ENGS-33
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Phase 6: Final Report

I. Introduction

We began our design process by researching and comparing different bridge structures which included pratt trusses, howe trusses, and arch bridges. We decided to incorporate both the truss and arch design as they distribute forces well away from the load to the supports. The arch is also more aesthetic than typical rectangular trusses, and we felt the integration of a truss support system beneath the arch would yield good results.

We decided early on that we wanted to use solid wood as our secondary material. We had a concern about the strength of bonds between plywood and other non-porous materials which may have negatively affected our bridges performance and compromise our design. We worried that a joint between wood and a secondary material would be more susceptible to breaking, but after we researched the bond strength of wood glue, we found it would be satisfactory. Many of the past bridges failed at faulty connections at the joints, and so we wanted to ensure that the joint itself would not lead to a premature failure. This also encouraged us to use gusset plates to connect our members rather than slots because it increases the surface area of bonds, and fails under a shear force rather than a normal force. Because it would take a large load to generate such a shear, we deduced gussets would make for a stronger bridge. We later decided to use Ash as a secondary material because it was recommended by Greg Elder, and was the strongest wood available at the wood shop.

Our first design was an inverted arch truss which we based off of a Youtube video of a record-breaking truss bridge at the University of Auckland [1] and fit to the specifications of this project (Appendix C). However, after analyzing the forces of the members, we found that the inverted arch did not behave as an arch as anticipated. The "arch" was in tension rather than in compression. Because we intended our arch to be made out of solid wood which works well under compression, we created a regular non-inverted arch truss which does put the arch in compression for our second iteration (Appendix A.1). By placing compressive loads on a secondary material that is stronger under compression, the bridge is optimized and will perform better.

We then explored variations of the design including changing the orientation of the truss members and changing the locations of our vertical members relative to the point loads. We also performed a 2D qualitative analysis of the design's compression and tension forces, relative magnitudes of internal member forces, and its shear and moment diagrams. We then quantitatively analyzed our initial bridge and variations and found the maximum load supported by the bridge before failure and the location of failure (Appendix D). The calculations under the test loading condition showed that an arch-truss design with point loads applied directly adjacent to the vertical members could take on a much greater load than our other variations. Our calculations were supported by the 3D CAD simulation of our model bridge, which indicated that the location of the highest stresses would be where the load was applied and in our arch. While this stress distribution was expected, we wanted to refortify those locations of higher stress to help our bridge perform better. As such, we incorporated braces across the outer vertical members that ran under the deck in order to greater utilize the truss and to strengthen the deck by providing wood shear strength in addition to glue shear strength. The braces across the outer vertical members also served the purpose of preventing twisting due to the buckling of a member, which was a common mode of failure seen during our research phase. Inter-arch supports were also added to prevent any additional twisting motion.

During assembly, rather than cutting out our truss members as one piece, we took care in printing out individual parts along the appropriate grain to maximize the strength of the plywood (Appendix A.2, B.1, B.2, B.3). We considered the kerf of the laser printer, and sized pieces 0.01 larger on sides where necessary to avoid loose connections and ensure maximum contact.

II. Analytical Results & Testing

We used our Solidworks model under a simulation to predict our maximum load, deflection and location of failure (Appendix A.3, A.4, A.5). For the simulation, we applied custom materials to our parts to closely model the plywood and ash that our bridge used. The values used were obtained from online sources [2]. The value for Young's Modulus that we found experimentally in lab were very different from the values we found online for the plywood, so we used the average when predicting the failure load. We predicted a maximum load of 2.5 kN, a displacement of 0.185mm at 1kN, and location of failure at a joint, specifically, by an outer vertical member detaching from its gusset. This prediction results from analyzing our bridge as a 2 dimensional planar truss, with the arch simplified into straight members joined together in an arch-like shape.

Our prediction was supplemented by a solidworks scale model of our bridge constructed with the proper materials and properties found online and throughout Labs 1 and 2. The deflection was calculated entirely by Solidworks, while the maximum load predicted was calculated by hand and supplemented by Solidworks.

III. Post Testing Discussion

During testing, our bridge failed at a load of 3.39 kN with 0.556mm displacement, and failed on the right-side under the outer vertical member where the brace beam sheared out of its braces (Appendix B.4, B.5). Our prediction for load was under by 0.89kN or 26% and displacement was under by 0.371mm or 66% (Table 1).

While we did initially predict a 3 kN failure load, we were concerned about the joints we constructed and slightly lowballed at 2.5 kN. As such, the failure at 3.39 kN is not surprising, neither is the location of failure. While we thought the outer vertical member would break first, the brace beam broke first because of how thin it was, something we considered but did not change as we figured the load would mostly be transferred to the deck and truss members. We did not predict this because we were concerned with joinery and believed that the joints of glue would fail before the plywood would shear. However, when examining the simulation retrospectively, we do not see any stresses along the brace beam. It also does not show any signs of deformation. This may be likely due to (another) assembly modeling error and meshing complications.

To improve the accuracy of the predictions, we would first determine a better simplification of the arch-truss system. Due to the arch design, it is difficult to implement a simplification that does not come at the cost of a less accurate prediction. One change we would make to our simplification, however, is to structure the simplify the arches as 6 members, no two of which are on the same line. In this manner, each panel of our truss has members that are not simplified to be zero force, and using the angular relation would give a better idea of the forces in the truss.

Another method to improve the accuracy of our predictions would be to analyze the forces in the members of the bridge not in the plane of the trusses. For example, we decided to add braces to the outer vertical member gussets after our phase 4 calculations, but we didn't recalculate the forces in the brace to see what the stresses and shears were on that member. As a result, that member was too thin and was the first to break.

Our analysis only considered the tension and compression forces on each member, and not shear, bending, and torsion. While it is difficult to account for all of these accurately by hand, it would be beneficial to do simplified calculations to determine whether one of those loads results in failure. We tried to account for these loads in Solidworks, but due to the complex nature of our bridge it was difficult to mesh the entire bridge and accurately run studies.

There are a few changes we would make to our design and construction process to strengthen the bridge. The bridge broke at our inter-brace supports, so the first change would be to use thicker, but cylindrical, pieces of wood running across the bottom. The circular cross section will decrease the stress concentration, give the beams more surface area to be held, and distribute the load better. Another problem with our bridge was our implementation of the gusset plates. While they were strong and lasted, we believe they would have performed better had we increased the surface area and made them slightly thicker to prevent shearing.

Another change we would make is to increase the surface area of attachment at all of the gussets by adding rectangular supports beneath our bridge to give the gussets more surface area to adhere to. We also would increase the thickness of the deck in general, but the current model is close to the volume limit, so material would have to be excised elsewhere, which is difficult to do as our design is already quite minimal. Interestingly, our arch and truss performed very well, so that design would remain unchanged in a new iteration.

A major factor that we influenced our results was the process of actually constructing our bridge. While most other bridges were made of large laser printed trusses, we focused on designing and cutting each piece separately to maximize the benefit of the grain being parallel to the load. While this definitely helped our bridge in its overall performance, it was very difficult to properly join the entire bridge and wait 24 hours between each stage to let the glue set. Furthermore, as our bridge was composed of over 70 moving parts, many of which are curved to fit with the arch, it was difficult to join and clamp them properly in an orderly fashion.

Table 1:

	Predicted Results	Actual Results
Load at Failure	2.5kN	3.39kN
Location of Failure	Outer vertical support member	Inter-brace beam
Deflection	.185mm	.556mm

References:

[1] https://www.youtube.com/watch?v=Z_h6gMlRf7k

[2] https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr190/chapter_12.pdf