Bridge Building Assignment

Team Members: Cindy Yang & Brandon Snow

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Bridge Design and Fabrication

The design for our bridge was heavily influenced by the results of topological optimization and intuition. We began the design process by simulating a block of the specified dimensions undergoing three point bending in the general purpose finite element software Abaqus. Elastic material properties were obtained for PLA from the internet ($E=4.8$GPa, $\nu=0.3$). The results of that simulation are shown in Fig. 1 where the contours show the mises equivalent stress in the material. It immediately becomes apparent that the peak stresses occur directly below the washer that applies the load and the majority of the stress is carried within quasi-linear bands between the washer and the supports.

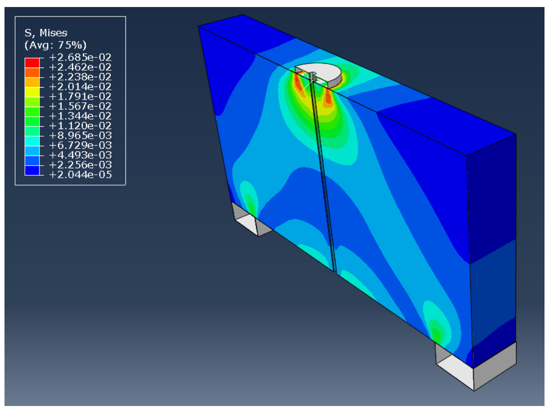

Figure 1: Abaqus stress analysis of block with hole.

Next, the topology optimization tool in Fusion 360 was used to iteratively remove low-stress material from the block and produce a design that will carry a similar load but with significantly less material. As expected, the topology optimization eventually converges to a shape outlining the regions of high stress identified in Abaqus. The resulting design is shown in Fig. 2 (a), which forms a parabolic shape with wavy boundaries resulting from mesh element boundaries. Since the wavy boundaries are more likely artifacts rather than optimal designs, we next used Fusion to generate the CAD model shown in Fig. 2(b) which has fileted corners and a parabolic underside to minimize any stress concentrations.

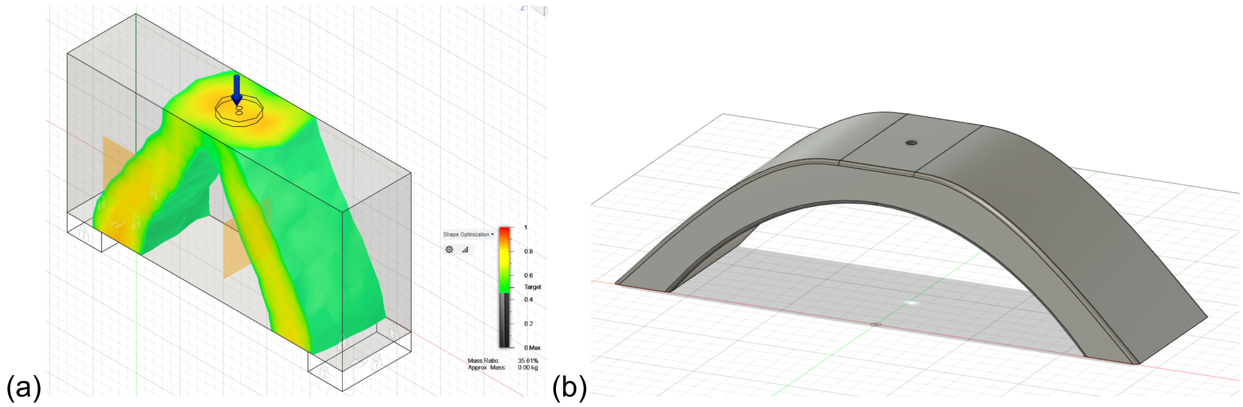

Figure 2: (a) Topology-optimized design and (b) the simplified CAD model based on the design.

The parabolic design fit within our intuition for a shape that is capable of withstanding large loads with an efficient use of material. It is a design that has been used for thousands of years (e.g. the Roman aqueduct in Fig. 3), so it is reassuring that modern software is confirming what we already know to be a quality design.

Figure 3. Example of arches used in ancient Roman architecture near the town of Vers-Pont-du-Gard in southern France.

Once the design was finalized, several small scale prototypes were made at ⅛ and ¼ scale, as shown in Fig. 3. The ⅛ model was used mostly to tangible object that we could hold and press on to increase our confidence in the design. The ¼ design aided the process of choosing the method of joining the separate printed parts since the bridge could not be printed in one piece. The puzzle-piece joint shown in Fig. 3 turns out to be much too compliant and fails by one piece sliding out of the other much before the material reaches its limits. From those observations, a new pressfit/post-in-hole joint was designed as shown in Fig. 4. The final dimensions of the bridge fit within a 14”x4”x2” box.

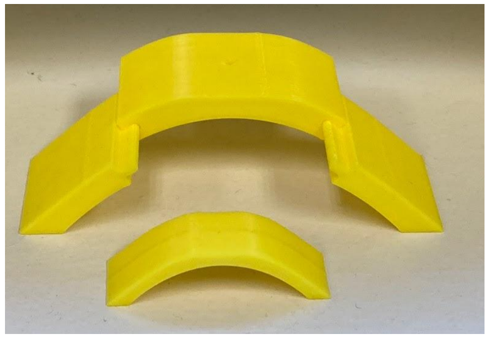

Figure 3: ⅛ and ¼ bridge prototypes printed on our Ender 3.

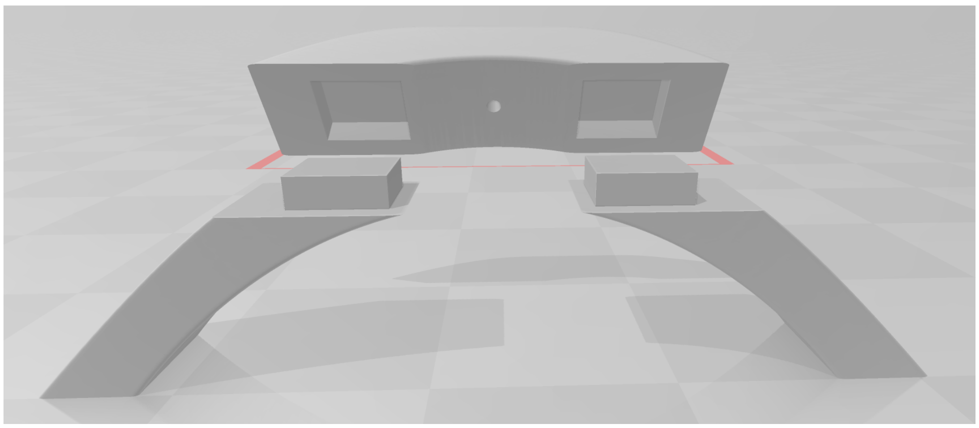

Figure 4: Improved post-in-hole joint design used in the final bridge design.

Lastly, the bridge design was given a cubic infill and sliced in Cura in preparation for printing. For this step, a 20% infill was chosen to ensure that the resulting bridge was underneath the maximum weight of 200g. The cubic infill pattern was chosen because some online sources (https://all3dp.com/2/infill-3d-printing-what-it-means-and-how-to-use-it/) suggested it as a good balance between strength and material.

We chose to print our bridge using both the Ender 3 and the LMP Ultimaker printers, mostly to save time. Each component of the bridge took about 15hrs to print, so utilizing two printers allowed us to complete the job in one day, and resulted in an aesthetically pleasing multicolor bridge. Nominal print settings were chosen, because we did not want to increase the print time any more. We chose to use the FFF printer for both convenience (since the Ender is always available) and because our experience in the printing assignment was that PLA parts were stiffer than SLA parts (at least at the low levels of curing and the basic resin that we had used). The orientation of the prints was chosen to minimize the amount of support material needed and to ensure that no support was needed within the central hole. A small amount of support material was needed to print the upper portion of the arch as well as the posts and holes, however it was relatively easy to remove. Once printed the legs of the bridge were press-fit into the holes in the upper arch. Because of slight expansion of the filament during printing, the printed hole was slightly smaller than the post, so it took significant effort to join the parts, however that tight press-fit ultimately helped with the performance of the bridge.

Additionally, the tight fit removed the need for any solvents or binders. The assembled printed bridge is shown in Fig. 5 with the sub-scale models for size reference.

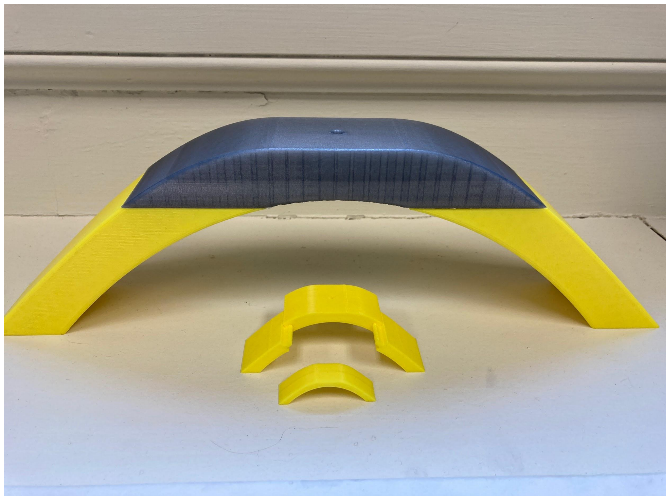

Figure 5. Three scales of 3D printed bridges. The largest is the bridge used in the competition.

<u>Results/Outcomes</u>

During the in-class competition, all bridges were subjected to loading until failure. The load-displacement curve for the bridge as well as high-speed video was captured during testing. A still image of our bridge experiencing brittle failure once it reached the peak load is shown in Fig. 6. It fractured in the center of the bridge where the bending moment and the stress concentration was largest. The crack initiated on the underside of the bridge where the maximum tensile stresses were present and propagated to the other side rapidly, cleaving the bridge into two pieces. This point of failure is exactly what we expected from the FEM analysis and indicates that the manufacturing process was good since we did not experience failure at a defect (debonding layers) or at the joints.

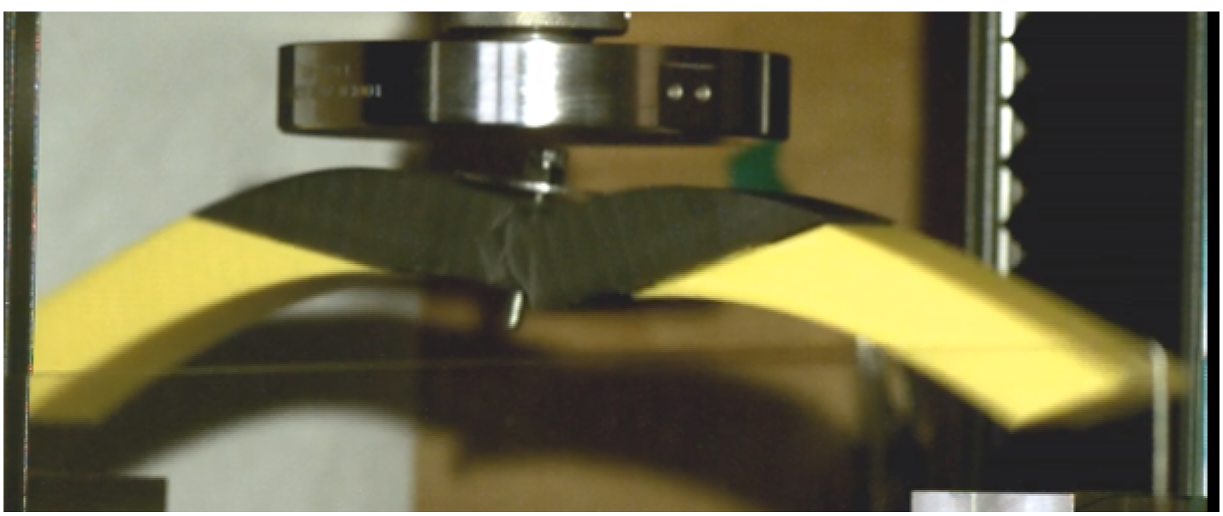

Figure 6: Our bridge at the moment of failure.

The resulting load-displacement curve is shown in Fig. 7, which is characteristic of brittle failure with the load dropping rapidly after the peak stress. A peak load of 2,037N (457 lbf) occurs at a displacement of 12.76 mm (0.5in), not bad for a bridge that only weighs 187 g (0.4 lbs)

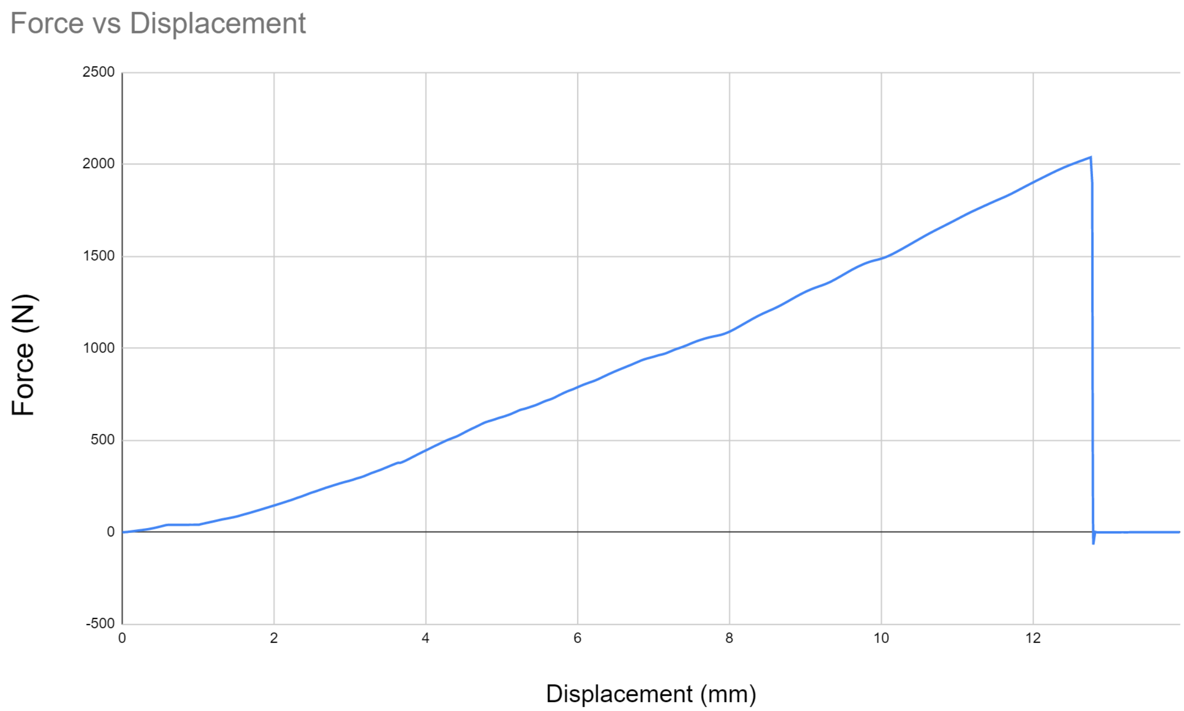

Figure 7. Load displacement curve for the bridge test.

Overall, our bridge performed well in the competition placing 4th overall in terms of the stiffness/mass ratio. From observing the other teams, it was very interesting to see all the different designs. Even though we all had access to the same tools, the designs varied greatly from I-beams, to multi-leg structures, to arches like ours. Among the top performing teams, the majority utilized an arch-like structure motivated by topology optimization. This design was successful because it places the majority of the material in compression, where the PLA has a higher failure stress. In fact, the first place team had a very similar design to ours, except it also included a cross-bar connecting the legs which prevented them from coming apart as easily. Ultimately the winning bridge failed at the pin joints that connected the central arch to its side pieces.

The joints between printed components appeared to be the most common failure point in all bridges. This emphasizes the need of carefully considering the loads that a joint will experience. As we noticed in our small scale tests, puzzle piece shaped joints may look very interesting and can do well in one direction of loading, however they perform poorly under moment loads or off-axis loading. In some cases, off-axis loading caused joints to become undone prior to any material damage either because of poor design or because of imperfect tolerances in the printed parts. The tight press-fit in our design enabled the loads in the material to be efficiently transmitted from one part to the other without significant stress concentrations.

Conclusions

In conclusion, we were very pleased with the performance of our bridge design, however, after seeing some of the other bridges and thinking more about the problem there are a few changes we think that could make our bridge even better:

- Increase the thickness in the center of the bridge to account for the stress concentration.
- Increase the infill density in the top of the bridge where the stresses were higher, and maybe reduce the infill in the legs where the performance is less critical to maintain constant mass.
- Experimentally explore different infill patterns to optimize the stiffness/mass ratio rather than going with an online suggestion.

Since we saw our bridge fail by material fracture, we were satisfied with the press-fit joints and would use that again. Since the top two teams used the second mounting option (includes a horizontal constraint) we would likely explore that option as well. Utilizing the the side walls would be an efficient way to prevent the bridge legs from bowing outward and could prevent the need for a cross-bar if properly designed.

Assignment details:

- <u>Bridge Design and Fabrication</u>
    - Describe the rationale for your design and how it was informed by analysis (including software), printing capabilities, material property information, and anything else you deemed relevant.
    - Provide schematics/drawings to clearly show your design and its key features, and summarize your analysis approach and findings to support the design.
    - Describe how you made and assembled the bridge. Explain your choice of machine/material, print settings, layer thickness, build time, orientation, etc. Discuss tradeoffs you considered.
- <u>Results/Outcomes</u>
    - Discuss the deformation behavior and failure mechanism of your bridge, as informed by the video and loading data. Comment on the predicted/expected performance of the bridge versus how it performed during the competition.
    - Compare the performance of your bridge to others in the competition, both qualitatively and quantitatively. What designs performed the best and why; what attributes stood out to you as particularly creative and effective? Consider structural design, assembly/joining, and fabrication in your response.
        - 4th place
        - Teams that used the generative design tool in Fusion typically had multiple legs. Some performed very well, while others did poorly because they chose joints that were less stable
        - Those that did topology optimization on a brick (like us) generally came up with an arch-like design. The performance of these structures seemed limited by the material/infil itself
        - Other groups used I-beam like designs that did very well because they were very light (except for the huge one) but they had issues with off-axis moments that caused the beam to fall or buckling in the thin sections
        - Overally, the joinery that was most effective appeared to be press-fits. Puzzle piece joints tended to break especially those loaded in tension ended up being a failure point

- <u>Conclusions</u>
    - Discuss how your bridge could be improved (made stronger, lighter, etc) in reflection of your results. You may comment on the design as well as how the printing/assembly process could be changed. Consider things under your control

such as the build orientation, joint dimensions, etc rather than inherent limitations of the printing process and constraints given. Would you adopt any strategies/features demonstrated by other teams if you were to refine your bridge design?