EngrXiv Technical Note

Buckling strength of additively manufactured cylindrical shells: An exploratory study of as-printed and reinforced ABS and PLA cases

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ABSTRACT

Additively-manufactured (AM) materials have a defined mesostructure and natural voids which impact their structural stability; thin shells which so not have bulk to support or absorb the effects of the variances in properties are particularly affected. Thin shells are a common feature in many designs, providing good strength-to-weight ratios for many applications, particularly in the aerospace and structural design domains. The use of AM processes to produce thin structures could both expand the use of AM and improve the application space for thin structures in design, but this problem has not yet been widely explored for buckling cases. The brief exploratory study presented in this paper examined the characteristics and critical buckling load of thin-walled ABS and PLA cylinders under static axial and angled radial loading. A designed $2^{(4-1)}$ factorial experiment was used to explore the buckling behavior, examining the impact of wall thickness, material, and two kinds of internal reinforcement (soft infill and polyurethane foam). Analysis of variance (ANOVA) (including model adequacy testing and proof of Fisher Assumption validity) was completed on data from two replications (32 total tests), providing useful information on the significance of the factors and their interactions. The data is provided in full, along with a discussion of the experimental design and testing method, the results, and the importance of this problem in further research efforts. The results of the tests showed a dramatic variance in the performance based on the characteristics of the cylinders. The data collected can be used to drive future work toward the modeling and design of hard polymer AM thin structures, as well as developing efficient and low-cost methods for testing and exploring these structures for practical design problems.

Keywords: Buckling; structural mechanics; additive manufacturing; thin polymer materials

INTRODUCTION

Thin-walled structures are common in engineering design, often seen in the form of domes, shells, plates, and membranes. They provide strong and flexible but relatively light-weight architectures, most commonly automotive components, boats, pressure vessels, tanks, piping, machine components, buildings, and aircraft structures [1-6]. There are numerous advantages to using these structures, but there are also tradeoffs; the mass and strength must be balanced, making the thin structures optimal relative to both but neither individually [7-8]. This has a significant impact on their performance, especially on buckling behavior since thin-wall buckling failure often occurs long before the yield point of the material [9-11]. Thin-walled structure are often defined as one that is has its smallest internal hollow section at least 20 times the thickness of the wall; the most simple and controllable geometry for exploring this is a thin cylinder [12].

As additive manufacturing (AM) becomes more widely accepted and used, it is increasingly important to understand the behavior of additively-fabricated structures. AM materials are highly anisotropic [13-14] and have a well-defined mesostructure that greatly affects the mechanical properties [15]. One of the most common and refined AM process for polymeric materials is the Fused Deposition Modeling (FDM) process, which works by selectively depositing material in layers as it is extruded from a heated die [16-17]. Under careful tuning, FDM can fabricate very precise geometry using a wide variety of materials with good properties and at a low cost without any special tooling; it can easily fabricate thin-walled and delicate structures, as demonstrated in several previous studies [18-25]. The mechanical behavior of FDM-processed material has been well-studied, but the buckling behavior of thin-walled FDM structures is still an open question and little is known about their behavior. Due to the structure of AM materials, it is likely that the structures will undergo local plastic yielding before buckling [26-28].

To explore this question, this article presents an exploratory experimental study done on the critical buckling load of FDM-processed ABS and PLA cylindrical shells. Several factors were studied, including wall thickness, material choice, and the use of reinforcement (3% infill and polyurethane foam) within the shell. Critical load tests were completed twice (two replications) on the selected cases, with a total of 32 tests conducted. This is a preliminary but detailed study to identify areas related to this problem that need further research attention in the future. This work expands the state-of-the-art in both polymer material testing and design for additive manufacturing by showing that work is needed on the problem, by providing a method for rapid and effective testing of these thin shells, and by collecting a preliminary dataset on their buckling behavior which may be used to understand and solve practical design problems.

MATERIALS AND METHODS

The analytical and finite element analysis (FEA) solutions to thin-wall buckling problems presented in previous works [12, 29-32] assumed that the shell was uniform and free of defects. This assumption does not hold for additively-manufactured structures, as the nature of the AM process produces a patterned structure with natural inclusions and voids [32-33]. Example geometry (single and double walled cylinders) produced by FDM from two common materials (acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA)) is shown in Figure 1a-1d. Figure 2a shows the basic parameters of this structure, while Figure 2b present a series of parameter measurements from 50 sample cylinders made from both materials and wall thicknesses.

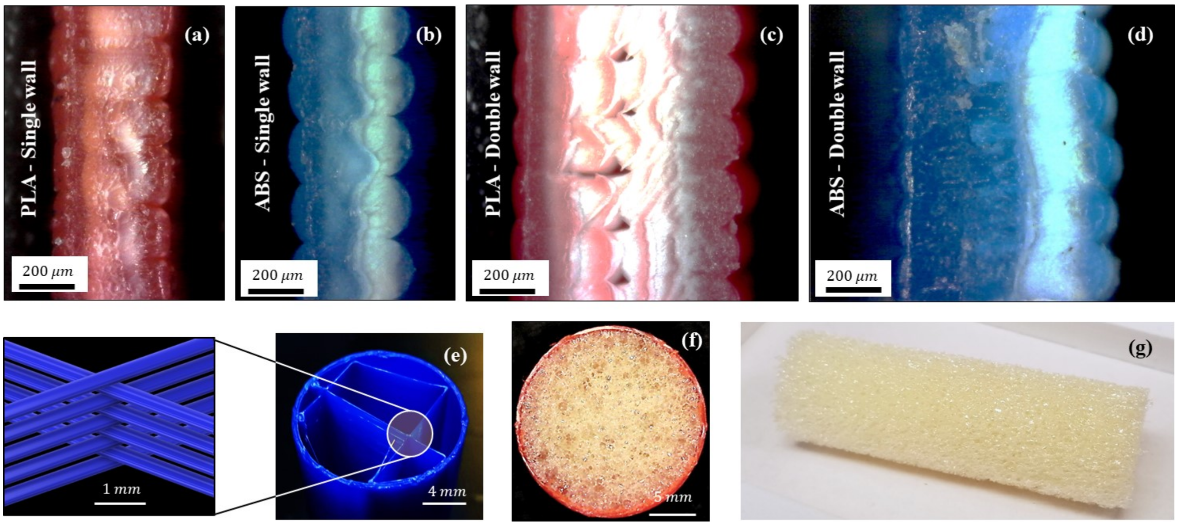

Figure 1: Example mesostructures for the (a) single wall PLA, (b) single wall ABS, (c) double wall PLA, and (d) double wall ABS. Also shown is the (e) soft infill and (f) foam reinforcements and (g) an example foam core

The values of ρ and y (Figure 2) were measured using a PosiTector® surface profile gauge and calipers, while $t = 200\ \mu m$ was set in the g-code when printing the samples. The parameters ρ and y were found to be close to the nominal values, as shown in Figure 2b and Table 1. After reviewing previous successful work (see [12]) on reinforcing thin-walled shells without greatly increasing the mass of the structure, two methods were selected for inclusion in this study: (1) light printed rectilinear infill (3% density with stacked-beam local geometry) (Figure 1e) and (2) polyurethane foam filling (Figure 1f). The infill structure was to be printed along with the shell, while a sprayed expanding polyurethane foam from Dow Chemical Company® [34] was used for the foam infill samples. A series of cores were made with the foam (produced inside of open-ended PVC cylinders and allowed to cure for 24 hours) to assess the uniformity of expansion and density; 10 randomly selected cores (Figure 1g shows an example) showed uniform bubble distribution and an average density of $35\ kg/m^3$.

A $2^{(4-1)}$ fractional factorial experiment was designed for this study, as shown in Table 2. The experiment used four factors with two levels each, two replications, and a response of the critical buckling load for each case. The fractional factorial design was used to reduce the experimental cost and allow two replications; Factors A-C were examined in full, with the generator D = ABC used for factor D. Two loading orientations were studied, the axial and angled-radial loading cases described in Figure 2 of [12] (see that open-access reference for more information). In this work, the dimensions $l = 100\ mm$, $d = 22\ mm$, and $\phi = \theta = 60°$ were used when building the experimental specimens.

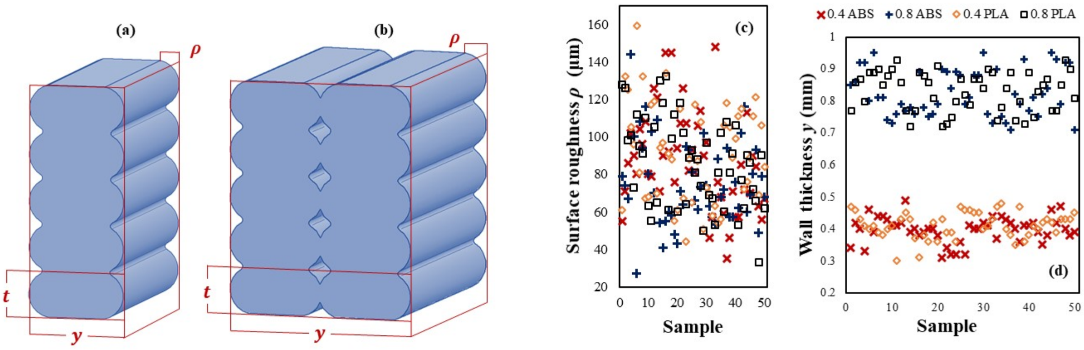

Figure 2: Mesostructure model for thin-walled FDM geometries, where (a) represents a single wall and (b) represents a double wall. A series of samples were fabricated and measured to find the realistic expected (c) surface roughness and (d) wall thickness.

Table 1: Surface roughness and wall dimensional accuracy measurements (from Figure 2)

ROUGHNESS AND DIMENSIONAL ACCURACY				
Case	ρ (μm) *(mean)*	ρ (μm) *(stdev)*	y (mm) *(mean)*	y (mm) *(stdev)*
Single wall ABS	86.7	26	0.397	0.040
Double wall ABS	75.5	23	0.825	0.072
Single wall PLA	90.8	26	0.411	0.040
Double wall PLA	86.0	24	0.832	0.061

Table 2: Selected experimental factors and levels

EXPERIMENTAL FACTORS		
Factor	*High*	*Low*
A: Foam infill	Yes	No
B: Wall thickness (mm)	0.80	0.40
C: Printed infill (3%)	Yes	No
D = ABC: Material choice	ABS	PLA

The wall thickness of $0.40\ mm$ was produced using a single shell (Figures 1a-b and 2a), while the thicker wall was produced using two shells (Figures 1c-d and 2b). The specimens were produced using a CTC Creator FDM machine with a $0.40\ mm$ brass extrusion nozzle, standard filament from Hatchbox®, printing temperatures of 230°C (ABS) and 200°C (PLA), build plate temperatures of 100°C (ABS) and 60°C (PLA), print speeds of $50\ mm/s$, a layer thickness of $0.20\ mm$, and an acceleration and jerk of $300\ mm/s^2$ and $8\ mm/s^2$, respectively. The temperature and humidity during the print and testing were measured to be 23-24°C and 48-54% throughout the several days needed to manufacture and test all the cases. All specimens were printed axially. The experiments were completed using a basic screw-driven press (Figure 3) designed for column buckling experiments with a $2500\ N$ load cell providing output and a speed of $0.03\ mm/s$. The collected data for the experiments was the maximum load applied to the cylinder immediately before collapse; the full compressive curves for these cylinders were not collected, as only the critical load was the needed for statistical analysis over a variety of sample configurations. Future work will focus on more in-depth characterization of cases identified by this study as being particularly interesting or impactful. A total of 32 samples were tested with no experimental failure nor repeated tests. In all cases, the wall collapse was dramatic and obvious, not simple local yielding; examples will be shown and discussed in the Discussion section.

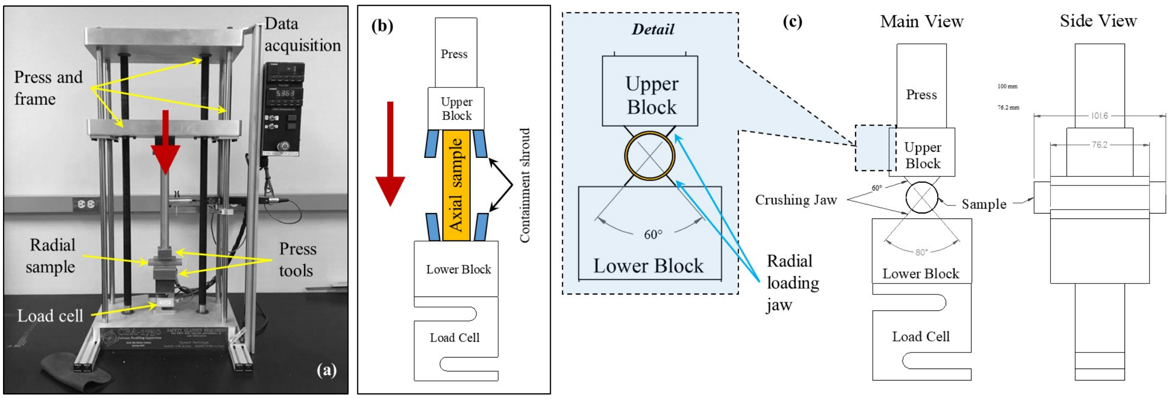

Figure 3: (a) Overall setup and testing apparatus with diagrams for (b) axial and (c) angled radial loading

RESULTS

The experimental design and collected raw data are shown in Table 3 and Figure 4. An analysis of variance (ANOVA) was completed on the data at $\alpha = 0.05$, after ensuring model adequacy by testing the Fisher assumptions [35-37] via the Anderson-Darling Test (normality), multiple comparisons test (equal variances), and run-order independence check (Table 3). For model adequacy, all p-values were above the level of significance, so use of ANOVA (Table 3) was valid. Analyses were completed using the Minitab® 18 software.

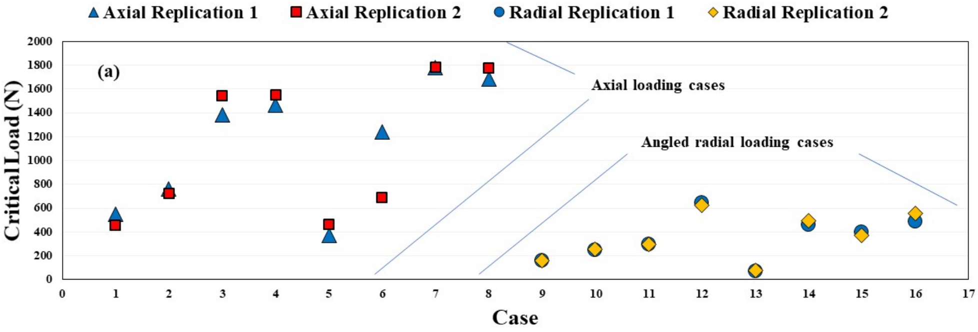

Figure 4: Experimental results

Table 3: Factorial experimental design, responses, and collected data. Factors and levels shown in Table 2.

CASE	A	B	C	D = ABC	RUN	LOADING	CRITICAL LOAD (N)		MEAN (N)	STDEV (N)
							Rep 1	Rep 2		
1	-	-	-	-	(1)	Axial	547.1	453.7	500.4	66.0
2	+	-	-	+	ad	Axial	760.7	720.6	740.7	28.4
3	-	+	-	+	bd	Axial	1383	1544	1464	113.8
4	+	+	-	-	ab	Axial	1464	1548	1506	59.4
5	-	-	+	+	cd	Axial	369.2	462.6	415.9	66.0
6	+	-	+	-	ac	Axial	1237	689.5	963.3	387.1
7	-	+	+	-	bc	Axial	1779	1781	1780	1.4
8	+	+	+	+	abcd	Axial	1681	1779	1730	69.3
9	-	-	-	-	(1)	Radial	160.1	160.1	160.1	0
10	+	-	-	+	ad	Radial	244.7	258.0	251.4	9.4
11	-	+	-	+	bd	Radial	298.0	293.6	295.8	3.1
12	+	+	-	-	ab	Radial	645.0	627.2	636.1	12.6
13	-	-	+	+	cd	Radial	71.2	80.1	75.7	6.3
14	+	-	+	-	ac	Radial	458.2	493.8	476.0	25.2
15	-	+	+	-	bc	Radial	400.3	373.7	387.0	18.9
16	+	+	+	+	abcd	Radial	484.9	556.0	520.5	50.3

Table 4: Model adequacy and ANOVA results ($\alpha = 0.05$ in all cases)

CASE	P-VALUES: MODEL ADEQUACY			P-VALUES: EXPERIMENTAL FACTORS			
	Normality	*Equal Variances*	*Independence*	*Factor A*	*Factor B*	*Factor C*	*Factor D*
Axial	0.554	0.275	Scatterplot	0.062	< 0.0005	0.990	0.313
Radial	0.961	0.178	Scatterplot	< 0.0005	< 0.0005	0.124	< 0.0005

DISCUSSION, CONCLUSIONS, AND FUTURE WORK

Figure 4 and Table 3 show the data collected during the experiments, where the consistency between replications was good with the exception of Case 6. Note also that the pattern of response values is very similar for both axial and radial cases, suggesting that the expected behavior of each factor combination is similar regardless of loading orientation. For the axial cases, only the wall thickness was found to be significant, while all the factors except the use of the soft printed infill were significant on the radial loadings. However, it should be noted that the p-values for Factor A and Factor C were below $p = 0.10$ for axial loading, so a larger sample size may show significance in a more extensive experiment. The dramatic difference between replications for Case 6 may have been caused by a hidden defect in the shell for Replication 2 or may be a feature of this combination of factors; this requires further analysis in future work.

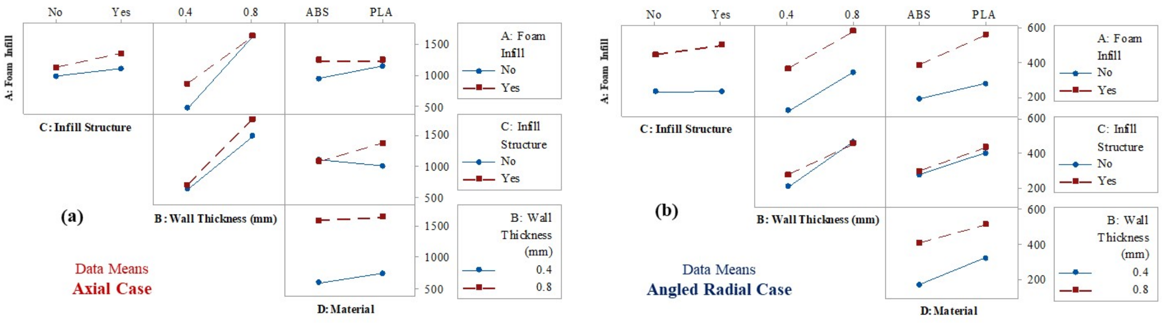

Figure 5: Interaction plots for the selected experimental factors for (a) axial loading and (b) angled radial loading

As demonstrated in Figure 5, there were some clear interactions between factors for several cases; for example, the use of an infill structure interacts with material choice for the axial case, while material choice and the use of foam reinforcement interacts for both loading cases. Figure 6 shows examples of some of the buckled ABS cylinders, both with and without foam reinforcement.

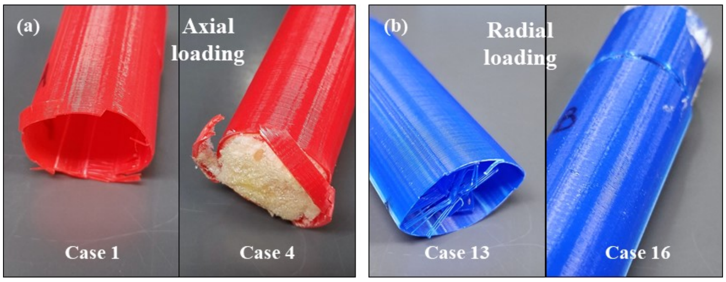

Figure 6: Examples of post-buckling specimens under (a) axial and (b) radial loadings

Note that the axial loading (both cases) and radial loading (with foam) resulted in fracture on shell collapse, while the other case shows more traditional buckling behavior expected (such as seen in [12]). The foam-filled shell in Case 4 (Figure 6a) also shows this, even though fracture did happen upon shell collapse. Future work should focus on examining these phenomena more closely, both experimentally and using finite-element models based on micro-, meso-, and macro-scale analyses. Factor interactions should also be more closely studied, using full-factorial experiments and two-way ANOVA to calculate p-values for the interactions; it is clear that there is some interaction and this needs to be understood in order to accurately model and predict this behavior. Other common materials, such as polycarbonate and PETG, can also be studied easily using the methods described here. In addition, the relevant AM processes for producing thin-walled structures are not limited to FDM but may include any polymer-processing AM method. Once the thin-walled buckling behavior of polymer materials is understood, the concepts can be expanded to metals. It is recommended that the polymer cases be explored first, as it is much easier and less expensive to experiment with the materials and many important conclusions will be transferable related to design and structural behavior. The community is urged to explore the buckling and other mechanical behavior of AM-produced shells in further research efforts, as this is one of the major unsolved problems remaining in design for additive manufacturing.

ACKNOWLEDGMENTS

The authors thank Joseph M. Patterson and Raghu Katragadda for assistance with completing the experiments. No conflicts of interest exist, and no external funding was used to complete the work nor fund its publication. All opinions and conclusions are solely those of the authors.

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