variation for the purposes of our evaluations in this paper. Finally, the samples were oriented in a manner so as to avoid the need for any support through the cells – since ULTEM-9085 has breakaway supports (as opposed to water soluble), having supports inside cells would have made it challenging to remove. Additionally, the focus of our work was not in trying to manufacture samples in a range of conditions, but to assess for a give condition, how valid our model would be.

Before the specimens were tested, we used calipers to ensure dimensional accuracy and that external dimensions were within 0.005 inch. However, we found manufactured thicknesses were significantly larger than the designed value of 0.060 inch. Taking multiple measurements we determined the value to have an average measurement of 0.066 inch – this is a 10% increase in thickness, which can have a large influence on stiffness in the predictions that we obtain both analytically and in our simulations. As a result the 0.060 inch value was used. Work is ongoing now using optical scanning to characterize this difference in more statistical depth and on these

particular samples has validated our findings. Thus 0.066 inch is the value used in all the mathematical models and the geometry used for simulation, with all other dimensions being identical to the as-designed value.

Once the samples were measured, they were labeled and sealed and within the span of 10 days, were tested on an INSTRON-8801 that was setup for compression and tension tests. The 8801 is a robust system with a 22,500 lbf capacity – while it is originally designed for fatigue, it lends itself well to monotonic testing as well. An image of the test setup is shown in Figure 6. Special fixtures were manufactured for the compression tests to provide a flat surface for the honeycomb structures (see top left image in Figure 3).

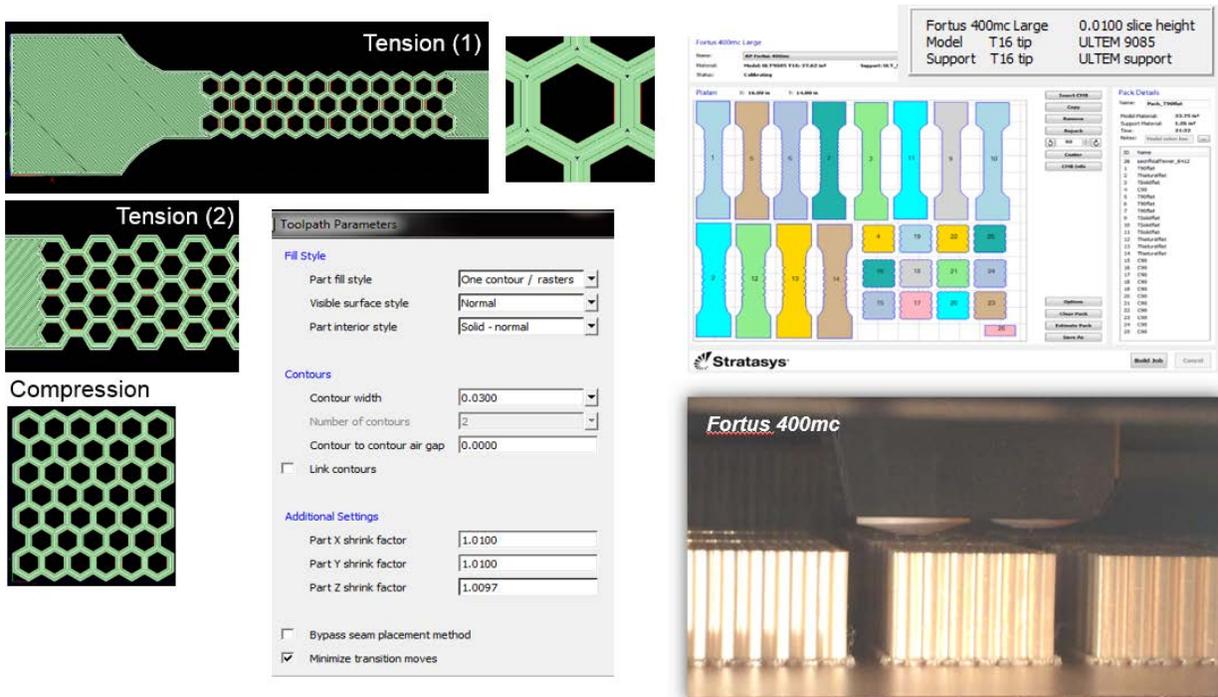


Figure 5. The process settings and layout for the Fortus 400mc FDM machine used in the experimental work

Test results from all five test conditions are shown in Figure 7. Since our primary interest for this work is only modeling stiffness, we did not investigate the nature of failure. The stiffness response of all samples for a given group were consistent though large variations were seen in the load-displacement response after failure. The compression and tension test results are consistent with the trends described by Gibson and Ashby (1) for brittle compression/crushing (as opposed to elastomeric or plastic compression). Compression tests were not carried on through densification but failure images shown in Figure 8 suggest that would be a likely expected outcome as more cell walls failed. The localization of failure for the compression test along a series of connected cells is also consistent with other observations (1). The tensile tests showed consistent fracture paths shown by the lines superimposed on the samples. The SEM images show the varying nature of failure – both between- and within layers. These images are only presented here for comparison –explaining or modeling the failure mechanisms is beyond the scope of the work in this paper.



Figure 6. The INSTRON 8801 setup for compression testing (left) and tension testing (right)

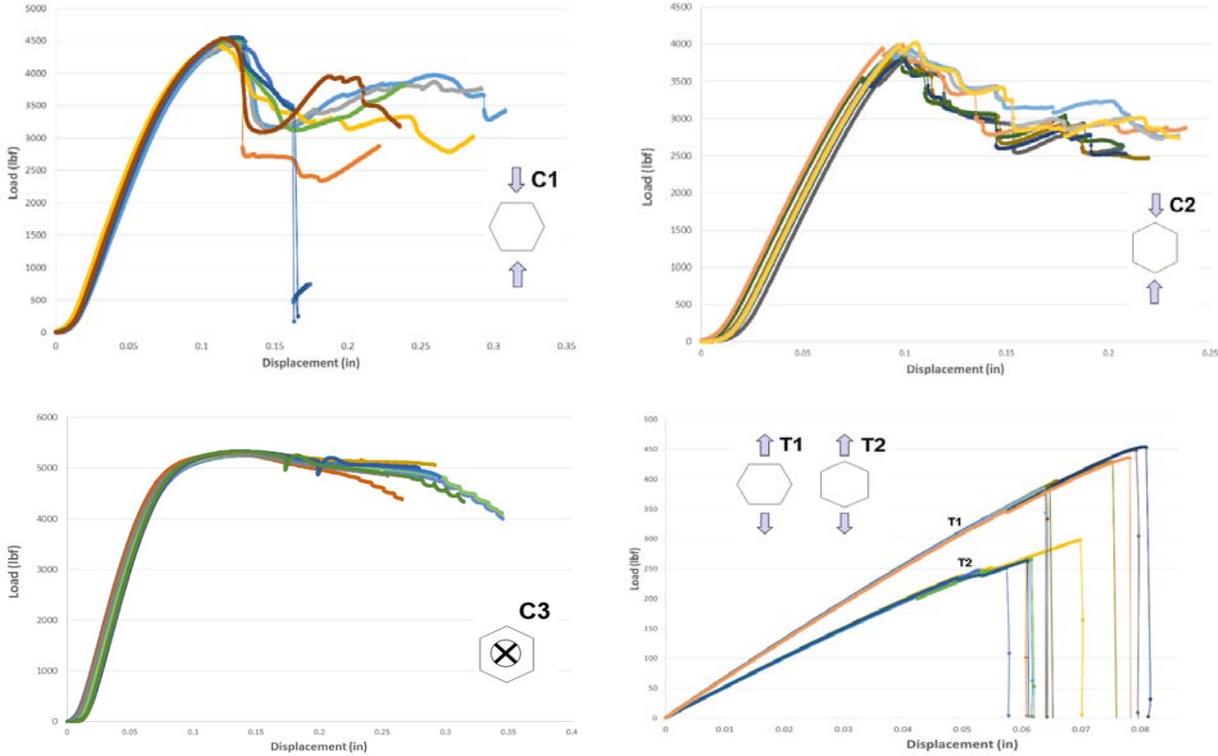


Figure 7. Compression test results for C1, C2 and C3 loading directions. Both T1 and T2 tension test results are shown in one graph. Each test condition had a sample size of 8.

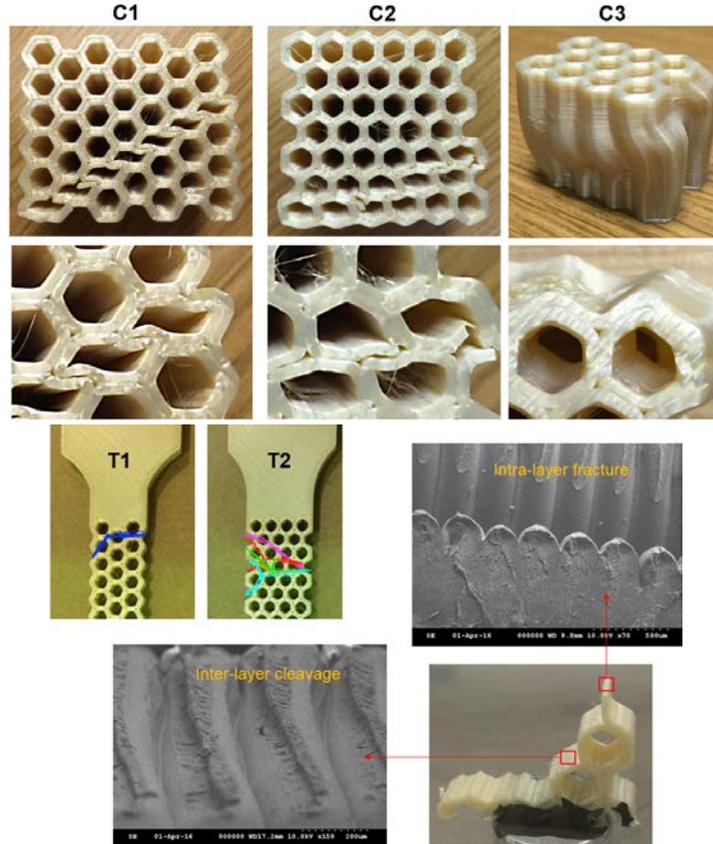


Figure 8. Images of specimens after failure: compression samples (left) and tensile samples (right)

Analytical Approach: Lattice Theory

We believe that the novel aspect of our work is to leverage existing analytical equations to not merely to study the *effective* performance of cellular structures, as is commonly done in the literature, but also to *extract a point-wise material property*. To demonstrate this point, consider Equation 1 below that describes the effective elastic modulus E_1^* in the 1-direction for a hexagonal prismatic (honeycomb) lattice structure in terms of a postulated material property E_s and ν_s , geometric descriptors of the lattice structure (t , h , l and θ), taken from (1) and demonstrated schematically in Figure 4:

$$E_1^* = E_s \left(\frac{t}{l} \right)^3 \frac{\cos \theta}{\left(\frac{h}{l} + \sin \theta \right) \sin^2 \theta} \frac{1}{1 + (2.4 + 1.5\nu_s + \cot^2 \theta) \left(\frac{t}{l} \right)^2} \quad (1)$$

This equation represents the effective modulus that applies for the most general case, when the t/l ratio exceeds 0.2 and includes shear and axial terms in addition to bending. Similar equations exist for the 2- and 3-directions:

$$E_2^* = E_s \left(\frac{t}{l} \right)^3 \frac{\left(\frac{h}{l} + \sin \theta \right)}{\cos^3 \theta} \frac{1}{\left[1 + \left(2.4 + 1.5\nu_s + \tan^2 \theta + \frac{2(h/l)}{\cos^2 \theta} \right) \left(\frac{t}{l} \right)^2 \right]} \quad (2)$$

$$E_3^* = E_s \left(\frac{t}{l} \right) \left[\frac{h/l + 2}{2(h/l + \sin \theta) \cos \theta} \right] \quad (3)$$

Typical approaches of using the above equations involve solving for the effective property (E^* in this case), assuming an established material property E_s . Our approach is, quite simply, to measure the effective property from experimental characterization and then solve for the material property instead. This approach allows us to extract material property behavior that is representative of the process parameters and scale of the lattice structure and eliminates the lattice geometry dependence of the result. For FDM, we essentially make the argument that it is adequate to represent the meso-structure of the beam cross-section. In other words, we hypothesize that results obtained from hexagonal lattice testing can be extended to any lattice structure.

Using the data obtained from the previously described compression tests, and a t value of 0.066 inch (instead of as designed value of 0.060 inches as discussed before), we estimated over a strain range of 0.02 to 0.04, the effective moduli E^* for each of the 3 directions. Using Equations 1, 2 and 3, we then solved for the E_s values in each case, which are listed in Table 1 along with the measured standard deviations from each sample of 8 tests.

Table 1. E_s values calculated from the average of 8 compression tests for the 1-, 2- and 3-directions, along with associated standard deviations

	C1	C2	C3
Es (Average, psi)	515290.8	515087.7	252006.5
Std. Dev.	13213.18	7637.45	6704.72

Discussion: The C1 and C2 values estimated in this approach are significantly higher than published values for FDM ULTEM-9085 that are typically in the range of 300,000 psi (3; 4). Bulk SABIC resin which is the raw material used in the FDM filaments is listed at 497,817 psi (9), which is much closer to the values reported here. We believe this is due to our use of pure contours in the printing of the honeycomb cells, with no raster, which closely approximates the bulk for in-plane loading. This is backed by our observation in Figure 1 that a two- and four-contour process both yield similar stiffness and it is the rastering that has the effect of lowering stiffness. On the other hand, the C3 value estimated here is significantly lower than any reported value. We believe this is primarily due to the fact that we have contours lying conformally on top of each other with no cross-rastering providing additional strength and this number is a closer approximate of true stiffness that accounts for the weak intra-layer bonds.

Numerical Approach: Simulation & Validation

So far we have discussed the use of an analytical model that is used with measured data to extract a material property. The next natural step is to study the validity of this model – in the limited time we had available we decided to apply the model to simulate the tensile test we had also conducted but not used in the characterization study. As we discussed before, the stress distribution across a tensile specimen with a small number of cells is unlikely to be uniform and as such cannot be used reliably for extracting material properties – however this makes it a very good candidate to validate our model: not only is the stress state non-uniform but the effective load direction is reversed as well (tension instead of compression).

We used ANSYS Release 16.0 (10) mechanical workbench for our simulation work. While the modeling was purely static structural, we simulated the applied load as a series of steps to mimic the experimentally applied loads, and sought to study the overall displacement to generate a load-displacement curve for comparison to the experimental result, as shown in Figure 9. We used a swept mesh and conducted a mesh refinement study to ensure changes in load-displacement response were within acceptable limits, as shown in Figure 10. We used an orthotropic elasticity material model, with the moduli value from Table 1 and aligned to the build direction (1- and 2- in plane, 3- out of plane).

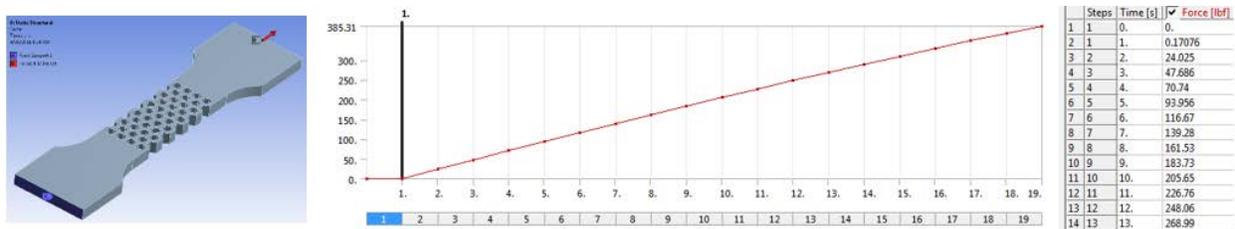


Figure 9. Loading conditions applied to simulated tension test specimen with load values taken from the experimentally applied ones

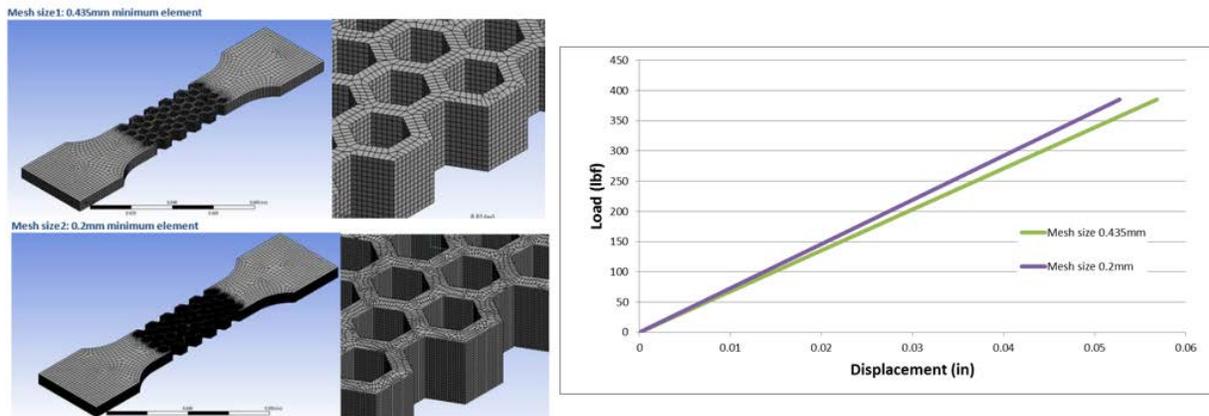


Figure 10. Mesh refinement study shows a fairly well converged result for displacement response

Results from the simulation were compared to the experimental results for both T1 and T2, as well as to the same simulation performed with datasheet values (3) and are shown in Figure 11 along with equivalent von-Mises stress contours associated with each test. It is also worth noting the non-uniformity in stress distribution, particularly for the T2 test condition where walls on the edges have lower stress than ones in the middle, making it difficult to estimate a representative

stress value for computation of elasticity. The results in Figure 11 show a significant improvement over the use of datasheet properties. At low strains the error is under 5%, and grows at higher strains, but this represents a significant improvement over the 50% error we obtained using published datasheet values before.

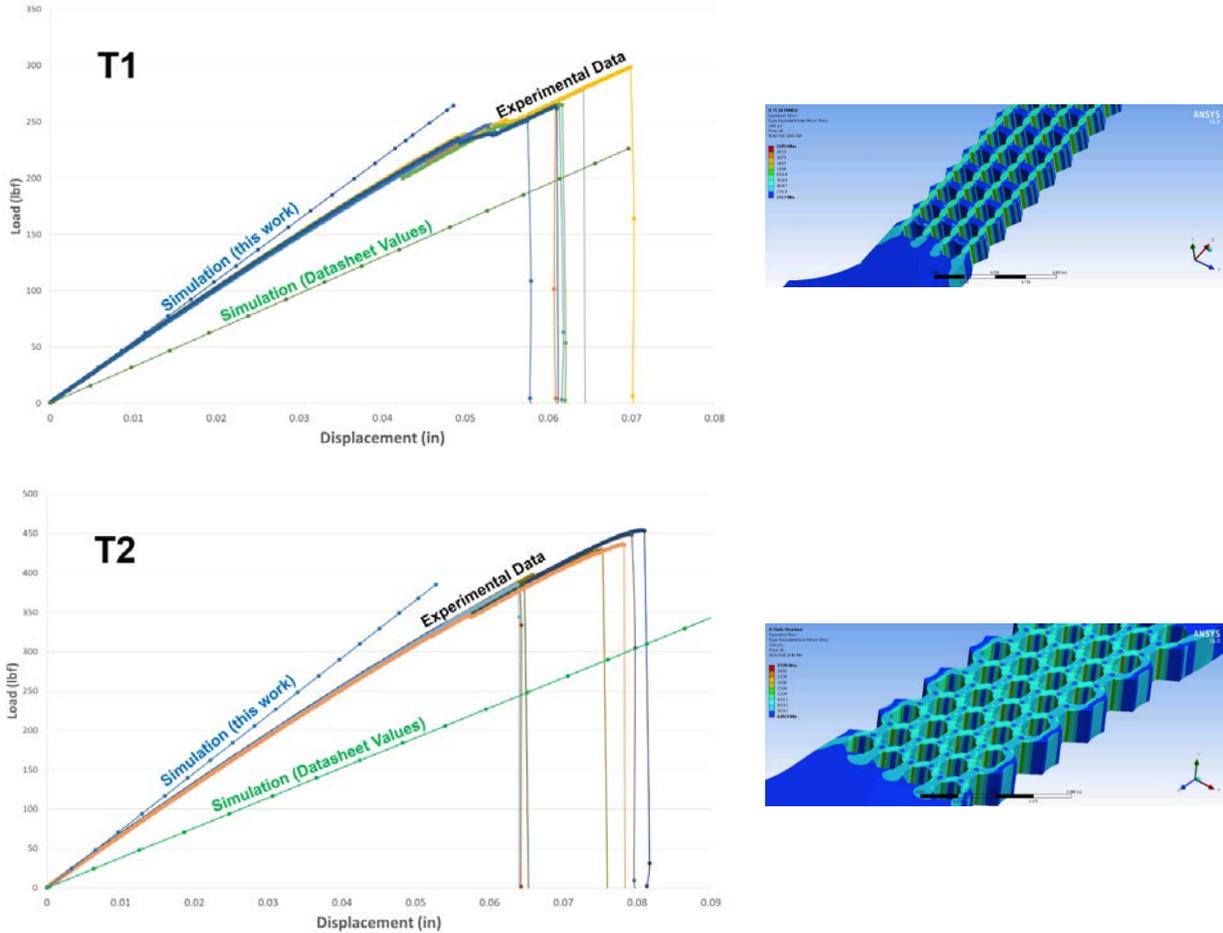


Figure 11. Finite element simulation results for tensile test specimen compared to experimental data and simulation result obtained using datasheet values. Results for loading in the 1-direction: T1 (above) and 2-direction: T2 (below)

Future Work

In this work we have demonstrated what we believe is a novel approach to predicting AM honeycomb structure behavior. This work does need further improvements to the approach as well as more validation studies and these are discussed in turn below and are ongoing at the time of writing this paper.

- a) Improved honeycomb thickness measurements: As mentioned before, the thickness values assumed in the models can have a strong influence on the accuracy of the predicted response. Ongoing work is looking at using optical scanning, future work will involve X-ray computed tomography (CT) scanning.
- b) Different shapes (square, triangular): This work is currently being extended to study its applicability to shapes beyond regular hexagonal cells, as well as to non-uniform distributions of cell sizes for any given shape.

- c) Different materials and processes: Our approach fundamentally does not make any FDM-specific assumptions and we believe is extendible to other processes for both metals and polymeric materials
- d) Foams: Analysis of foams is more involved, but is possibly of greater interest for metals due to the even lower volume fractions that are enabled. However, equations do exist for open- and close-cell foams of basic rectangular shapes (1) and the similar idea may be used to extract material properties from these equations
- e) Failure Modeling: Perhaps the most challenging work in this realm is in failure modeling for cellular structures, including quasi-static, shock and fatigue loading – developing the kinds of models presented in this paper is a key precursor to this work.

Acknowledgements

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