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Technical Note

Buckling Strength of 3-D Printed Thermoplastic Thin Shells: Notes on an Exploratory Study of As-Printed and Reinforced Cases

Tais Rocha Pereira [1,2], Albert E. Patterson [3,*] and Sherri L. Messimer [2]

[1] Department of Production Engineering, Federal University of Paraná, Rua XV de Novembro, 1299-Centro, Curitiba 80060-000, Brazil; taisrocha@ufpr.br

[2] Department of Industrial & Systems Engineering and Engineering Management, University of Alabama in Huntsville, OKT N143, 301 Sparkman Drive, Huntsville, AL 35899, USA; messims@uah.edu

[3] Department of Industrial and Enterprise Systems Engineering, University of Illinois at Urbana-Champaign, Transportation Building 117, 104 South Mathews Avenue, Urbana, IL 61801, USA

* Correspondence: pttrsnv2@illinois.edu

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Abstract: Additively-manufactured (AM) materials have a defined mesostructure and natural voids which impact their structural stability; thin shells, which do not have the 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 to fabricate 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 discussed for buckling cases. This short technical note explored this problem for thermoplastic thin shells fabricated by fused deposition modeling (FDM), providing insight into the problem, some initial experimental results, and discussion of design implications. A designed $2^{(4-1)}$ factorial experiment was used to study the buckling behavior, examining the impact of wall thickness, material, and two methods for 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.

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

1. 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 trade-offs; 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]. A thin-walled structure is often defined as one that 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 processes for polymeric materials is the Fused Deposition Modeling (FDM) process, which works by selectively extruding material from a heated die. It traces out a calculated path for each layer of the part build, making it a scanning-type AM (ST-AM) process. The selective deposition provides the source of raw material, while a polymer melt reaction between each of the elements (and with the previous layer) provides the fusion to join each layer [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 short technical note presents the results of an exploratory experimental study done on the critical buckling load of FDM-processed ABS and PLA cylindrical shells. Some interesting phenomena were observed, which are discussed along with notes taken during the study. 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 study was intended to collect initial data on the problem and provide this information to the mechanical engineering, mechanics, and design communities to further highlight the problem and encourage more attention in this area. It should be fully noted that it was a screening study to demonstrate the importance of research in this area and to collect some useful observations to help guide future work. In the conduct of the project, a number of useful conclusions and observations were made, which will prove of value to the research community when initiating projects in this area. Section 2 presents a brief overview of the essential problems with FDM-processed thermoplastic thin-walled shells and Section 3 provides a detailed overview of the experimental approach taken to explore the described problem. The collected results are given in Section 4, followed by some essential observations about the collected data in Section 5. Finally, Section 6 provides closing remarks, which include lessons-learned from this study and a discussion of the needed research in this area.

2. The Basic Problem

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–d. Figure 2a shows the basic parameters of this structure, while Figure 2b presents a series of parameter measurements from 50 sample cylinders made from both materials and wall thicknesses. The values of ρ and y (Figure 2) were measured using a PosiTector® (Defelsko Corp, Ogdensburg, New York, USA) surface profile gauge and calipers, while $t = 200$ µm 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® (Midland, Michigan, USA) [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 h) 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.

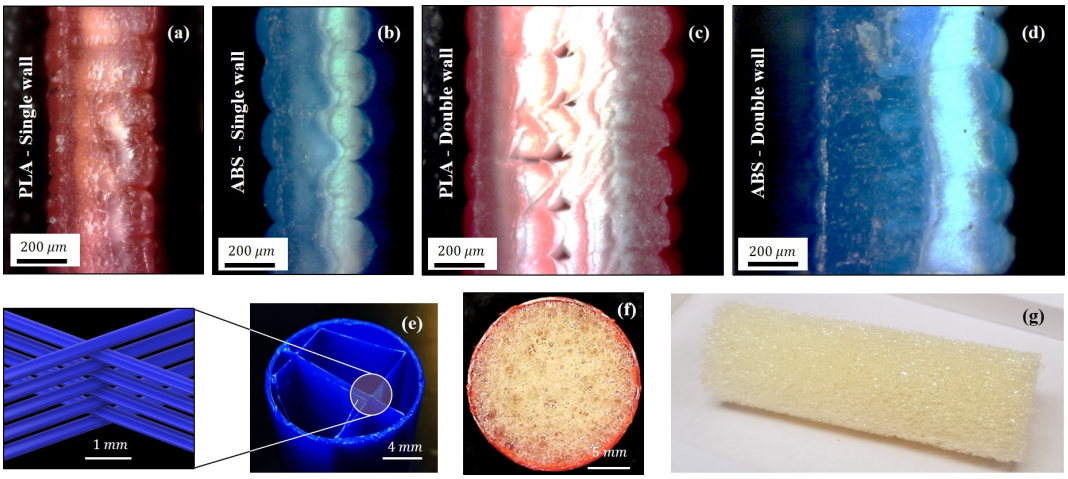

Figure 1. Example mesostructures for the: (**a**) single wall polylactic acid (PLA), (**b**) single wall acrylonitrile butadiene styrene (ABS), (**c**) double wall PLA, and (**d**) double wall ABS. Also shown is the (**e**) soft infill and (**f**) foam reinforcements and (**g**) an example foam core.

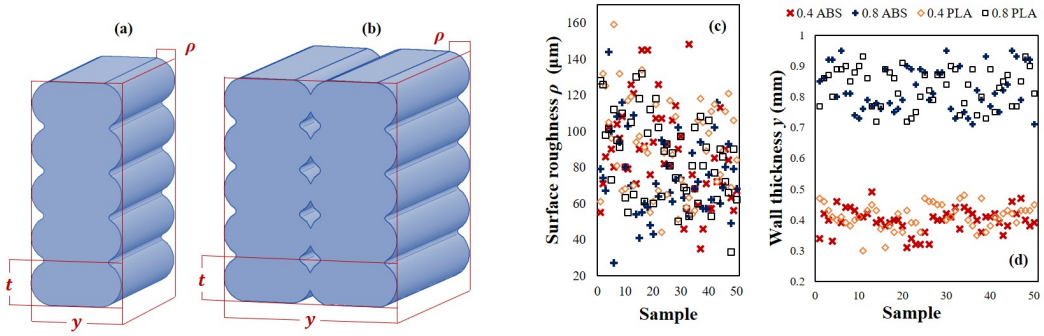

Figure 2. Mesostructure model for thin-walled fused deposition modeling (FDM) geometries, where: (**a**) represents a single wall and (**b**) represents a double wall. A series of samples were fabricated and measured to find the realistic expected (**c**) surface roughness and (**d**) wall thickness.

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

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

3. Materials and Methods

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 3a,c (taken from the cases described in [12]). In this work, the dimensions $l = 100$ mm, $d = 22$ mm, and $\phi = \theta = 60^\circ$ were used when building the experimental specimens.

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 and 8 mm/s^2 [16], 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 4) 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 needed for statistical analysis over a variety of sample configurations. 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 Section 5.

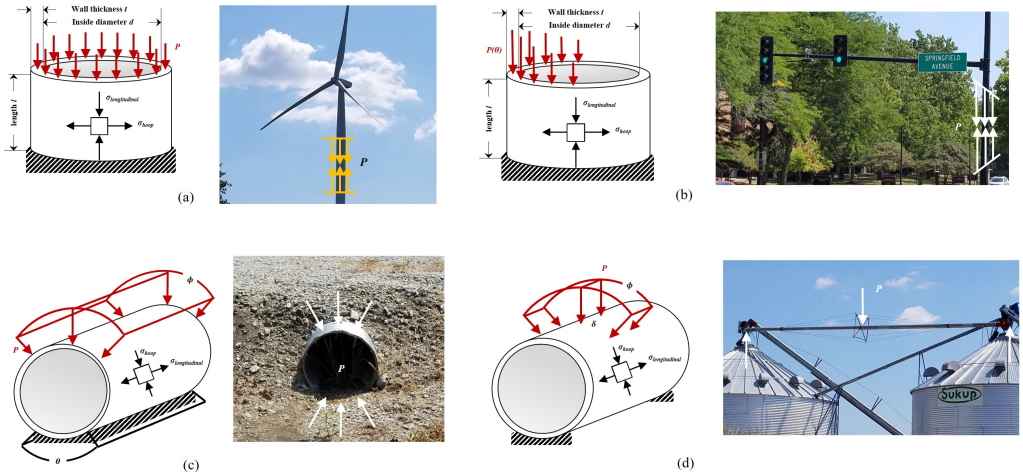

Figure 3. Example loadings (taken from [12] and reused under CC-by 4.0 license): (**a**) uniform axial (e.g., balanced windmill tower), (**b**) non-uniform axial (e.g., non-symmetric traffic light tower), (**c**) angled radial (full-length loading) (e.g., culvert under a road), and (**d**) angled radial (local loading) (e.g., grain bin transfer shaft with guide wires).

Table 2. Selected experimental factors and levels.

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

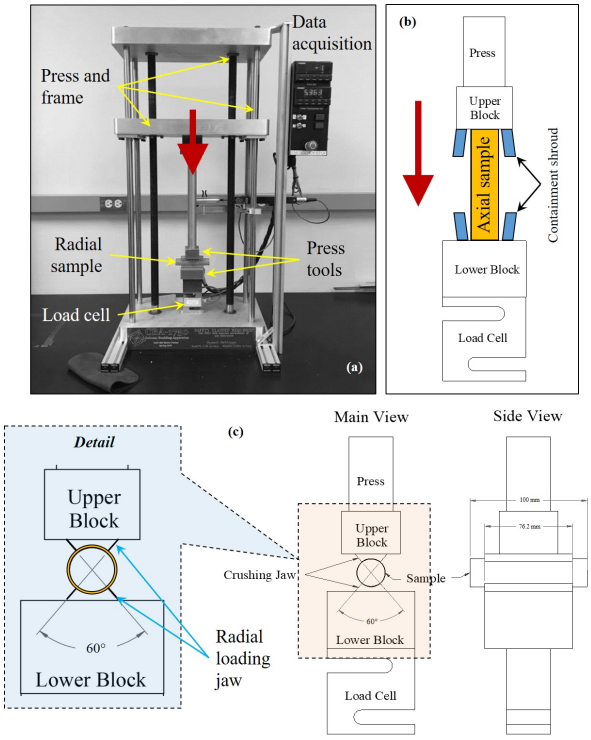

Figure 4. (**a**) Setup and testing apparatus with diagrams for (**b**) axial and (**c**) angled radial loading.

4. Results

The experimental design and collected raw data are shown in Tables 3 and 4 and Figure 5. 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 the use of ANOVA (Table 3) was valid. Analyses were completed using the Minitab® 18 software.

Table 3. Model adequacy and ANOVA results.

Case	*p*-Values: Model Adequacy ($\alpha = 0.05$)			*p*-Values: Factors ($\alpha = 0.05$)			
	Normality	Equal Variances	Independence	Factor A	Factor B	Factor C	Factor D
Axial	0.554	0.275	Scatterplot	0.062	<0.0005	0.099	0.313
Radial	0.961	0.178	Scatterplot	<0.0005	<0.0005	0.124	<0.0005

Table 4. $2^{(4-1)}$ factorial experimental design and responses.

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	1463.5	113.8
4	+	+	-	-	ab	Axial	1464	1548	1506.0	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	1730.0	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

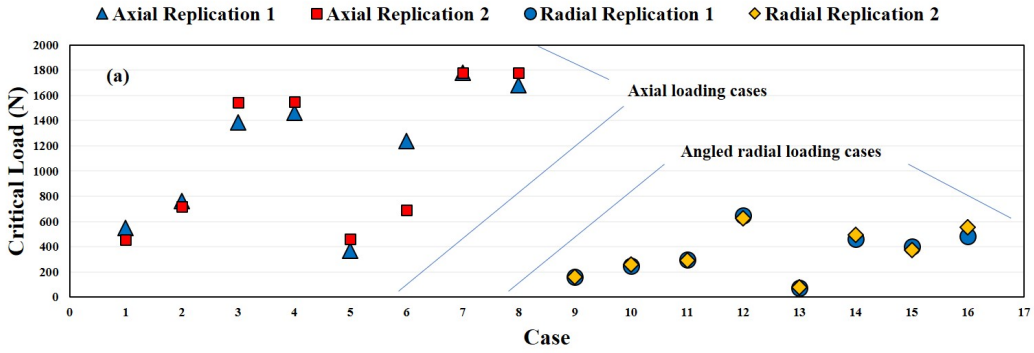

Figure 5. Experimental results.

5. Observations and Discussion

Figure 5 and Table 4 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 6 shows examples of some of the buckled ABS cylinders, both with and without foam reinforcement. 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.

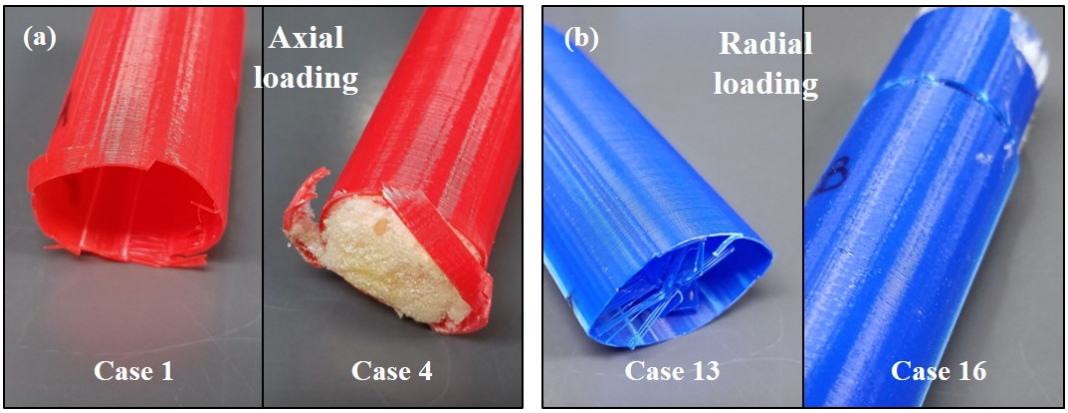

Figure 6. Examples of post-buckling specimens under: (**a**) axial and (**b**) radial loadings.

Before the experiments were completed, it was reasonable to expect that the choice of PLA (far more stiff and dense than ABS) for the build material and the use of a thicker wall would provide much higher strength in general. However, the dramatic effect of using the foam and soft infill reinforcements was not anticipated, since these media are too soft to support much load on their own. It could be concluded from this that the infill, especially in the axial loading cases, provided a "pressure" on the cylinder wall that prevented buckling far more effectively than the strength of the reinforcing material itself.

The fact that these factors can be observed to have a large impact on the results but not be significant factors (especially in the axial case) demonstrate that a more rigorous experiment is needed to explore the factor interactions. An initial exploration of this was done (Figure 7) along with this study, but a two-way ANOVA with a full factorial experiment would be able to provide more information. Some interactions that can be observed are the use of an infill structure with material choice for the axial case and material choice with the use of foam reinforcement for both loading cases.

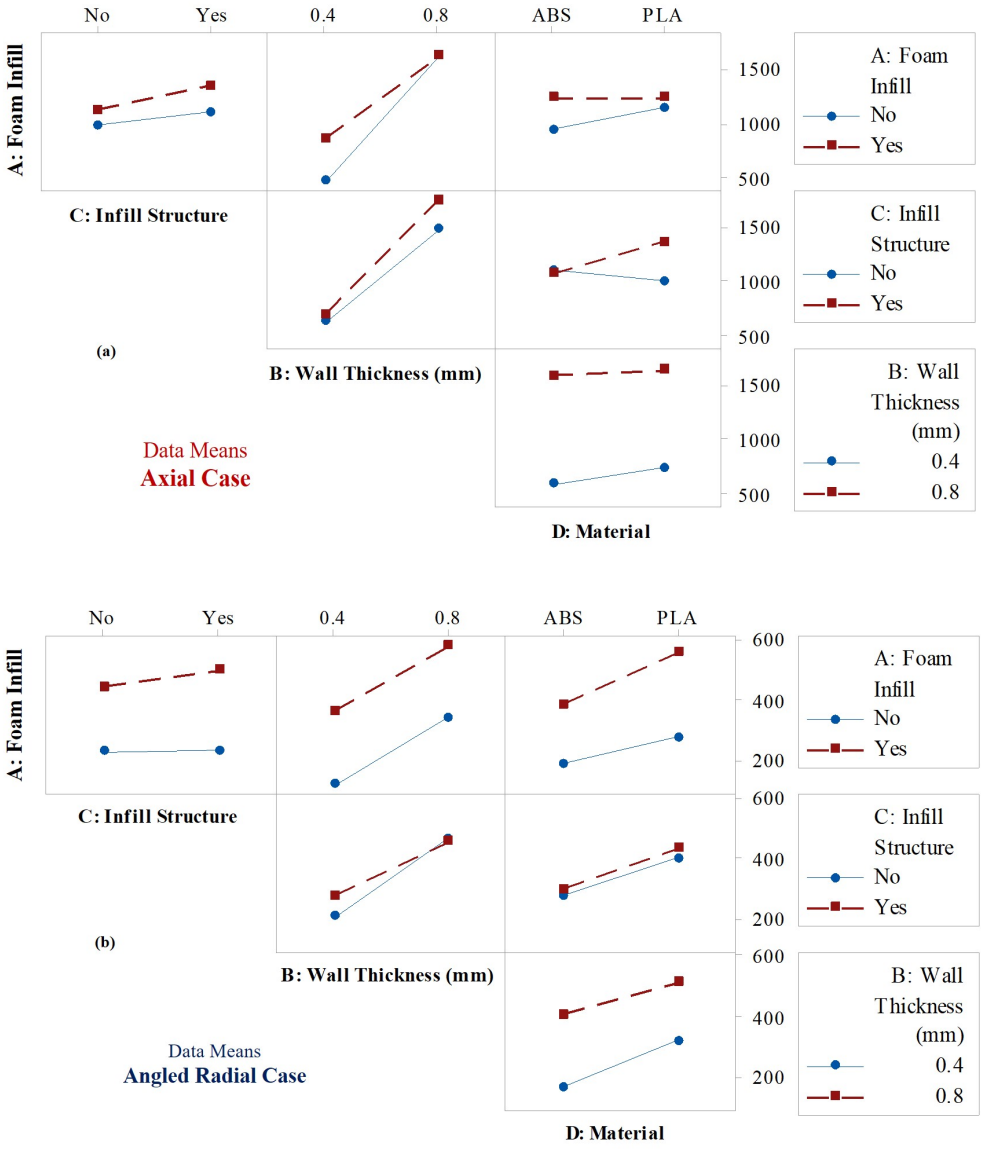

Figure 7. Interaction plots for the selected experimental factors for: (**a**) axial loading and (**b**) angled radial loading.

6. Closing Remarks

Much important research work has been done in recent years on the advancement of additively manufactured materials, both from the characterization and design perspectives. One of the main areas that has not been explored much up to now is the use of printed thin-walled structures from thermoplastic materials. Conversations that the authors have had with other members of the AM, mechanics, and design communities suggest that this is not widely considered a feasible application for thermoplastic AM. However, the results of this screening study show otherwise; in most cases, the critical buckling strength of the cylinders was significant and certainly sufficient for many design and structural applications. While this study showed that the use of FDM for building useful thin-walled structures (for at least some applications), a number of important lessons were also taken from this screening study. These may be useful for the community in the future and help to motivate and guide future research efforts. Looking at this problem primarily from an experimental point of view (as opposed to detailed modeling) is useful, as most designers and users of the technology

are not specialists in materials science or mechanics and therefore need clear and easy-to-understand information to guide their decisions.

- First and most importantly, the orientation of the loading must be carefully considered when completing experiments using thin walls or shells, as the AM-generated mesostructure varies significantly depending on orientation.
- The factorial experimental approach for this screening study was effective within the intended scope of the work. However, it is clear that some factor interactions exist for problems like this and so a full factorial experiment should be done when possible. When practical, additional fractional factorial or Taguchi designs can be used to screen factors and materials; after a set of potentially impactful factors is determined, they can be used to complete a full experiment.
- Since this was a screening experiment, designed to essentially determine if the problem was feasible and useful to study, some simplifications and assumptions were made which should not be carried over into a full study. In particular,

    1. Two replications of the experiment were completed, but an ideal experiment should include at least five replications. In general, only one is required for a screening experiment but two were done in order to calculate a variance (to show repeatability) and to test the Fisher Assumptions.
    2. Only two materials were used, but FDM can process dozens of different materials; a full set of experiments should include a wide set of materials.
    3. Only the critical buckling load of each case was recorded, but full experiments should include the full compression curves.

- A set of testing standards for AM materials is needed, but it is likely that more standards will be needed for thin-walled structures due to the unique behavior observed.
- The Fisher assumptions should always be testing explicitly for AM-related experiments, as was done in this screening study.
- The final important lesson is that anyone using AM to manufacture thin-walled structured should expect some variance in the outcome due to the relatively large size of any defects or voids relative to the thin walls. One potential method for overcoming this is to develop a "variance factor of safety" or similar concept as a measure of how much variance in structure and properties can be tolerated.

Future research efforts in this area, particularly modeling and behavior prediction, will likely rely heavily on rigorous and clear experimental results. This technical note demonstrated that the problem is feasible to work on, that a reasonable amount of data can be extracted at a relatively low cost, and that it is possible to manufacture and use thin-walled structured made by FDM. It is hoped by the authors that the research community will see the value in undertaking additional work in this area, this advancing both mechanical design and opening up the application space for AM to be used for end-user manufacturing the future.

Author Contributions: T.R.P. proposed the initial concepts behind the study and established the need for an initial experimental exploration. A.E.P. and S.L.M. designed the experiments and acquired lab space for completing the work. T.R.P. and A.E.P. manufactured the samples and completed the experiments. A.E.P. and S.L.M. completed the data analysis. All authors contributed to writing, revising, and polishing the manuscript before submission. All authors have read and agreed to the published version of the manuscript.

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