PRINTING ORIENTATION AND HOW IMPLICIT IT IS

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Abstract

A study on how implicit the printing orientation is for people with no previous experience in additive manufacturing was conducted. The study was developed with middle and high school students divided into two groups, where only one group was introduced a series of activities to show the importance of printing orientation and its relation with stress and strength of parts. Both of the groups were evaluated in the construction of a wing-box using 3-D printing pens. The study also took into consideration the amount of filament that was used in the assembly of the structure, to keep track of the most optimized models. The wing-box were then tested until failure to study its structural integrity. Finally, a detailed comparison between the two studied groups was perform to show how implicit the printing orientation is in the design process of parts.

Introduction

The Maker Movement contributes to action-based learning methods by facilitating the understanding of topics such as engineering. One of the tools utilized in "making" are 3D printers [1,2]. While there are many avenues for utilizing 3D printers, knowledge in the technical printing process parameters are necessary for designs to be printable. Most courses that have been developed for learning about additive manufacturing design are conducted within collegiate settings [3,4]. A challenge in educating about 3D printing parameters is that there may be one defined solution depending on the geometries to be printed [5]. While there are manuals and general resources available for learning printing parameters, more research needs to be conducted for creating a readily applicable, proven model for education [6]. Companies like MakerBot and Stratasys have free resources with project ideas and modules, which were utilized to help inspire an aerospace aligned activity to demonstrate printing parameters [7,8].

Methodology

The 3D Printed Wing-Box project was performed by teens, ages 13-18, whose experience in additive manufacturing varied from none, to school-projects with 3-D printers. In total, there was a total of 150 campers who attended the Aerospace Career Exploration, Aerospace, and 3-D Printing Summer Camps at Embry-Riddle Aeronautical University.

The project started with a tour of the Makerspace Lab at Embry-Riddle. Here, the campers had a first-hand experience with 3-D printing, 3-D scanning, and virtual reality modeling. The idea behind the Makerspace lab tour, was to give to the campers an introduction into the fundamentals of additive manufacturing, focusing in 3-D printing with the use of doodle pens. The campers learned how to use the 3D printing pens by creating keychains. They printed the keychains by following templates of defined shapes with the doodle-pen.

Figure 1 Use of a 3D Printing Pen in the construction of a keychain

Once the campers were done with the introductory tour, only the 3-D printing camp received a tutorial about printing orientation and printing settings, and how this affect the strength of the prints. This lesson covered the following topics:

- Print orientation
- Infill
- Surface thickness
- Layer Height
- Extrusion width
- Extrusion multiplier
- Print temperature

The project continued with a lesson about the importance of wings on an aircraft. Here, the campers learned how wings allow airplanes to flight by the production of lift. Since this principle was explained, they also learned how this force is distributed over the surface of a wing. Considering that the creation of an elliptical load distribution is complicated, the loading in this project was represented by a simplified linear-varying distributed load along the length of the wing.

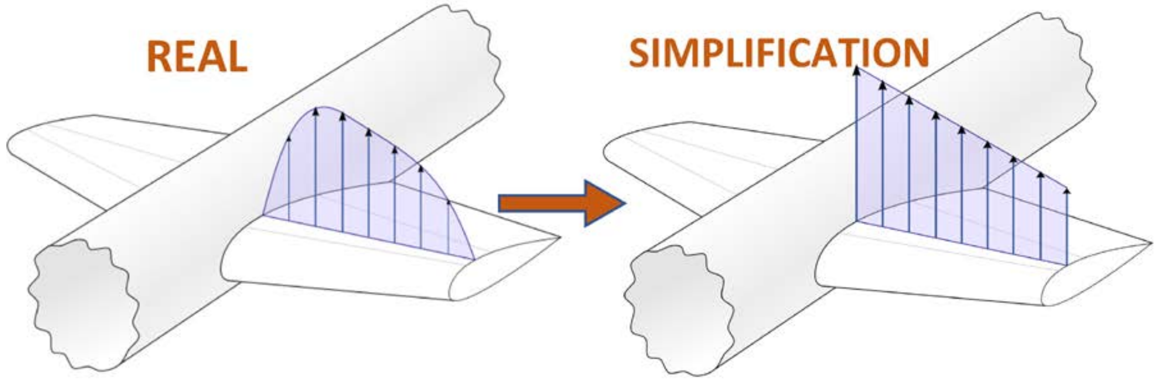

Figure 2 Lift distribution over a wing and its simplified distribution for testing [9]

Once the loading was explained, the next lesson topic was the internal structure of a wing. The campers were explained how the internal structure has to support all the lift generated by the wing, and how this structure must be as light as possible in order to make the structure efficient. After watching different examples of wings with their internal structure, the campers were able to relate how the internal structure of a wing assimilate with the structure of a truss-bridge. The campers were also guided to identified the main two differences between these two structures, the supports and the loading direction. While a wing has only one support at one end; a bridge has at least two supports along its span. Also, the resultant maximum loading on a wing will be pointing upwards; whereas in a bridge, it will be pointing downwards.

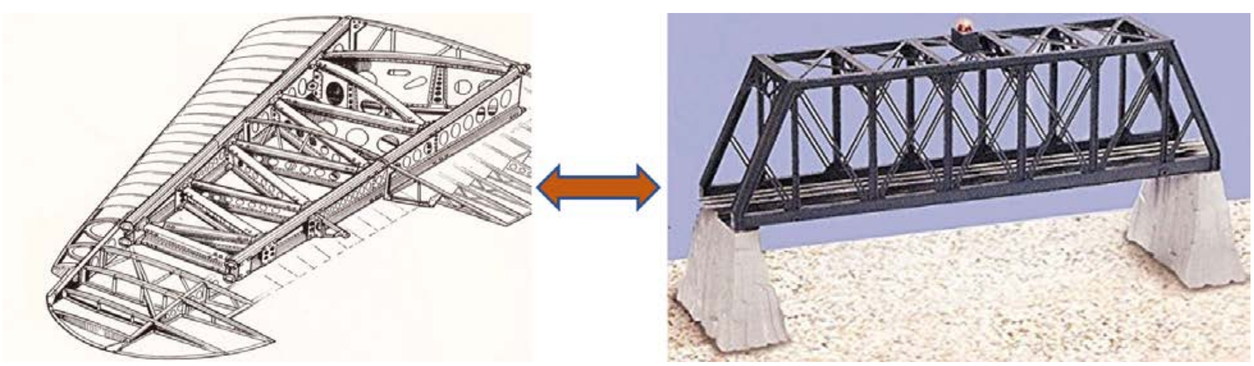

Figure 3 Wing internal structure and its similitude with a truss-bridge structure. [10]

Finally, the last portion of the lesson was the definition of the tasks and goals that the campers were required to perform on the project. For this, the campers were organized in teams of 3-5 people. Each team was assigned a doodle pen, 11feet of filament for the 3D printing pen, and a template with the overall dimensions.

Since most of the campers were more familiar with a truss-bridge structure rather than a wing-structure, they were required to design a flat bridge with the doodle-pens first. The bridge dimensions were constrained to a length of 7 inches and a width of 1.5 inches. To test this flat structure, the bridge was going to be supported at each end, and then the structure was loaded with weights along its length in order to simulate a distributed-load.

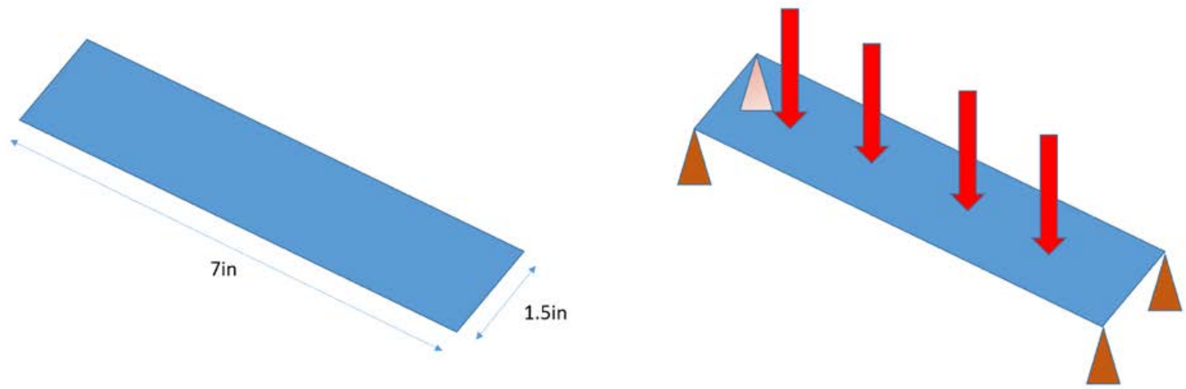

Figure 4 Bridge dimensions and loading set-up

Only the campers who passed the first testing moved to the next phase of the project, the creation of a wing-box. Now the structure would represent a wing, so it could only have had one support at one end. In order for the structure to support any kind of vertical loading, the campers were required to add additional structures around the flat bridge. Besides the fixed dimensions of the bridge, the wing-box was constrained to have a maximum height of 1inch.

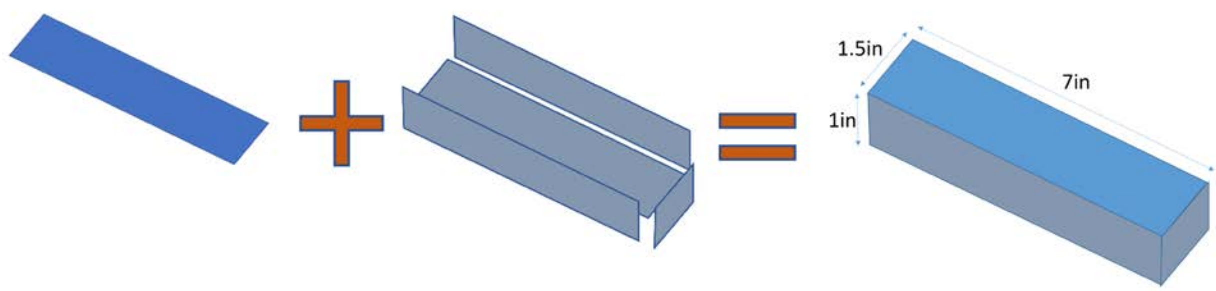

Figure 5 Wing-box creation using the flat bridge as a base

For the final design-phase, the campers were given an attachment to use it at one end of their structure. This attachment had 2 ribs that facilitated the connection with the wing-box. Once the full wing-box was connected to the attachment, the whole structure was mounted on a base that simulated the side portion of the fuselage. This fix structure was loaded by distributing weights along its length to test its structural integrity.

Figure 6 Attachment, base, and assembly for the wing-box testing

The campers were only designing wing-box. They did not have to designed the skin of the wing. The requirements for the wing-box were:

- The structure had to meet the constrained dimensions of length, width, and height: 7in x 1.5in x 1in(max) respectively.
- It had to have a flat upper section, in order to keep the weights on place at testing.
- It had to be made only with the use of the 3D-printing pen. Any additional material was forbidden.
- The teams had a defined time limit of 20 minutes for the bridge construction, and 1 hour for the wing-box construction.
- Each team was assigned 11ft of filament (ABS) for the pens.

Results and Discussion

Before the teams started using the 3D printing pens to create the bridge, they received a template sheet with the overall dimensions of both, the bridge and the wing-box, so that they could use it to track it with the printing pens. They had the freedom to design both structures with any shape or additional features in order to increase the its strength.

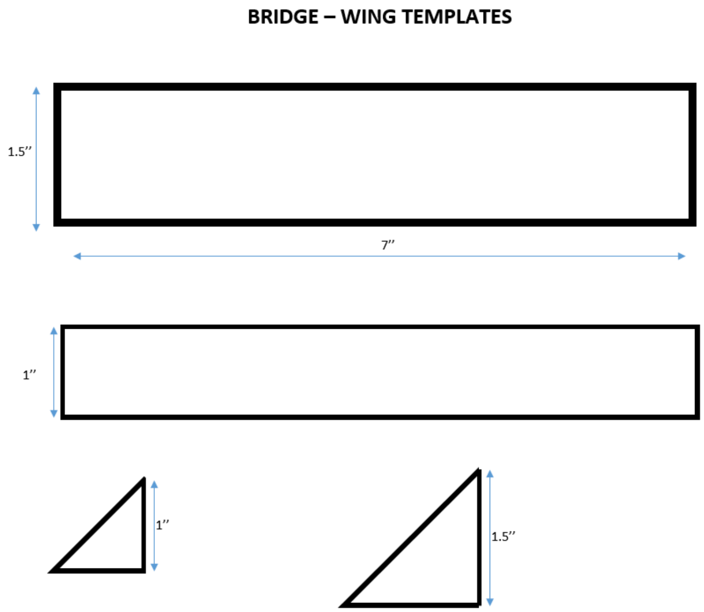

Figure 7 Bridge - Wing template sheet showing the overall dimensions

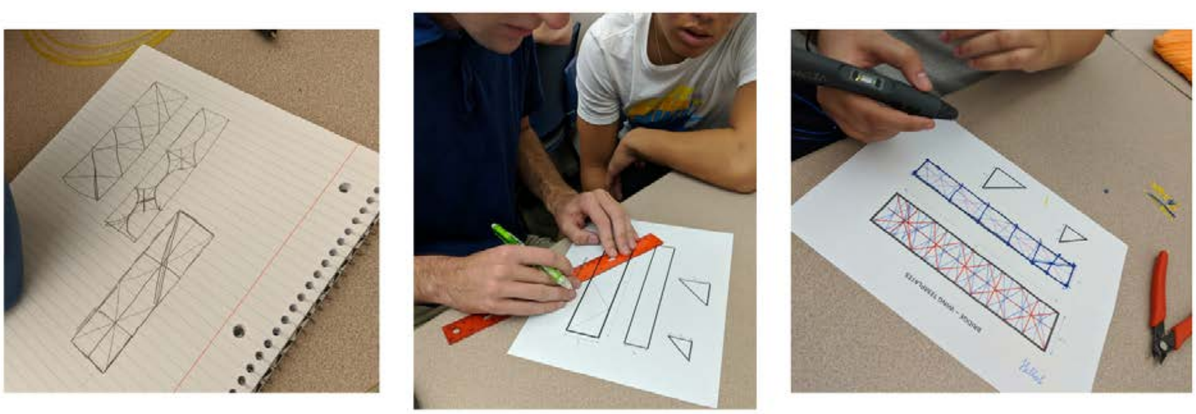

Figure 8 Additional features designed by the campers on the template sheet

After the layout of the bridge template (top rectangle from Figure 7) was finalized, they used the 3D printing pens to create the flat surface for the first testing. The bride, once it was printed, was set it up with two supports, one on each end, and hold it in place in order to simulate fix supports at each end. For testing, the bridge was loaded by distributing 500 grams along its length.

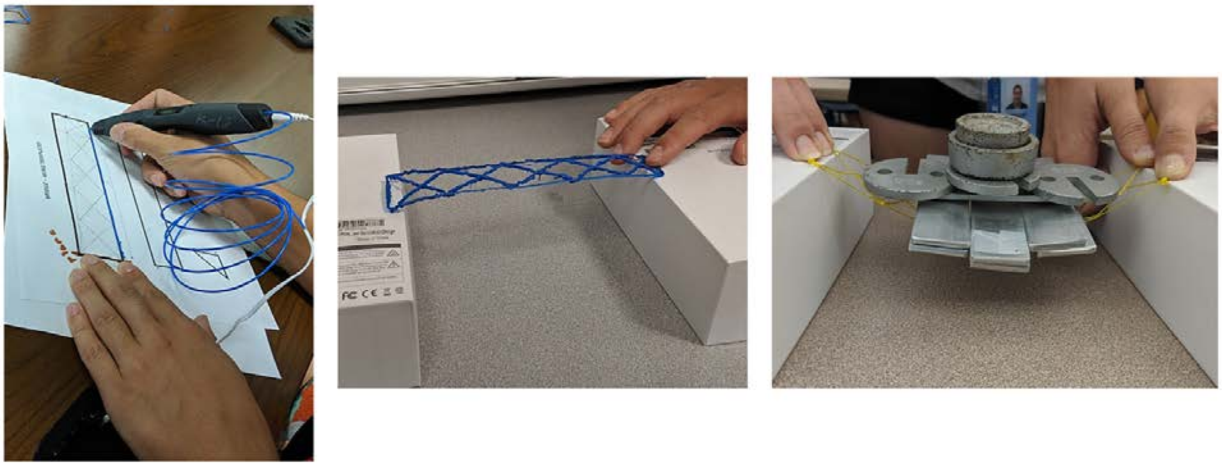

Figure 9 Bridge printing, set-up, and testing

This phase of the project was developed in order to made the campers more familiar with the 3D printing pens, as well as to show them the main problems that they could encounter whenever they started printing the wing-box. Since it was just the introductory activity, there was not a specific data recording of results of this phase. Only the teams whose bridge passed the loading-test, moved to the printing of the wing-box. The teams that failed the test were due mostly for two reasons:

- Poor fusion of the material at the joints
- Poor layer thickness

The teams that failed this phase had to re-design the structure, or fixed the original structure by adding more structural supports, increasing the layer thickness, or improving their joint fusion. They had to re-design or improve their structure until they passed the loading-test.

The next phase was the construction of the wing box by using the previously designed bridge as the upper portion of the box. Each team also received one attachment that they had to implemented at one end of the wing-box. The most common approach used in this phase was printing each side of the box individually, and then all the sides were fused together around the attachment (see Figure 10).

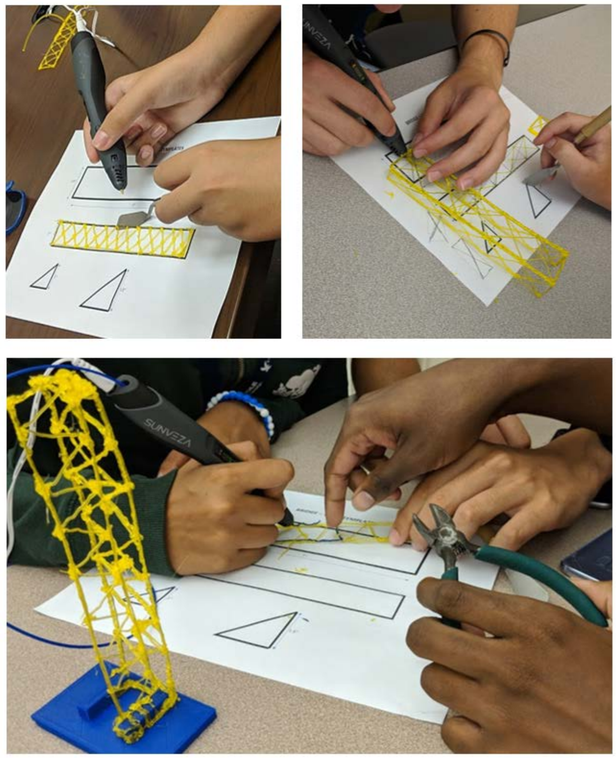

Figure 10 Top left: printing of a side panel for the wing box. Top right: fusion of the panels together. Bottom: fusion between the wing-box and the attachment

A not so common approach, but still used by some teams, was to fused the bridge straight onto the attachment, and then all of the additional structure was printed by extruding the pens away from the bridge without following any template (see Figure 11).

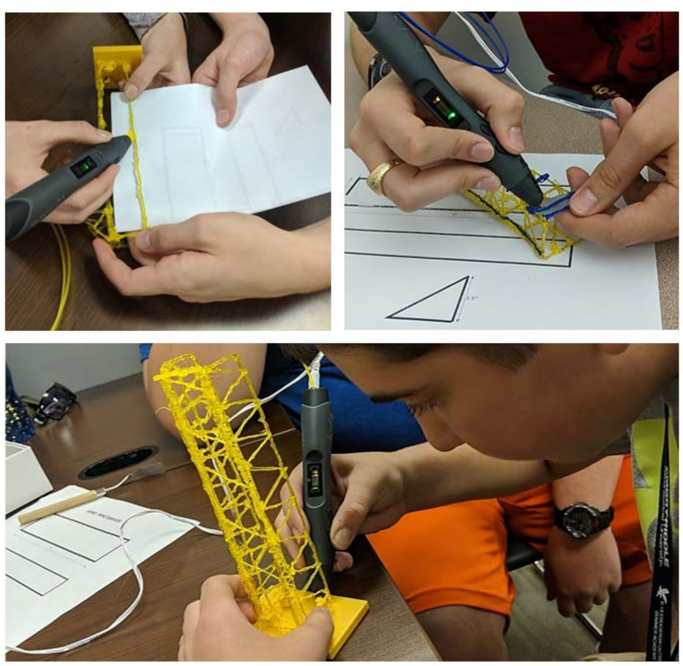

Figure 11 Wing-box created by printing directly onto the bridge

Once the wing-box structure was finished, it was assembled on the base. Then, it was tested by loading it with distributed weights, from tip to root, until failure occurred or it reached a maximum loading of 2100 grams.

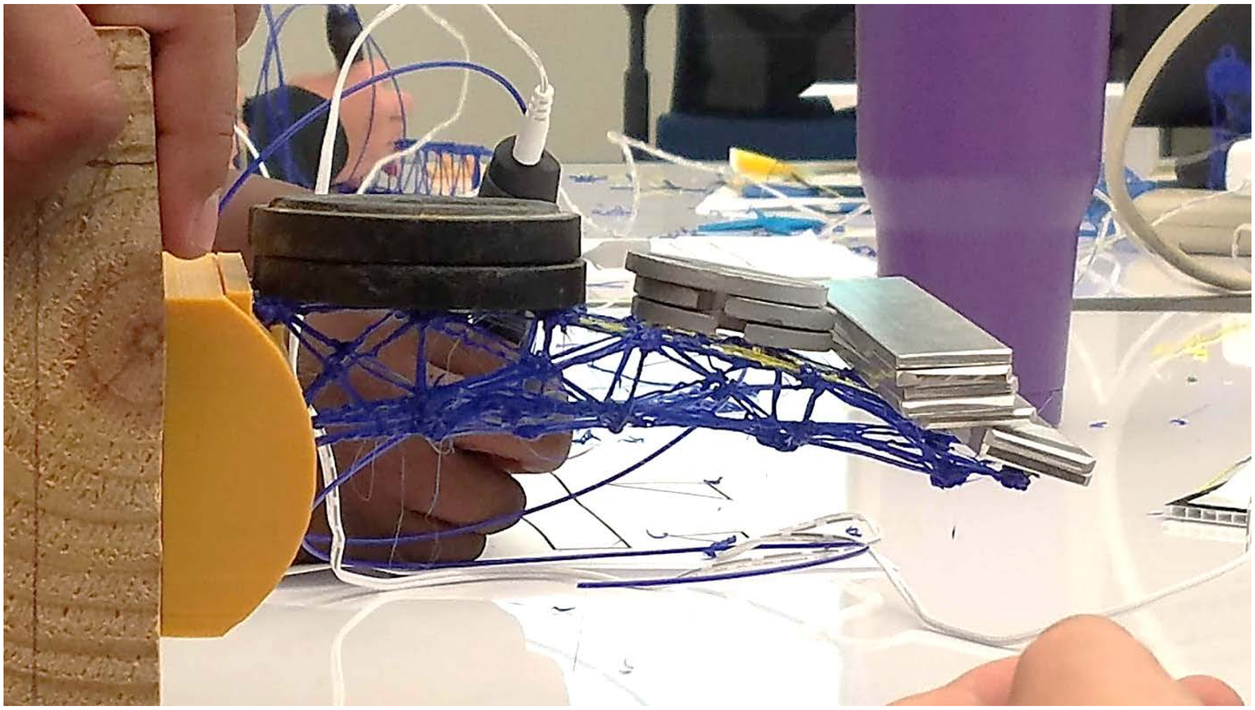

Figure 12 Wing-box testing with a total load of 2100 grams

Out of the 40 wing-boxes that were tested, only 2 reached the maximum loading of 2100 grams. The rest of the wing-boxes failed the test before reaching the maximum loading by breaking at different portions of its structure. The most common problem that caused structural failure was the poor fusion of the material at the joints (see Figure 13). After a detailed inspection on the joints that failed, they all have in common two characteristics: not enough material to join two parts together; and most important, the material was bonded in the same direction as the mechanical stress acting between these elements. As Catrell J. said [11], specimens that have a print orientation parallel to the stress direction, have a lower modulus and poorer strength values. This is due to the concentrated loads at the bonding region between the layers of material.

The second most common reason for failure was a poor fusion between the structure and the attachment (see Figure 14). This was caused by the same two reasons that created failure at the joints. It can be seen that in these cases, the campers did not consider reinforcing these connections by printing material at a different direction. The wing-boxes that supported most of the loading have reinforced joints and a reinforced fusion with the attachment. This was obtained by adding layers of material at different directions. This helped maintain the bonding together between different parts.

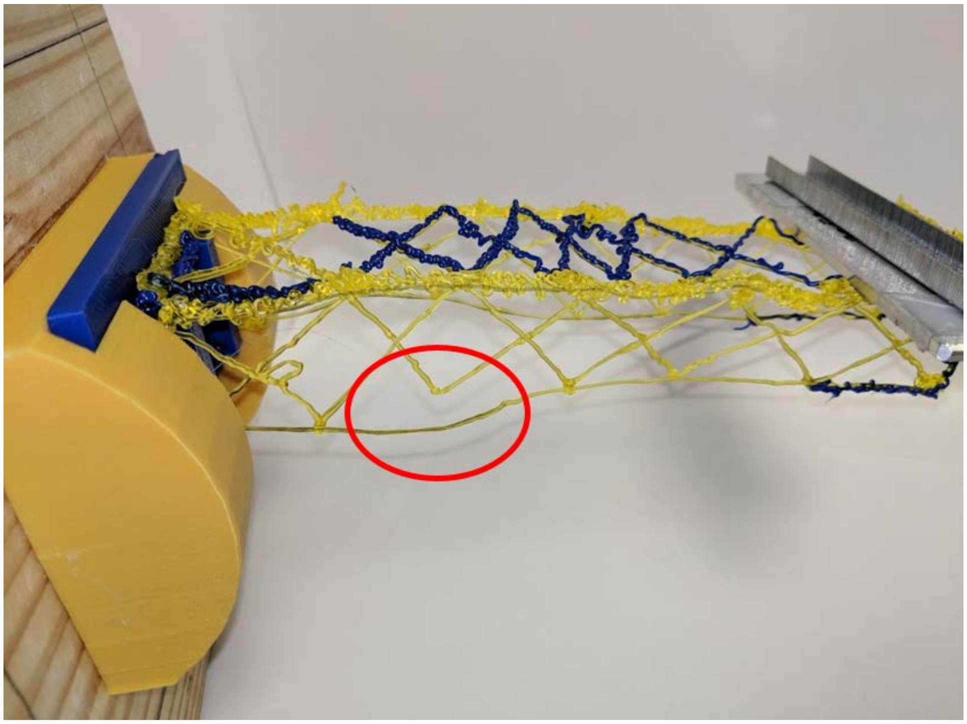

Figure 13 Wing-box with poor fused material at the joints

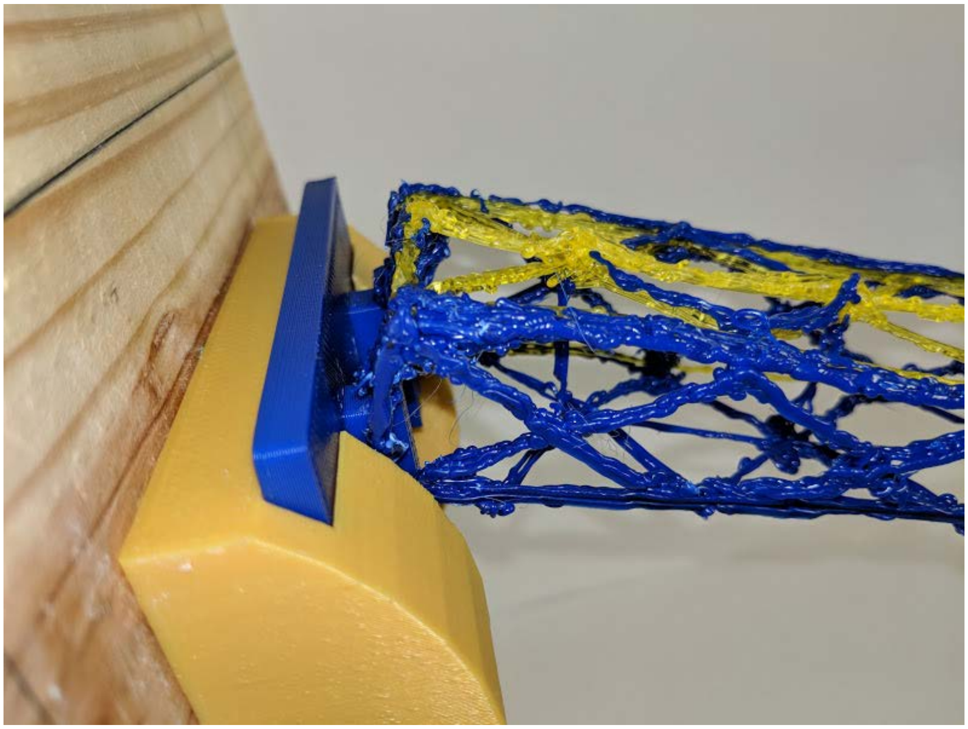

Figure 14 Wing-box with poor fused material at the attachment

In the case of the other wing-boxes that failed for other reasons rather than poor bonding orientation, was due to a poor structural support. In some cases, there were structures that did not have enough elements to support all the bending created by the weights on top (see Figure 15). Also, there were structures that had elements that were poorly printed. Some examples are elements with gaps in between the material (see Figure 16), and elements with non-uniform layer thickness (see Figure 17). These problems could be addressed by teaching to the campers the importance of a constant layer thickness, and how the infill of prints is related with the strength of parts.

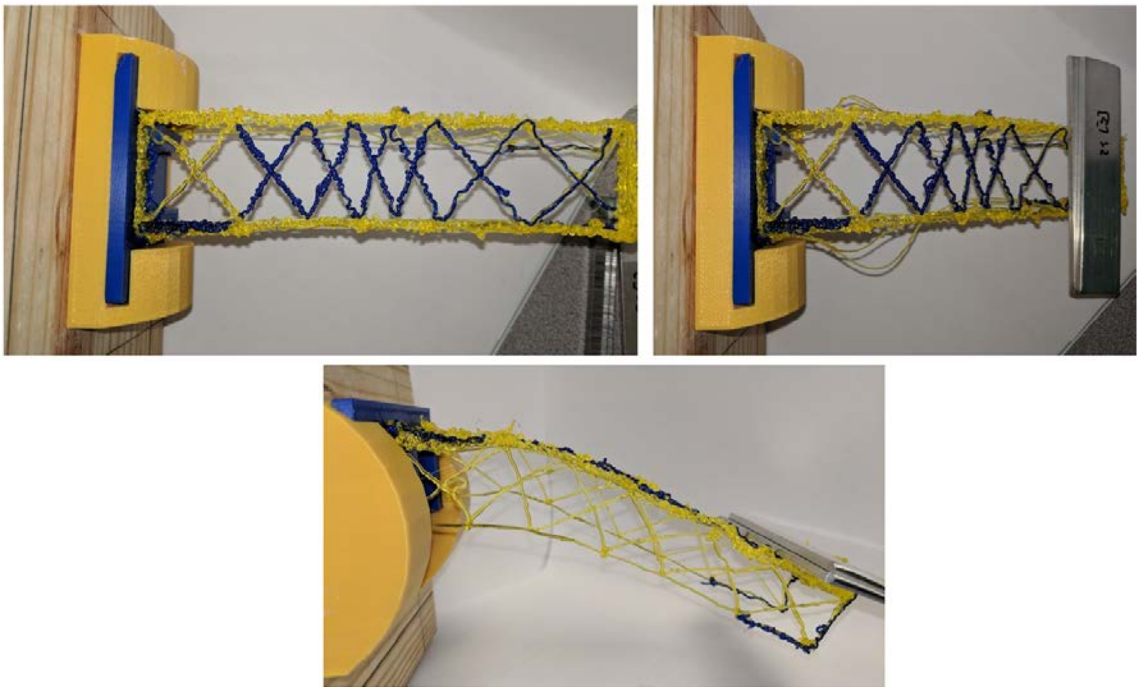

Figure 15 Wing-box unloaded (top-left) and loaded (top right) showing a poor structural support

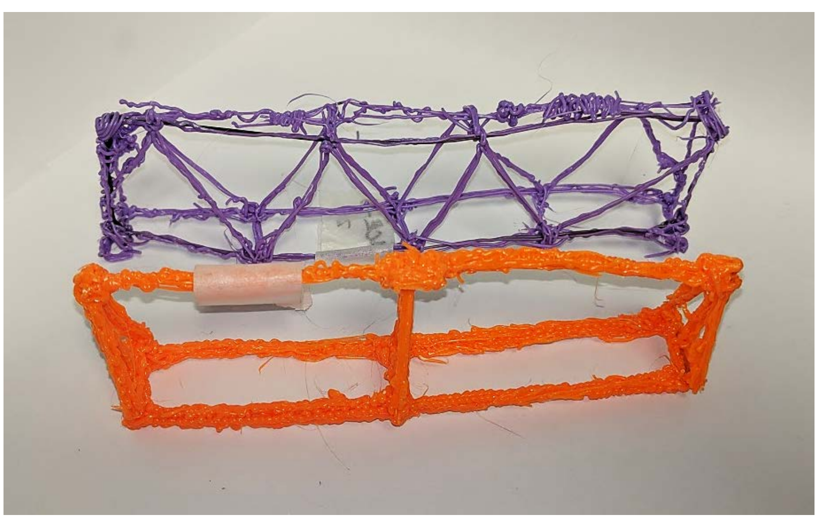

Figure 16 Sample of two wing-boxes; one with multiple gaps between its layers (purple) and one with no gaps between its layers (orange)

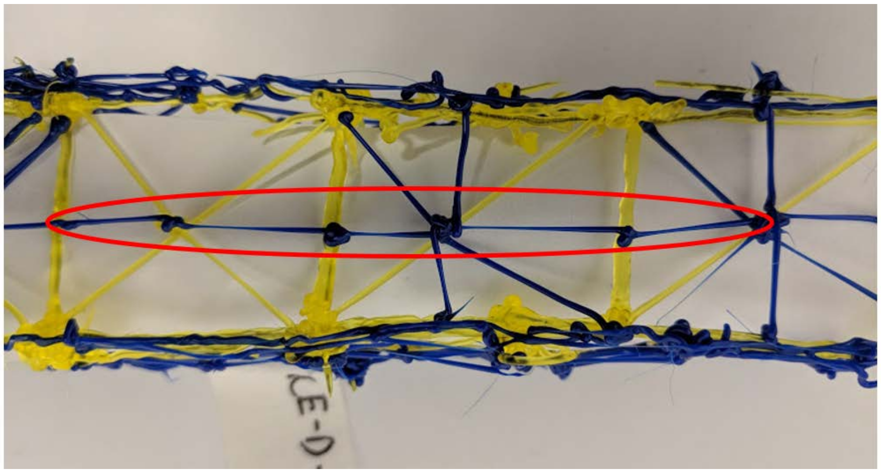

Figure 17 Non-uniform layer thickness

Since the results showed that, overall, the campers who received a tutorial about printing orientation and printing settings performed the best; it was decided to do the same with another group of campers. The Aerospace Camp was the last group of teens who performed the wing-box activity, and it was decided to make them create the wing-box three times. First, without any tutorial about printing orientation. The second time, they had a tutorial purely on printing orientation. And for the last attempt, they had another tutorial that covered the importance of printing settings; and how they could apply them with the 3D printing pens.

Figure 18 shows the results recorded from these 3 attempts. It can be seen that after each attempt, the efficiency of the structure (maximum loading divided by weight of the structure) increases significantly for almost every team.

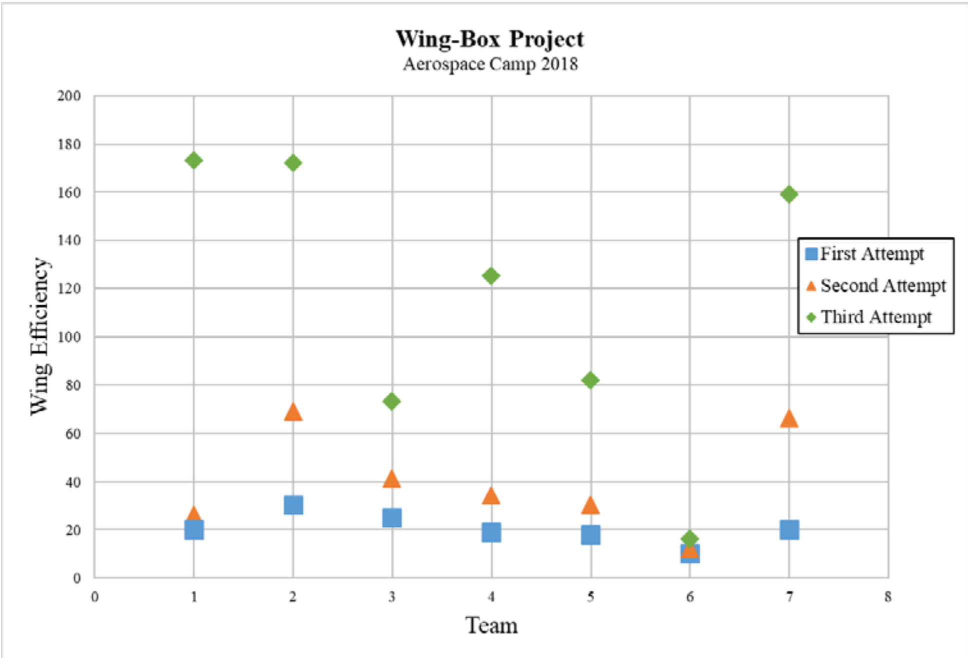

Figure 18 Results of the three wing-box attempts from the Aerospace Camp

Conclusions and Future Work

From the 40 wing-boxes that were created in total, only two reached the maximum loading of 2100 grams. Out of the top-5 tests, 4 of the groups where from the 3D printing camp (5 groups in total). These were the only campers that had a lecture about the importance of printing orientation and printing settings.

Also, a summer camp was able to re-do the wing-box from scratch three times. First, without any lecture about printing orientation. Second, with an introduction about the importance of printing orientation. Finally, with another lecture about the importance of printing settings. Results showed that after each try, their structure improved significantly.

As recommendations for future work, another hands-on activity could be developed in order to teach the importance of sizing and tolerancing. This could had helped to multiple teams that encountered some problems the moment that they were trying to fuse their structure with the attachment. Since they did not take into consideration the internal dimension of the structure, they were not able to fit it on the attachment.

Another activity could be developed to teach the importance of supports at printing, and how to improve the printing efficiency.

References

[1] American Society for Engineering Education. (2016). Envisioning the Future of the Maker Movement: Summit Report. Washington, DC.

[2] Geraedts, J., Doubrovski, E., Verlinden, J., & Stellingwerff, M. (2012). Three Views on Additive Manufacturing: Business, Research, and Education. In ResearchGate (p. 55). Karlsruhe, Germany. Retrieved from https://www.researchgate.net/publication/235725722_Three_Views_on_Additive_Manufacturing_Business_Research_and_Education

[3] Gatto, A., Bassoli, E., Denti, L., Iuliano, L., & Minetola, P. (2015). Multi-disciplinary approach in engineering education: learning with additive manufacturing and reverse engineering. Rapid Prototyping Journal, 21-5, 598-603. http://dx.doi.org/10.1108/RPJ-09-2014-0134

[4] Go, J., & Hart, A. J. (2016). A framework for teaching the fundamentals of additive manufacturing and enabling rapid innovation. Additive Manufacturing, 10, 76–87. https://doi.org/10.1016/j.addma.2016.03.001

[5] Serdar, T. (2016). Educational Challenges in Design for Additive Manufacturing: American Society for Engineering Education. Retrieved from https://www.asee.org/public/conferences/64/papers/15625/view

[6] Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2015). Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of Manufacturing Science and Engineering, 137(1), 014001-014001-10. https://doi.org/10.1115/1.4028725

[7] MakerBot. (2015). MakerBot in the Classroom. Brooklyn, NY.

[8] Stratasys, “3D Printing Education Resources – Education Materials”, URL: http://www.stratasys.com/resources/education-materials

[9] Cai, L., Byrd, P., Zhang, H., Schlarman, K., “Effect of Printing Orientation on Strength of 3D Printed ABS Plastics”, Indiana University-Purdue University, Indianapolis; TMS, 2016.

[10] O. Cleynen, Lift distribution over a three-dimensional wing, URL: https://en.wikipedia.org/wiki/Lifting-line_theory

[11] Cutler, John (1992). Understanding Aircraft Structures. 2nd Edition. Blackwell Scientific Publications, Oxford.

[12] Cantrell, J., Rohde, S., Damiani, D., “Experimental Characterization of the Mechanical Properties of 3D_Printed ABS and Polycarbonate Parts”, University of Florida, and University of California

[13] Form Labs, “Validating Isotropy in SLA 3D Printing”, URL: https://formlabs.com/blog/isotropy-in-SLA-3D-printing/