The Effects of Material, Geometry, and Wall Thickness on 3-D Printed Specimens

By

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Abstract:

This report seeks to analyze the effects of three different factors: geometry, material, and wall thickness, on the strength to weight ration of 3-D printed replica drone arms. The study was done with ANOVA testing and a 2^{3rd} factorial design to measure the largest contributor to the ratio of interest.

Introduction

This year the LUNAR senior design team decided to use a drone as the payload delivery method. In order to compete, the drone will be contained completely inside the diameter of the rocket prior to deployment. The drone will need to fold inside an allotted space and self-open to begin delivery of a golf ball. This produces unique forces on each part of the vehicle as it will have to withstand take-off and being ejected out of the rocket into windy environments. Further complicated by having a maximum allowed weight of one kilogram for the whole drone. Parts for the drone will be fabricated with 3-D printers for cost and speed. Designing an arm that can withstand theses forced while still being light enough to not compromise weight is the problem this study seeks to understand.

Design of Experiment

Three factors were selected which were presumed to have the greatest impact on the strength and weight of each specimen. The first was geometry, specifically the cross-sectional area of the specimen. Second, the material with which the part was printed. And third was the wall thickness of the part before infill material was laid. Each factor was then given two levels for comparison. The cross-sectional area was dived into a square and channel shape. PLA and ABS were chosen as the two most common and affordable printing materials. Finally, a wall thickness of 3 and 5 layers was selected for testing. A 2^{3rd} factorial design for the experiment was selected for studying the interaction and effects of each factor. Each treatment combination was allowed three runs, enough for a large sample size while also accounting for minimal possible lab time.

Factors Held Constant

Several factors were held constant to keep the scope of the experiment with-in reason. For the printing process, in-full density, infill pattern, and print orientation were not changed between samples. Each part was printed with an internal honeycomb pattern and oriented on the X-axis. Additionally, to validate the ratio, each sample part will be a constant length and height, so the controllable variance in weight will only be based on designed factors.

Uncontrollable Factors

Factors beyond the control of the experiment will largely be the ambient atmosphere around the printer and the temperature of the room as it varies from day to day during printing. To minimize this however, each run was printed at the same time.

Blocking Factors

In order to block some nuisance factors, each run was printed at the same time with the same roll of print material, on the same printer. Due to cost constraints, the PLA and ABS were not from the same vendor. However, because the difference in material is being studies, it should not affect the goal of the experiment.

Summery Table

Levels | & Factors ->	Geometry (A_c)	Materiel	Wall Thickness
	Channel	PLA	3
	Square	ABS	5

Sample Design

The specimens were design to replicate the geometry of drone arms and with ASTM standards[1] for accuracy and validity. A length of 5 inches or 127mm was selected, along with a width of 0.5 inches (12.7mm) and thickness of 0.125 inches (3.175mm). See Appendix for complete SOLIDWORKS drawings.

Data Collection

Data was collected on an Instron bend tester, with a 3-piont bend test set up. A support span of 100mm was used for all tests. Force speed was held at 1 Newton per second for each test to allow observation and minimize shock effects. Once the part broke under pressure, the max force was then documented. The weight of each part was obtained with the same scale and measured in kilograms. Captured data was logged into Excel.

Figure 1: Instron 3-Point Bend Test[2]

Results and Analysis

Minitab was used for all statistical calculations and graphs produced. [See Appendix for Excel sheet of raw data] To validate the experiment, an analysis of variance (ANOVA) test was run initially at a 95% confidence level with the assumption being equal means for the Null Hypothesis. Equal variance was not assumed. The output is shown below in Figure 2.

Welch's Test

Source	DF Num	DF Den	F-Value	P-Value
Treatment	7	6.64645	9.35	0.005

Figure 2: Initial Welch's ANOVA Test

[1] Flexural Properties. Plastics Technology Laboratories. https://www.ptli.com/testlopedia/tests/Flex-D790.asp

[2] Special thanks to LeTourneau's Civil Engineering Lab for use of the machine.

The F-value of 9.35, and correspond P-value being less than 0.05, rejects the Null Hypothesis and suggests the means are not equal. With a significant difference in strength to weight ratios established, the factorial design could be run. Full interactions were selected with a confidence interval of 95%. The results are shown below.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	203769079	29109868	9.79	0.000
Linear	3	200726426	66908809	22.51	0.000
Material	1	365270	365270	0.12	0.731
Geometry	1	199356010	199356010	67.06	0.000
Wall Thickness	1	1005146	1005146	0.34	0.569
2-Way Interactions	3	2079100	693033	0.23	0.872
Material*Geometry	1	96027	96027	0.03	0.860
Material*Wall Thickness	1	638607	638607	0.21	0.649
Geometry*Wall Thickness	1	1344467	1344467	0.45	0.511
3-Way Interactions	1	963553	963553	0.32	0.577
Material*Geometry*Wall Thickness	1	963553	963553	0.32	0.577
Error	16	47562408	2972651		
Total	23	251331487			

Figure 3: ANOVA Significance Levels

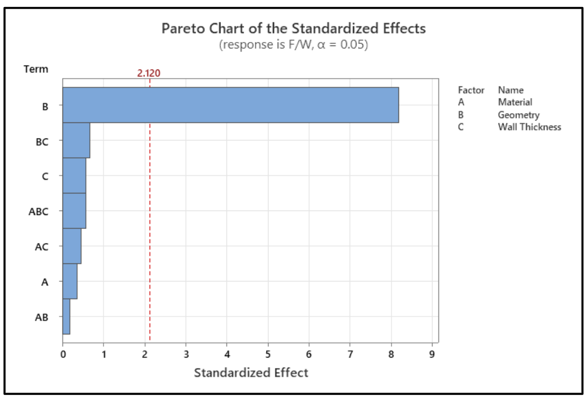

Figure 4: Pareto Chart of Significance for Full Factorial

The red line in Figure 4 represents the lowest F-value for the factor or interaction to be significant. It is clear from Figures 3 and 4 that geometry holds the largest significance in affecting the strength to weight ratio. All other factors and their interactions are deemed insignificant to the experiment. This is not entirely surprising as geometry is the largest physical change between samples. However, the fact that no other factors are considered significant by a large margin is note worthy. This suggests that a larger difference between low and high values should have been considered for material and wall thickness. Removing geometry as a factor in order to see if that causes any other factors to become more significant yields the following results.

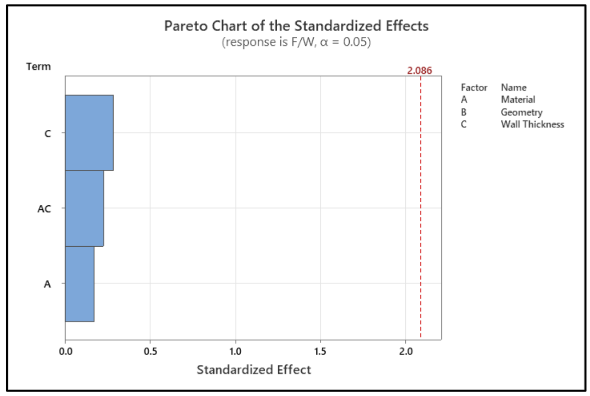

Figure 5: Pareto Chart of Significance for Reduced Factorial

Further demonstrating that geometry is the only factor that has a significant impact on the strength-to-weight ratio.

Model Prediction

The experiment can be modeled through an equation produced by Minitab and shown below.

Regression Equation in Uncoded Units

F/W = 22860 + 529 Material + 1935 Geometry + 205 Wall Thickness - 865 Material*Geometry - 163 Material*Wall Thickness + 237 Geometry*Wall Thickness + 200 Material*Geometry*Wall Thickness

Figure 6: Experiment Model Equation

Because of the qualitative nature of the data, the resulting equation does not represent all types of materials or geometries. While it would not be accurate for different materials or geometries, it would allow for experimentation with wall thickness as a numerical input. However, to observe the accuracy of the available equation, the residuals are plotted. The residuals are found from the difference in predicted values and actual data and plotted against normal probability in the graph below.

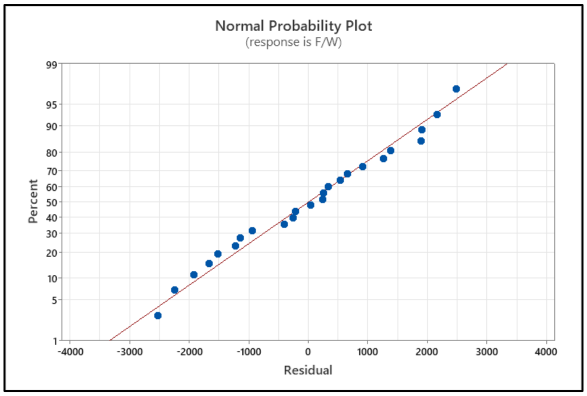

Figure 7: Residuals and Probability

While the residuals do follow the linear line with some accuracy, there is slight deviation above and below the mid-point. In general, however, the predicative model appears to be an accurate representation of the data.

Model Optimization

With the predictive model shown to be adequate, the best combination of factors can be calculated for the maximum strength to weight ratio.

Solution

Solution	Material	Geometry	Wall Thickness	F/W Fit	Composite Desirability
1	PLA	Square	5	27151.8	0.801058

Figure 8: Optimized Specimen for Maximum Strength to Weight Ratio

The suggested specimen is fabricated with each value on the high setting: square, PLA, and a wall thickness of 5. Pre-experiment, it was expected that ABS would yield the highest ratio. Using the average values of strength and weight for the ratio (24000 N/kg) as the target, an optimization of square geometry, and ABS with a wall thickness of 3 is suggested.

Solution

Solution	Material	Geometry	Wall Thickness	F/W Fit	Composite Desirability
1	ABS	Square	3	25895.9	0.643635

Figure 9: Specimen with Average Strength to Weight Ratio as Target

Conclusion

Samples representing drone arms were tested at three factors with two levels each. Using ANOVA and 2[3rd] factorial designs, geometry was shown to be the largest predictor in the strength to weight ratio. Other factors and interactions, such as printed wall thickness and material, were insignificant in affecting the desired ratio for the size of test specimens. In order to attain a balance between strength and weight, a design of square, ABS, with wall thickness of 3 is recommended as the fabrication method for small drone arms. While conclusive for small test parts, more study should be done on larger scale samples. With increased weight and size, more factors may become significant in the desirable ratio.

Appendix

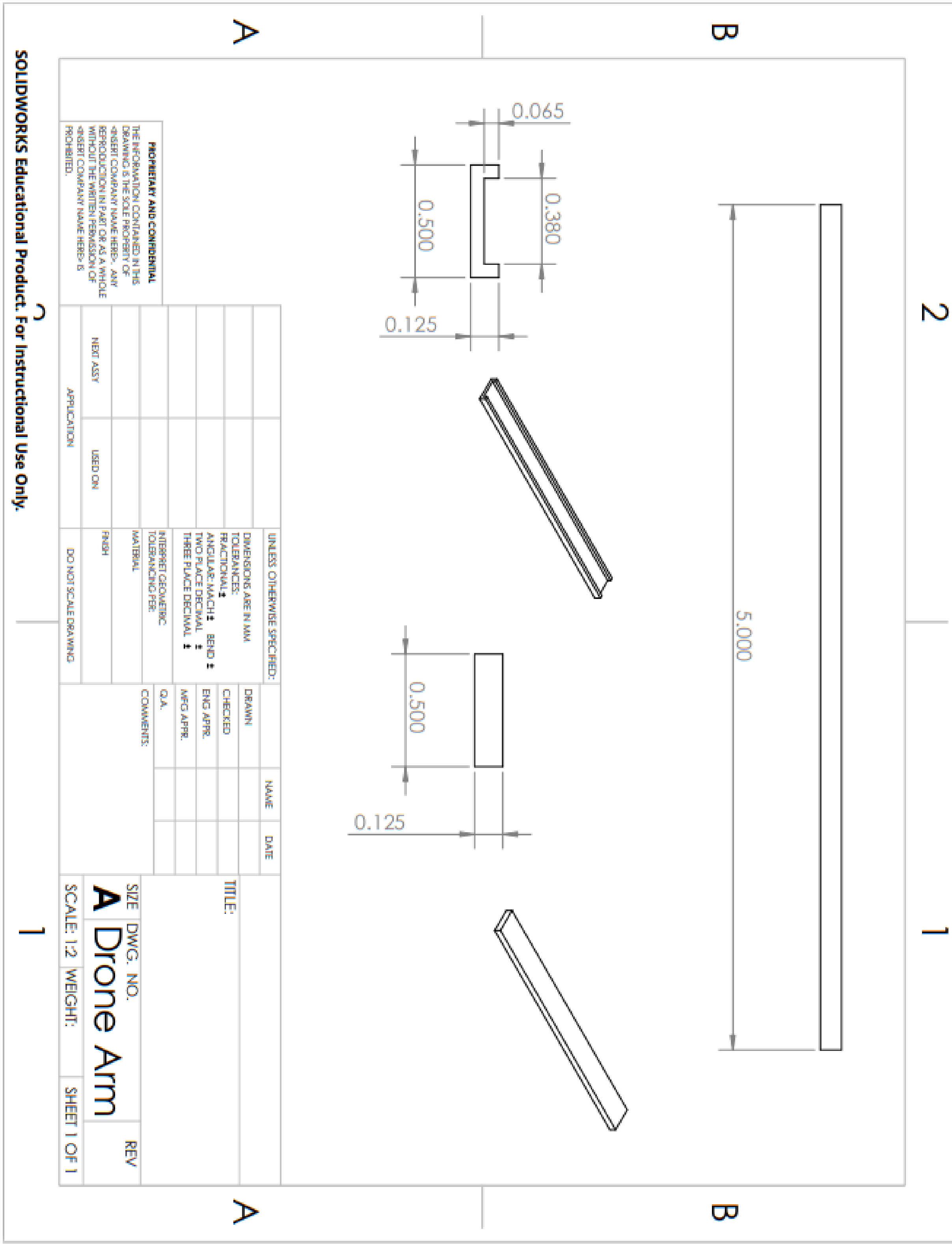

Figure A-1 Specimen Part Drawing

		F (N)	W (kg)	F/W	Material	Geometry	Wall Thinkness
1	CP3	71.0673	0.0035	20304.94	PLA	Channel	3
2	CP3	66.1822	0.00351	18855.33	PLA	Channel	3
3	CP3	78.0092	0.00348	22416.44	PLA	Channel	3
4	CP5	82.4198	0.00367	22457.71	PLA	Channel	5
5	CP5	72.7644	0.0037	19666.05	PLA	Channel	5
6	CP5	79.3342	0.0037	21441.68	PLA	Channel	5
7	SP3	106.5916	0.00401	26581.45	PLA	Square	3
8	SP3	100.7794	0.004	25194.85	PLA	Square	3
9	SP3	109.0186	0.004	27254.65	PLA	Square	3
10	SP5	131.6474	0.00449	29320.13	PLA	Square	5
11	SP5	113.3157	0.00437	25930.37	PLA	Square	5
12	SP5	115.8259	0.00442	26204.95	PLA	Square	5
13	CA3	59.0782	0.00285	20729.19	ABS	Channel	3
14	CA3	59.0782	0.00283	20875.69	ABS	Channel	3
15	CA3	61.4537	0.00282	21792.09	ABS	Channel	3
16	CA5	63.4243	0.00292	21720.65	ABS	Channel	5
17	CA5	53.0522	0.00288	18420.9	ABS	Channel	5
18	CA5	60.9762	0.00292	20882.26	ABS	Channel	5
19	SA3	89.6718	0.00316	28377.15	ABS	Square	3
20	SA3	82.489	0.00318	25939.94	ABS	Square	3
21	SA3	73.6175	0.00315	23370.63	ABS	Square	3
22	SA5	100.9318	0.00351	28755.5	ABS	Square	5
23	SA5	94.6412	0.00348	27195.75	ABS	Square	5
24	SA5	85.8818	0.00349	24607.97	ABS	Square	5

Figure A-2: Raw Excel Data