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A comparative analysis of 3d printed gridshell structures using finite element models and experimental load-deflection tests

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Abstract

Small-scale, physical modeling of gridshells is difficult and rarely done due to their complex form and meticulous construction process. Additive manufacturing (AM) has opened the design space and allowed for architects and engineers to rapidly print, bend and load-test gridshells. However AM is complex and highly sensitive to the printing parameters selected by the user, including the print method, infill density, infill pattern and print orientation. Careful selection of the printing parameters and validation of their effectiveness is critical. This research provides recommendations on the selection of printing parameters to accurately mimic the structural behavior of gridshells. A total of 125 printed gridshells were experimentally loaded, their deflections measured and compared to a finite element model (FEM). A simply-supported, symmetric, hexagonal gridshell with a triangular topology served as the base geometry for the parametric study. The varied printing parameters included: the print method - fused deposition modeling (FDM) versus selective laser sintering (SLS) and the print orientation. The varied geometric parameters included the grid density. There was a significant difference in the structural performances as the print parameters were varied. This research demonstrated that prints made using SLS at a zero-degree orientation yielded the closest results to the FEM and illustrates the effectiveness of AM in gridshell modeling.

Keywords: gridshells, additive manufacturing, experimental load-testing, finite element analysis, fused deposition modeling, selective laser sintering.

1. Introduction

In civil engineering and architecture, shell structures are highly desirable for both their aesthetics and their structural efficiency. Shell structures are curved, load-bearing surfaces that, in addition to their material selection, provide strength and stiffness, through their geometric shape.

Gridshells are a type of shell structure that, instead of being a continuous surface, are a lattice. They were originally contrived by bending on-site timber lattices to form curved, load-bearing surfaces. Recently, they have been made from metal, and preformed into the curved surface; examples shown in Figure 1 include the timber Pavilion Za in Cluj, Romania and the metal Great Court at the British Museum Naicu et al. [1].

Gridshells have seen an increase in use in the built-environment; however, due to their complex form and meticulous construction process, small-scale, physical modeling of gridshells is difficult and rarely done. Additive manufacturing (AM) has created a new design possibility and allows the rapid design, printing, and testing of gridshells by architects and engineers. This new AM design possibility has exceptional benefits that can greatly enhance the development of gridshells for broader use, but it is not without challenges. The printing of AM parts is complex and isotropic material properties cannot be guaranteed due to the highly sensitive nature of these properties to user selected printing parameters, including the print method, infill density, infill pattern and print orientation Jaksch et al. [2]. Additionally, challenges exist in repeatability between prints and the overall part thickness can impact material properties, particularly for thin parts less than about 2 mm Rodriguez et al. [3] and Sindinger et al. [4]. Acknowledging these challenges is important, but this does not negate the substantial benefits of the introduction of AM into the gridshell environment.

Two types of widely-used printing methods and materials are: Fused Deposition Modeling (FDM) with polyactic acid (PLA) filament, and Selective Laser Sintering (SLS) with polyamide 12 (PA12) powder. FDM is one of the most prolific AM methods based on its minimal cost and waste when compared to other AM methods. PLA material is often used with FDM because it is inexpensive, biodegradable, and composed of renewable resources. Nozzle temperature, nozzle speed, molten flow rate, ambient and bed temperatures, raster design, and infill density are typical parameters that are controlled to optimize FDM parts based on the part shape and size.

SLS is one of the most common AM methods used to create end-use parts as opposed to form and fit prototyping. PA12 powder is often used with SLS because it is relatively stable throughout its large sintering temperature window Schmid et al. [5], and Razaviye et al. [6]. PA12's ideal sintering temperature window, coupled with its relatively high strength, durability, chemical resistance, and long-term stability once cooled, make it one of the most used materials in SLS. The laser parameters (speed, power, and hatch pattern) and temperatures (ambient, top layer, and bed) are set by the user.

Figure 1: (left to right) Pavilion Za - image Dragos Naicu; Great Court - image Samar Malek

2. Methodology

A hexagonal gridshell with a side length of 75mm, and a triangular topology served as the base geometry for the parametric study. The gridshell size was limited due to the available AM printing size constraints. All models (experimental and computational) were flat, and then bent into a barrel vault, simply-supported and then point-loaded at the midspan. The triangular topology density was also varied to include 4, 6, 8, 10, 12 (Figure 2).

2.1. Physical Models

Two different AM methods coupled with two different materials were studied based on current AM industry trends. FDM was tested with PLA filament and SLS was tested with PA12 powder. For FDM, this study focused on varying infill pattern and part size to optimize experimental gridshell models; for SLS, this study focused on varying hatch pattern of the laser to optimize experimental gridshell models.

All FDM prints used an UltiMaker S3 printer and used a uniform triangle infill pattern with a 20% infill density and 1.0 mm perimeter thickness with a layer height of 0.1 mm. The gridshells were printed flat on the build plate and so supports were not required. The slicing parameters were held constant for each gridshell size that was tested.

All SLS prints used a FormLabs Fuse1 SLS machine with Formlabs branded Polyamide 12 (PA12) powder Formlabs [7]. All prints used the same size gridshell based on the results of the FDM testing and also utilized the same layer height (0.1 mm), temperatures, and laser speed and power for all prints. Infill hatch pattern was maintained at constant x-y travel without perimeters. Using this simplistic infill pattern allowed testing of a more isotropic versus a more directionally strong print based on orientation on the bed. It has been shown that orientation of printed parts can vary the material properties Rodriguez et al. [3]. Aligning the long edge of the gridshell 15-degrees off the x-axis (laser direction) on the print bed, minimized the variation between hatch lengths and allowed for a relatively constant laser burst for each sintering movement. This reduced the anisotropy of the entire part. The second orientation aligned one of the long sides of the gridshell to the x-axis (zero-degree orientation). This greatly increased the laser on-time along these gridshell members and so increased the strength of these specific members.

All shells were printed flat, but, when bent, had a span-to-height ratio of 2.35 for the PLA (FDM-printed) shells, and 2.42 for the PA12 (SLS-printed) shells. Five samples were made for each shell to increase the tested sample size. The gridshells were loaded using an ADMET Universal Testing Machine (Figure 2). The first sample of each material and grid density was loaded to failure in order to calibrate the experimental test setup, specifically the displacement rate. The remaining four copies were loaded to failure.

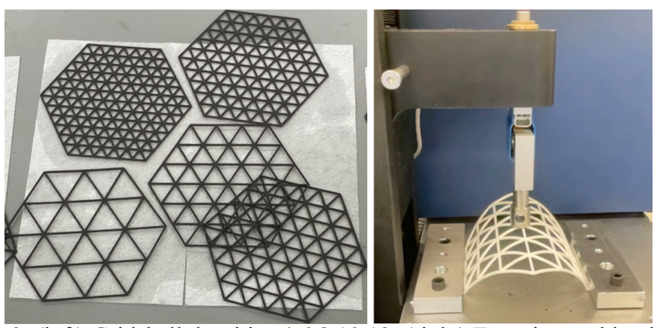

Figure 2: (left) Gridshell densities 4,6,8,10,12; (right) Experimental load set-up

2.1. Finite Element Models

In addition to the experimental models, finite element analysis was used to validate and compare the load-deflection measurements. The finite element software package used was Bentley Systems ADINA [8]. An FEM was created for each of the five different grid densities (4,6,8,10,12). The kinematics of the analysis were large-deformation and small-strain; the computational model mimicked the physical bending of the flat gridshell into its curved shape, before securing the supports and then applying the point load. Gravity was also included in the analysis. The members were modeled using a Hermitian beam element, and a mesh convergence study was done to determine the proper mesh density.

3. Results

The results are presented in the following order – first, the use of finite element analysis (FEA) to evaluate the impact of different grid densities; second, the comparison of FEA and experimental results for PLA (FDM-printed); third, the comparison of zero-degree and 15-degree orientation for SLS; fourth, the comparison of FEA and experimental results for PA12 (SLS-printed).

Figure 3 compares the load-displacement of the finite element analyses for the PLA of all five grid densities (4,6,8,10,12). The plotted points from left to right are decreasing in grid density. As expected, a denser gridshell is stiffer and displaces less. The gridshells with densities of 4 and 6 exhibit snap-through deformation.

Figure 4 compares the load-displacement for the experimental and finite element models of the PLA gridshells with densities 4,6,8. As stated in the Methodology section, each gridshell had five copies made to load-test. The plots shown in this paper, however, are representative of one data set, not the five data sets averaged. There is overall good agreement in the load-displacement relationships between the experimental and finite element model. The results from the finite element models were most accurate for the grid density 4, whereas for grid densities 6 and 8, there is a larger spread in the data. The finite element model predicted a greater displacement than the experimental. This was surprising as the FEM is modeling a fully-dense, homogeneous member, and would be expected to be stiffer than the printed member. It is well known that one of the challenges of AM is consistency in material properties due to a variety of factors including the impact of thin structures. This may have impacted these results and requires further investigation.

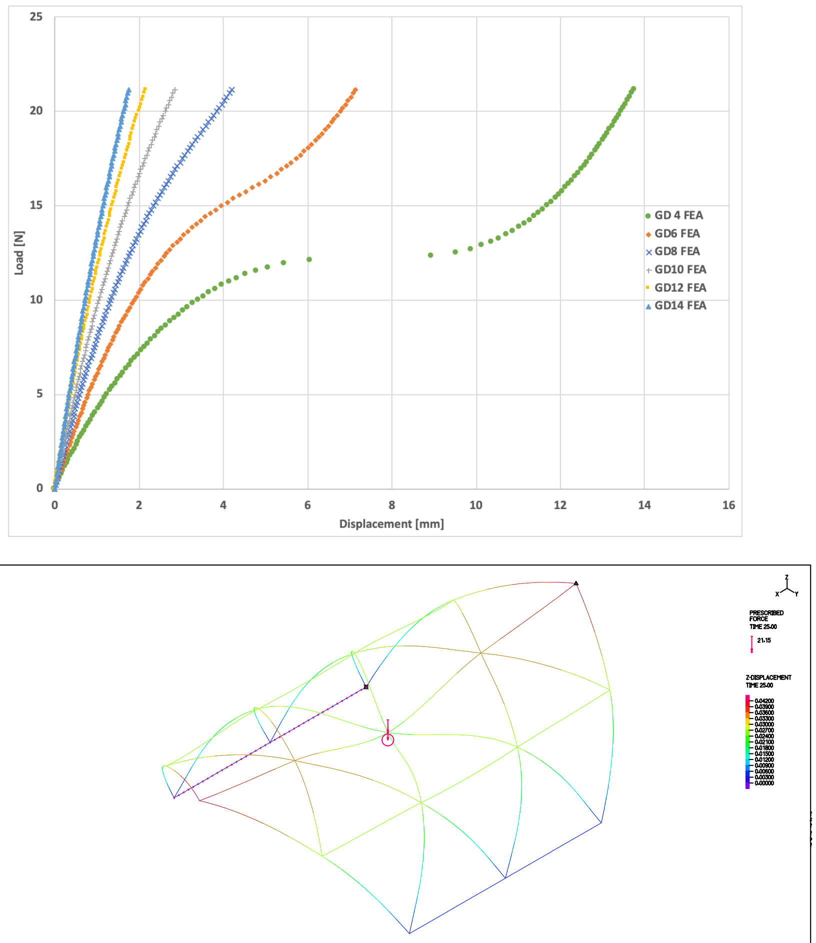

Figure 3: (top) Load-displacement plot of the finite element models for PLA (FDM-printed) gridshells with densities of 4,6,8,10,12; (bottom) Snap-through deformation of FEM of PLA gridshell with density of 4

Figure 5 compares the effect of the print orientation (zero and 15 degrees) for SLS printing for gridshells with densities 4,6, 8; gridshell densities 10, 12 exhibited similar trends. In all cases, a zero-degree print orientation created a stiffer model. The zero-degree orientation aligned one of the long sides of the gridshell to the x-axis, greatly increasing the laser on-time along these gridshell members and so increased the strength of these specific members. When compared to the finite element models, Figure 6, the SLS zero-degree orientation matched the FEA closest. This is likely the case because the long members along the x-axis most closely matched the material properties of a fully-dense, homogenous FEA part and were aligned in the test rig to take the majority of the initial load that produced elastic deformation. Since the other members were taking slightly less load, the effect of the decreased stiffness and strength in these members was minimized. The finite element models of the PA12 predicted less displacement than the physical models. This is expected as explained earlier, however, the FEMs were substantially stiffer. The computer models used the manufacturer's provided material properties, however, at the United States Naval Academy Type 5 ASTM tensile test were performed on over 144 samples Formlabs branded PA12 and yielded a Young's Modulus 11% weaker than the distributor's datasheet Formlabs [7], and Ibrahim et al. [9]. It is necessary to determine the as-printed material properties and further material tests are needed from both the PLA and PA12 models.

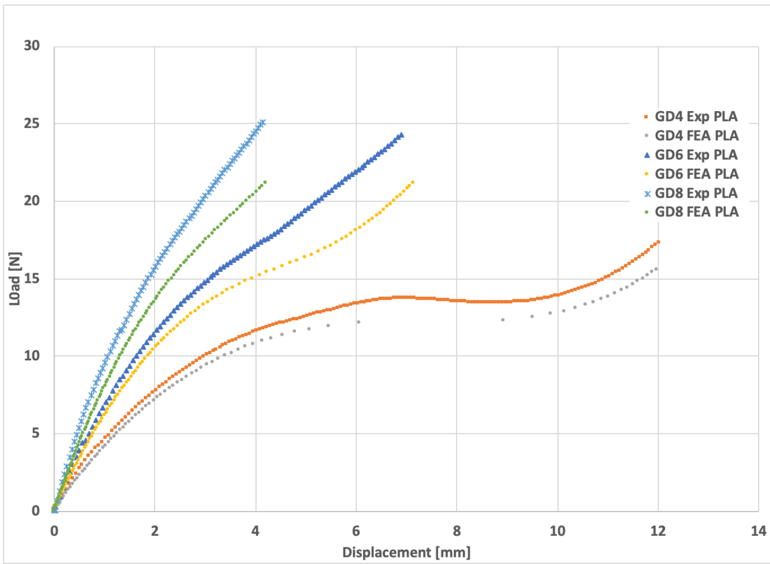

Figure 4: Load-displacement of finite element and experimental models - PLA gridshells with densities of 4,6,8

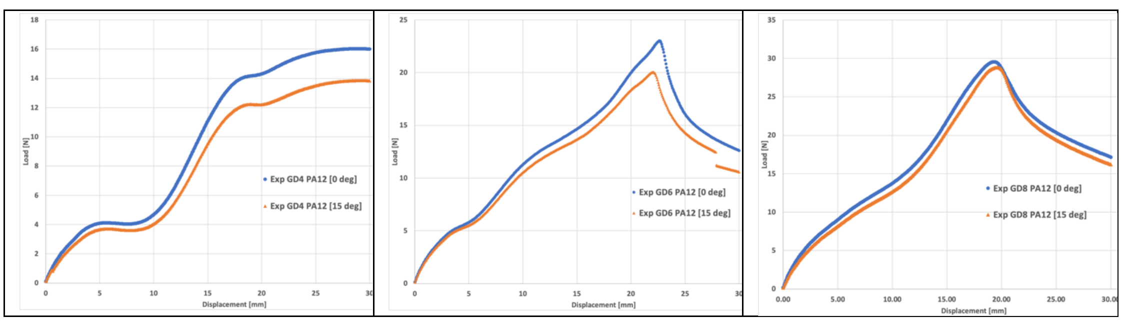

Figure 5: Comparison of zero and 15 degree print orientations for experimental models printed by SLS. Load-displacement gridshells with densities of 4,6,8

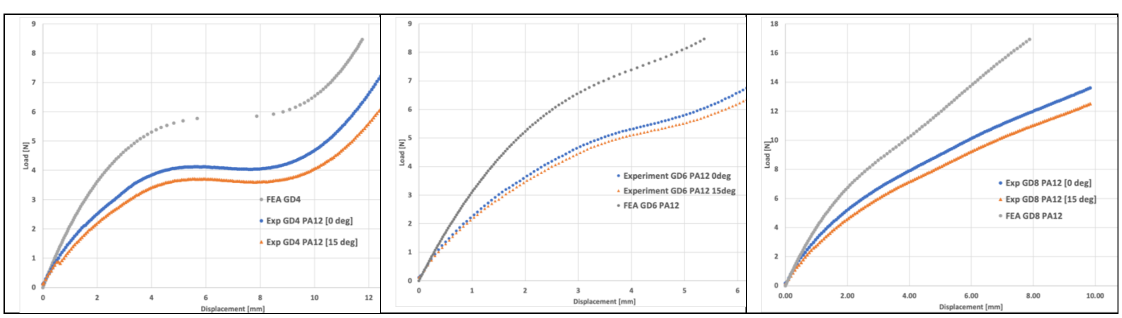

Figure 6: Comparison of finite element and experimental models for PA12 for densities of 4,6,8

4. Conclusions

This work experimentally loaded printed gridshells using an ADMET universal testing machine, measured their deflections and compared them to a finite element model. Two print methods and materials were studied: FDM with PLA filament, and SLS with PA12 powder. There was reasonable agreement between the finite element models and the experimental results from both FDM and SLS print methods. Additionally, for SLS prints, it was generally observed that a print orientation of zero-degrees was generally stronger than 15-degrees. This work illustrates the effectiveness of using AM in gridshell development, but there are challenges that need to be addressed: material characterization, and scaling. The provided mechanical properties for a particular material must be further evaluated due to the impact of varying AM printing parameters. Determining the scaling factor to translate these small-scale models to a full-scale elastically bent gridshells is also needed. This will further support the use of AM in the field of gridshells.

Acknowledgements

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