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Balsa Wood Drawbridge

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BALSA WOOD DRAWBRIDGE

By

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Abstract

Which truss design is best suited to a drawbridge when precision equipment is unavailable for the construction process and what design is suitable for the articulation system? To address this problem, several different designs were considered for a truss made of balsa wood. Initially a warren truss, a k-truss, and a bowstring truss were considered. The designs were evaluated using a decision matrix, the winning design was produced and tested. The testing methods used were a mass limit of the bridge, a minimum length requirement, loading requirements, and a minimum height for the roadway to reach when raised. Various other smaller tests were conducted but they had little to no impact on the design of the bridge. The design was evaluated during the testing phase using a pass-fail system for each of the requirements. The warren truss design was able to sustain the twenty-kilogram loading, span the four-hundred millimeters between the abutments, and the final mass of the bridge was fifty-four grams without the articulation system attached, which was less than the maximum allowable weight of eighty-five grams. During the articulation process the bridge was lifted with the center of the roadway reaching a height greater than fourteen centimeters from the resting position. The bridge was also able to maintain this position without assistance for the ten second required before being lowered.

Contents

1. INTRODUCTION

a. Description

The design and testing of structure like bridges often need to be tested at a smaller scale in order to observe how the structure reacts to being loaded to the critical point without failing. The bridge was designed to act as a drawbridge with the roadway raising when needed, while also allowing a car to pass over the bridge.

b. Motivation

The motivation to construct this project was brought along by the need to safely complete a capstone project with minimal resources due to the conditions created by covid-19. There was also a need to demonstrate the knowledge accumulated during the time spent in the engineering program through a project.

c. Function Statement

This structure will hold a specified distributed load on the road way while also having the ability to raise and lower the roadway to accommodate something passing under it. The roadway will span across two abutments and have the clearance on the roadway to allow a car to pass over the bridge unobstructed.

d. Requirements

The design of the structure is defined by the numerous constraints that will guide the production of the project.

- The span of the bridge must be 400 mm at a minimum.
- The bridge must hold a load of 18.9-20 kg without structural failure.
- The weight of the bridge without the articulation must not exceed 85 g.
- All structural materials for the bridge will consist of balsa wood and glue only.
- The roadway of the structure must be 38 mm wide and have enough clearance for a 32 mm wide by 25 mm tall block to pass through unobstructed.
- The roadway must not rise above 12 mm of the abutments.
- When at rest the bridge will be fully supported by the two abutments.
- 50% of the bridge roadway will be able to be lifted 280 mm from the original position using the articulation.
- The articulation of the bridge may be accomplished by either manual or automated means.

e. Engineering Merit

The project necessitates the designing and building of bridge under several constraints. The merit of the project is the associated calculations for the forces acting through each member, the stress concentrations, and designing an articulation system to raise the roadway with a motor.

f. Scope of Effort

- Pick out the stock size of wood and cut it to size.
- Pick out the type of glue for the joints and the motor that will be used for the articulation.
- Create the drawings for the design.
- Determine a safety factor to base the dimensions off of.
- Calculate the forces acting in each member of the structure and where stress will concentrate.
- Design a pulley system to lift the road of the bridge with a motor.
- Maintain a weight of less than 85 grams while the design sustains the target loading.

g. Success Criteria

The bridge will be able to sustain the load defined in the requirements while minimizing the total weight of the structure. The articulation will be able to lift at least one side of the roadway to the extent listed in the requirements.

2. DESIGN & ANALYSIS

a. Approach: Proposed Solution.

This design was conceived due to the conditions created by COVID-19 as it restricted the resources available for the production of the bridge. The design of the bridge is based off of a Warren truss but modified to work as a drawbridge.

b. Design Description

The design of the bridge can be broken into two sections, the side profile of the bridge and the articulation method to raise the bridge. The bridge will be designed to withstand a load of 20 kg with a safety factor of two when statically loaded. The project was not expected to undergo side loading, but it was designed to handle a small side loading representing a cross wind. Using the articulation system powered by two small motor, the entire frame of the bridge will be lifted from one end similarly to how a single deck drawbridge operates.

c. Benchmark

The design of the bridge parameters for this project is similar to the requirements for the physics balsa wood hosted by the Notre Dame Secondary School in British Columbia, Canada. The project can also be compared to an upscaled truss problem from a statics course.

d. Performance Predictions

The bridge will be able to sustain the load of 20 kg without failing. The bridge will be able to raise in approximately 30 seconds using the power of two small motors with one motor on either side of the bridge. The weight of the bridge without the articulation system will fall under 85 grams.

e. Description of Analysis

Below are the detailed descriptions for the various types of analysis that are being done for this project. The analyses will be completed in order to design the structure of the bridge within the strengths possible using the properties of the materials involved. In the following descriptions, the methods and equations will be explained including why they were applicable, as well as the results that were obtained by the analysis.

f. Scope of Testing and Evaluation

The design of the bridge was tested under several different criteria. The primary criteria were whether the loading that the bridge could sustain, and to avoid fracturing the bridge before the evaluation period, the full loading of 20 kg will not be applied. The secondary testing criteria was the articulation of the bridge, and that will be evaluated by a pass fail system of whether the height of the bridge is above the minimum height from the horizontal position of the bridge from the requirements.

g. Analysis

A-1

This analysis was completed to determine the minimum cross-sectional area for each member of the bridge struts. The requirement for the project is that the bridge must be able to sustain a load of 20 kg at the center. The method used to complete the analysis was the method of joints on one half of the bridge with a factor of safety of 5.0 under the assumption that the force will be evenly distributed between the two sides of the bridge. Please see appendix A-1 to see the analysis green sheets.

A-2

The purpose of the analysis was to find the minimum torque that a motor would need to produce in order for the articulation portion of the design requirements to be met. The method used for the analysis was model the drawbridge as a beam with a pinned joint acting as the pivot. The forces were then balanced for the roadway when fully horizontal to find the tension in the string. The torque was then found using the relationship between the force in the rope and the distance from the pivot point. The minimum torque that would be needed for this design would be 0.00296 N•m. A FS90R servo motor was chosen to be used in this design due to the motor providing enough torque and having a low cost. The calculations for this value can be seen in appendix A-2.

After a redesign of the articulation method for the bridge the loading on the motors due to the now being required to lift the 60 gram bridge frame. The servos were still able to preform as expected despite the increased loading.

A-3

The dimension that is being solved for in this analysis is the pin diameter that the road of the bridge will pivot upwards from. The diameter of the pin was calculated using the equation for shear if the pin was in double shear. The pin diameter was calculated to be 0.012 mm which is not practical for the design of this bridge. The location of the pin was altered, but a similar sized pin was used in the hinges that the bridge pivots upon.

A-4

The fourth analysis was completed to find the diameter of the string that will be used to raise the road of the bridge. Nylon string was decided as the material that would be used due to the available information on the properties of the material as well as the availability of it at a reasonable price. The diameter of the string was determined using the tensile stress that would be developed in the string while lifting the road of the bridge. The diameter of the string was determined to be 0.03 mm. Due to the inability to find string that fine, #9 string will be used in the design of the bridge, the diameter of this string is 1.07 mm. The calculations for this design parameter can be seen in appendix A-4. The diameter of the twine was too large to be practical in the pulleys that were used in the design, this was due to a misunderstanding of the sizing used for string. The diameter of 1.07 mm was for one the three strands twisted together.

A-5

The goal of this analysis was to find minimum thickness they pulley would need to be designed for in order to prevent it from failing due to external loading. The calculated value for the thickness of material around the inner diameter of the channel was significantly smaller than what would be practical for 3D printing at 0.003 mm. The pulley will be designed with a thickness of 1.0 mm in order to allow it to be printed without need for significant alteration after printing. The analysis was conducted by calculating the forces acting on the pulley due to the tension in the nylon string that will be running over it while the road of the bridge is being raised. This can be seen in appendix A-5.

The thickness had to be increased again to make the pulley usable in a practical sense. The final thickness used in the pulley was 2.5 mm with a 20% infill.

A-6

The purpose of this analysis was to find the dimensions of a bearing that could be used to pivot the road of the bridge when the motors are engaged. The minimum cross-sectional area of the bushing was found to be 0.00013 mm^2 which is too small to be widely available. To reduce the costs associated with obtaining this bushing, an assembled part was found with the dimensions of 2 mm inner diameter, 7 mm outer diameter, and it is 3.5 mm wide. The analysis was completed by using the reaction force in the bar that the bearing will be resting upon due to the force applied to raise the road of the bridge. The calculations associated can be seen in appendix A-6.

The bearing was later removed from the design of the bridge. It was replaced with two small hinges.

A-7
This analysis was completed in order to find the number of screws that would be needed to secure the pulley housing to the mounting adaptor on the axel of the motor. The diameter of the hole was 1mm which limited the screws available to M1 metric screws which was used for this analysis. The minimum number of screws needed to resist the shear force was found to be 0.000009 screws, but in order to properly secure the two parts together two screws will be used. The screws were analyzed in single shear using the shear force equation. The calculations can be seen in appendix A-7.

Due to issues with 3D printing the pulley with holes for the screws, the pulley was attached to the mounting bracket using superglue instead.
A-8
Analysis eight was focused on determining the shaft thickness needed for the Arduino motor. The minimum diameter with no safety factor was found to be 1.69 mm based on the torsion that the shaft will experience due to the motor and the force acting through the string and the pulley. The torque of the motor was calculated using the relationship between the voltage and current used in the motor and the torque on the shaft was calculated as the net torque due to the loading and what was applied by the motor. The shaft that is included with the motor is hollow and the cross-sectional area was found to be 13.53 mm^2 which was significantly larger than the 2.25 mm^2 calculated from the minimum required diameter shaft. The shaft that will be used was decided to be the one included with the motors and these calculations can be seen in appendix A-8.

A-9
Analysis nine was completed in order to account for a hypothetical side loading on the bridge that would represent heavy wind. The bridge will not be tested in side loading, instead the cross beams will serve to prevent the members of the truss from twisting due to a flaw in the manufacturing process. The cross-sectional area of the seven cross beams was calculated to need to be 7.38 mm^2 based off of a safety factor of 4. The size of the cross beams that were used were decided to be $\frac{1}{8}\,in.$ square sticks, these have a cross sectional area of 10.008 mm^2 which brings the safety factor to around 5 from the failure stress of balsa wood. The analysis was completed by assuming each of the members to experience the same external loading due to the simulated wind load. The calculations for thus analysis can be seen in appendix A-9.

A-10
This goal of this analysis was to determine a thickness for the roadway of the bridge to prevent it from failing under the distributed load created by the plate placed upon it during testing. The roadway was modeled as a two separated overhang beams due to the bridge being designed to

split in the middle when the roadway is raised. The loading was assumed to be evenly split between the two halves of the roadway, so it was reduced to half its original magnitude. The minimum thickness required for the roadway based off of the maximum shear found from a shear diagram was calculated to be 0.0026 mm. The thickness that will be used for the roadway will be 1 mm as that is the minimum thickness for sheets of balsa wood that is widely available. The complete analysis can be seen in appendix A-10 as well as the shear and moment diagrams.

After further review of the roadway design using modeling software, the thickness of the road deck was increased to 0.125 inches to decrease the chances of the roadway fracturing due to the distributed load around the hole where the loading was applied.

A-11
The purpose of this analysis was to verify the thickness of the rod that would be needed for the pulley based off the loading created by the tension in the nylon thread. The minimum diameter calculated was 0.167×10^{-6} mm, but the diameter that will be used in the design will be 2 mm for consistency with the other stainless-steel rods being used as the pivot points for the roadway. This analysis was completed by representing the rod as a cantilever beam with the loading created by the pulley being simplified to a point load. The calculations for this analysis can be seen in appendix A-11.

The location of the rod was changed but the conclusion that the diameter should be 2 mm did not.

A-12
This analysis was completed to calculate the maximum stress that will be concentrated at a joint in the truss representing the side of the bridge and verifying that the glue will not fail under the loading. The calculated stress the glue will experience assuming that the thickness of the glue is negligible was found to be 1.51 MPa. The average stress that glue is able to withstand is 24 MPa therefore any brand of glue would be sufficient for the joints. Elmer's Superglue was decided as the best fit because of the speed that it dries at as well as the low cost associated with the product. The calculations for the stress can be seen in appendix A-12.

h. Device: Parts, Shapes, and Conformation.

The sizes of each the individual members included in the trusses of the bridge were based off of the length that the bridge would need to span. After that condition was met the angle of the trusses were decided to be 60 degrees because the design is based off of the warren truss. The number sections of the truss were to be composed of 11 triangles so that the two members connected to the center of the bridge would be in tension. A general safety factor of 5 was used for each of the members in the truss when they are under direct shear. A general tolerance of the balsa wood of 0.1 mm for the dimensions of the planks. This value was chosen because the tools that were available for the manufacturing process had limited accuracy, but the members needed to be similar in length to prevent stresses from being built into the structure.

i. Device Assembly
The bridge design consists of two main assemblies, the side truss, and the articulation system. The side truss was made twice to support the loading of the bridge, while the articulation system consisted of the pulleys, motors, roadway, and the cross beams.

j. Technical Risk Analysis
The technical risks associated with this project was the strengths of the materials and the tuning of the Arduino motors. The materials used in the manufacturing of the bridge were optimized to minimize the overall weight. There was a balance that had to be found between minimizing the weight and ensuring the bridge would be able to hold the designed weight. This was addressed by using the previous experience with building balsa wood bridges to choose the general safety factor of 4 for each of the members of the truss. The tuning of the Arduino motor was addressed by trial and error due to the inconsistency present in cheap Arduino motors. The primary concern was the time that had to be spent on this process.

k. Failure Mode Analysis
The failure modes that were addressed in the components were direct shear, maximum shear stress theory, and maximum bending of a beam. These failure methods can be seen in the analyses of appendix A.

l. Operation Limits and Safety
The bridge was optimized so the maximum loading is 20 kg on the center of the bridge, Loadings above 20 kg should be avoided, and the loading should be centered on the bridge. The maximum height of a vehicle that could drive over the bridge would be 50 mm, anything over this height would come into contact with the cross beams on the bridge.

3. METHODS & CONSTRUCTION

a. Methods
This project was conceived, analyzed, and designed so that the project could be completed with limited resources while working remotely from home. Due to the lack of available resources the parts were designed to use simple geometries and a design was chosen that had minimal members in the truss to minimize the problems that would arise with the lack of precision equipment available. The engineering disciplines that are being focused on in this project is primarily mechanical engineering, and to a lesser extent civil engineering.

i. Process Decisions
The production of the project was broken into three different sections, the gathering of materials, the alteration of the materials, and the construction of the project. The initial design was decided using a decision matrix that be seen in appendix F table one. The criteria used to

determine the bridge truss design was based off of several factors ranging from practicality, cost, and the aesthetics of the design. The point system used in the matrix is a 1-3 scale with a 3 representing the best of the possible designs, and a multiplier was used based off of the importance of the criterion to the overall project. The design that was chosen due to the simpler construction methods that would be needed to complete the construction based off of the overall difficulty and the modularity, meaning that the parts could be produced using the same methods for the majority of the design. The cost of the overall design was predicted to be similar for all three of the designs so that was not a deciding factor between the designs. The final criteria included in the decision matrix is the predicted weight of the bridge, and the first design was predicted to be the least, the second design would require lamination of the top beam which would use a significant amount of glue increasing the overall weight. The third design includes a large amount of balsa wood in the side truss of the bridge which brought the predicted weight to be larger than that of the first design. The final design of the bridge is a modified version of the first design to fit the parameters required such as the distance the bridge must span and the maximum mass of 85 grams.

Due to the availability of balsa wood locally within the budget that was set during the beginning stages of the project, the designing process of the bridge underwent several changes. The dimensions of the materials used had to be altered be measured in inches instead of millimeters in order for the balsa wood to be acquired within the necessary dimensions. At the same time the dimensions were rounded to the nearest standard size that was available. Due to necessary cross section of the lower beam not being available in sticks of balsa wood that were long enough to accommodate the design, the member was changed to be laminated. Due to the relatively low weight of design, it was decided that some of the remaining weight could be allocated to this member to avoid any weaknesses created by gluing two shorter members together to span the abutments.

Due to issues found during the manufacturing process the geometry of the side truss elements had to be altered to accomplish the goal of the project. The design of the compression and tension members were replaced with a new support member which increased the surface area at the joints where the glue was applied. The new joints consequently altered how the upper and lower beams interact with truss by setting the joint within the cross section of the beams. To accommodate this change in design the beams were broken into several different components including a truss cross beam that supports the shape of the joints. A separate cut of balsa wood was then laminated onto the op and bottom of the truss to satisfy the calculated cross section of previous beams.

Near the end of the manufacturing period of the bridge an oversight in the design was found relating to the design parameters set for the project to accomplish. The initial design had the roadway articulate but the frame of the bridge remains stationary, which did not meet the intent for something to be able to pass under the bridge. To accommodate this revelation a new articulation system was designed and manufactured utilizing several of the existing components. The new design lifted the bridge from one end instead of being split in the middle.

b. Construction

i. Description

The construction of the bridge will take place in three stages, building the trusses that will be used on the left and right sides of the bridge, constructing the roadway and the cross beams, and the last step will be attaching the articulation system. The parts that were 3D printed were manufactured using a IIIP printer provided by Greg Bertolucci. The parts that need to be adjusted from stock cuts of wood will be completed remotely, and the stainless-steel shafts were cut to length and filed down to meet the required specifications for the assembly. The steel frame of the articulation system was cut using a Sawzall and the holes were drilled using a hand drill.

ii. Drawing Tree, Drawing ID's

The drawing tree of the project can be seen in appendix B as well as the other part drawings associated with the design of the bridge and the articulation system.

iii. Parts

In this assembly there are several parts that needed to be bought or outsourced to be manufactured. The stainless-steel bearings will be bought and used without modification, while the stainless-steel rods needed to be reduced in length for them to fit into the design parameters. The Arduino motor assembly was used without any major modifications, just some minor tuning to make them synchronous, and the nylon sting will need to be cut to length from the stock spool. The parts that were outsourced were the two pulley designs, they were both printed using the 3D printer at Hogue Hall. These parts were chosen to be outsourced because no existing part could be found that were built using the dimensions that would correspond with the other purchased parts. The remaining parts used in the design were all made of balsa wood and needed to be cut to the proper lengths using a fine-toothed handsaw.

iv. Manufacturing Issues

The manufacturing issues that were expected were getting the correct tolerancing on the parts that were manufactured remotely, as well as the parts that will be fabricated at Hogue Hall using the 3D printer. Due to the small scale of many of the parts there is expected to be corrections need for the project to be fully assembled. The compression and tension members of the truss were also expected to be difficult to manufacture due to the angles involved in the ends of the members required to create the desired joints. This was solved using a miter box and manufacturing these parts using during one period of time to prevent issues from compounding. The process to create these parts were to complete all of one specific cut for the members before completing the next cut. All of the initial cuts to bring the members to their specified lengths were completed before any of the angled cuts were started. After the members were cut to their proper lengths then the angled cuts were completed in two stages based off of the drawing of the tension support member in appendix B with the 30-degree angle from the horizontal being cut for both ends of all the parts before the other angled cut.

A second issue that was encountered during the manufacturing process was compounding error in the lengths of each of the tension and compression members causing the bottom support beam to accommodate the supports. To deal with this issue the tolerance for the top and bottom beams were increased significantly, with the parts being sanded down once the truss sub assembly was completed. After several failed attempts with the tension and compression members, the design was altered to use new parts with a more optimized joint structure. The new design nearly doubles the contact area between the different members which allowed the individual members to be set into the side trusses. The truss was broken into smaller sections consisting of two support beams and one truss cross beam that were glued together. A go-no-go check was preformed to see if the sub-assemblies were uniformly created. Using this quality control method roughly 25% of the elements failed with a total of 12 being needed within specifications. The truss design consists of 6 of these sub-assemblies connected by 5 truss cross beams and a laminated beam on the upper and lower bounds of the truss.

The new articulation assembly was wrought with issues due to the slim timeline available to produce it. The design called for several holes to be tapped in order for screws to be used to hold the members together. The holes had to be drilled using hand drill which introduced issues related to the placement and the angles of those holes. The hand tap that was available was not designed for steel, leading to a redesign using 3D printed dowel pins and superglue. This redesign was successful but required additional planning to align the parts in a way to minimize the issues from the irregular hole placements.

v. Discussion of Assembly

The construction of the bridge can be broken into two main sub-assemblies, the truss that makes up the sides of the bridge, and roadway/articulation system as seen in the drawing tree on the previous page and appendix B-1. There were two trusses built that are identical to each other that will be used as the sides of the bridge that carry the weight from the loading on the bridge. The drawings of the assemblies can be seen in appendix B. The individual members that will make up the truss can be seen in appendix B. The articulation system drawing can be seen in appendix B as well as the drawings for the pulleys.

4. TESTING

a. Introduction

The bridge will be tested for several different criteria including the loading it can sustain, the height of the deck of the bridge when raised, the weight of the bridge, and various other checks.

These requirements will be tested to show that the bridge meets the criteria set out in the introduction and design and analysis sections.

b. Method/Approach

The loading that the bridge can sustain was tested by spacing a 38 mm square by 6 mm plate on the deck of the bridge with a rod running through the hole at the center of the bridge. The rod was then be connected to a set of weights that will gradually increase till the target loading of 20 kg is met.

The weight of the bridge minus the articulation method will be evaluated by verifying the mass of the articulation system separately, then subtracting that from the total mass of the bridge. The ability of a “vehicle” to traverse the bridge, the articulation height of the bridge, and whether the bridge is resting on the abutments were all checked using a go/no-go method with photographic proof.

c. Test Procedure

The testing method for the loading of the bridge was securing the load to the plate on the roadway of the bridge while the loading was increased gradually to the target load of 20 kg.

The weight of the bridge without the articulation method was assessed after detaching the articulation system from the frame of the bridge. The hinges that are used as the pivot point during the raising of the roadway can not be removed, but their weight is negligible.

The ability for a “vehicle” to pass over the bridge, as well as the bridge resting on the abutments, and the articulation height were all checked using a pass-fail system with either a measuring device or a stand in device acting as the vehicle. The dimensions of the “vehicle” used during the testing was 32mm wide by 25 mm high. The vehicle used was hot wheels toy car.

The testing of applied loading of the bridge was tested last to allow for the possibility that the design fails during testing. The bridge was rested on top of the abutments that were forty centimeters apart. A small plate was placed on the road deck with a hook threaded to the plate to hold the load. A bucket was then filled with water slowly up to five gallons which is approximately the twenty-kilogram requirement.

d. Deliverables

The deliverable for the loading test was the failure loading of the bridge, for the weight of the bridge minus the articulation method, the deliverable was the measured weight. For the vehicle test, abutment test, and the articulation height, the deliverables are pictures and videos showing the design meeting the corresponding requirements.

The first test that was completed during the final stages of the project was the articulation of the bridge. The deliverables of the of the test was three different pass-fail values from the results. The bridge was lifted to maximum height of 153 mm from the horizontal which surpassed the minimum value of 140 mm of the testing criteria meaning the test s passed. The second portion of the test was whether the bridge could maintain the articulated position for a minimum of 10 seconds without any external intervention. The articulation was done using two servo motor which wen in their neutral powered position were able to hold the bridge in the upright position. Due to how the bridge was articulated, it could be held in perpetuity as long as the servos are powered which exceeds the 10 second requirement. The third portion of the test was regarding the expected speed and effectiveness of the servo motors. The motors were advertised as operating at 130 revolutions per minute when unloaded, but there were concerns over whether they would be able to lift the bridge during the construction of the articulation system. The deliverable results of the test were the height that the bridge was able to articulate after a 2 second period of time compared to an expected value based on the manufacturer specifications. The expected value was 90 mm from the horizontal and the actual value was 75 mm representing a 16.7% error from expected. This discrepancy is larger than what would be ideal, but it does not affect the bridge design or any of the other testing requirements, so it was not pursued further. During the testing process there were a few issues that arose, but they were all relatively easy to deal with. The Arduino board that was being used to control the servo motors had the wrong code uploaded initially leading to the servos operating at different speeds. This led to the two strings lifting the bridge to have differing amounts of tension acting through them. To deal with this the board was reset, the servos were repositioned, so the strings had equal tension, and the correct code was uploaded to the board. During the filming of the 2 second test the servos started to rotate in opposing directions despite the code not changing. There was no clear reason for this issue, but the board was reset to remedy the problem.

The second test of project was the ability of a “car” to pass over the roadway of the bridge without obstruction. The deliverables of the test were the dimensions of the test block used of 32 x 25 mm, and a go-no-go criterion of if the block was able to pass over the roadway. During the testing process the only issue that was encountered was the test block rotating while being pulled across the roadway due to how light it was. In order to address this issue weights were added into the hollow portion of the test block to create more tension in the nylon sting used to pull the block. This was not as successful as was hoped but it was still an improvement over the initial iteration. Despite the rotation of the block causing it to hit the side trusses of the bridge, it was still able to cross the bridge without getting hung up on anything, so the test was considered a success.

The final test that was performed was the weight loading of the bridge. The test consisted of loading water into a five-gallon bucket that is suspended by the roadway of the bridge. The deliverables of the test were the total weight held by the bridge and a pass/fail criterion if the bridge was able to sustain the five gallons of water or not. The primary issue encountered during this test was the scale not having a wide enough platform to measure the weight of the bucket when filled with water. The scale could not balance the weight, nor could it measure the expected weight as the scale maxed at 50 pounds. Instead, the total weight applied to the bridge was calculated by measuring the diameter and depth of the bucket to find the volume. The weight was then calculated based off of the density of water at room temperature and added to the weight of the equipment used that could be measured. The calculated weight of the water was 50 pounds, and the measured weight of the testing equipment was 1.38 pounds for a total of 51.4 pounds applied to the roadway. The test was successful as the bridge design surpassed the target weight of 44 pounds.

5. BUDGET

a. Parts

The projected cost of this design was initially calculated to be $130 with the largest portion of that cost being the price of the balsa wood. However, as the manufacturing process began it became apparent that the design was not practical based on the tooling available, as well as the joints not providing enough surface area to secure the members of the truss. The design initially was intended for the material to bought using metric sizing but that was not available locally. Instead, the design was changed to use English units and the cross sections were altered to be in standard sizes which drastically lowered the cost of the wood. The design was altered to provide more surface area to be glued at the joints which caused some of the previous material to become incompatible and thrown out, increasing the cost of the project by requiring more balsa wood to be bought. The cost per part to manufacture dropped significantly from around $1.50 per part to $0.15 per part which allowed for greater flexibility in the budget. The projected final cost of the project after the construction of the current design was roughly $83 which is significantly lower than the expected budget that the project was based off of at $130. Due to the balsa wood being bought in 36 inch increments there was no real setback from parts that fell outside of the part specifications.

All of the balsa wood was bought during the first week of the manufacturing process and more for the initial design using English units, and more was bought on a bi-weekly basis as parts falling outside of the manufacturing specs used up the existing material. The other material that are used in the articulation system were bought in the second week and were all delivered by the third week of the manufacturing process. A setback in terms of the budget was the need to purchase a miter box that could accommodate the 30-degree angles that the design called for. Initially it was expected that there would be one available from a family member, but upon further investigation it became clear that was not the case. The largest adjustment to the budget was the articulation system redesign which called for 36 inches of steel beams to be purchased. The cost of the material was $30 and accounted for a third of the actual cost of the design.

During the testing portion of the project and additional $18 was spent on testing equipment for the weight test. A bucket, steel plate, and eyebolt were purchased which brought the total cost of the project to $104. This brough the total percentage of the budget to 80% which is still well below what was initially expected. There were no errors during the testing process that affected the budget of the project.

b. Outsourcing

No portion of this project was outsourced, the 3-D printed components were originally planned to be outsourced to the lab technician at Hague Hall, but a printer became available after the planning phase of the project.

c. Labor

The associated labor for this project was the ten parts that were 3D printed using the IIIP printer.

d. Estimated Total Project Cost

The total estimated cost of this project is $130 which is accounting for the associated costs due to shipping, tax, materials, and use of the 3D printer owned by Greg Bertollocci, along with the filament used. The estimated cost was inflated due to the costs expected costs from shipping and the expectation that the raw material would be available in sizes close to what would be required for one part unit.

e. Funding Source

The funding source of this project will be the individual designing the project. If budgetary concerns arise then materials may be donated from family members in order to complete the project. The tools used in the construction of the design were provided by Dale Engebretson.

6. Schedule

The complete schedule for the project can be seen in appendix E.

a. Design

For the design portion of the project, the analyses, drawings, and the proposal are meant to be completed. The three sections of the design process will be completed concurrently throughout the fall quarter with the report being due on the final day of class. The analyses will be completed at a rate of two per week, one drawing per week, and weekly updates to the project proposal. The completion of the assembly model and drawing of the bridge was set for the sixth week of the quarter and was finished ahead of schedule at the end of the fifth week.

b. Construction

The construction of the bridge will be competed in winter quarter with the final product being completed by week ten of the quarter. The overall progress of the project should correspond with the time available in the quarter, with one quarter of the project being done by the end of the third week, half by the middle of the quarter, and three-quarters of the construction being completed by the eighth week. The goal was to complete the manufacturing process of the individual parts during the first five weeks of class, then spend two weeks to complete the side trusses, then complete articulation system by the end of week eight. This schedule was intended to provide ample time to deal with any issues as they arise while allowing time after the completed system was delivered to address the changes in the report and associated documentation.

During the manufacturing process there were several issues that were encountered which continually pushed back the schedule. The first major issue that was encountered was that the wood glue that was initially chosen took too long to set to be feasible for the rest of the manufacturing process. The bottle stated that the joint would need to set for approximately thirty minutes, but in practice the time that needed to be allotted was closer to ninety minutes. To deal with this issue the glue was changed from wood glue to a hot glue gun which reduced the time down to less than four minutes per joint. The second major roadblock was the initial design for the tension and compression members was not providing enough surface area to sufficiently secure the joints. This was the largest setback encountered because it required a redesign of all of the parts manufactured from balsa wood which increased the surface area per joint twofold. This change happened during week five which was when the individual parts were expected to be finished. This ultimately pushed the whole schedule back a week from what was planned, but the construction portion of the project was still completed within the allotted ten weeks.

c. Testing

The testing specific portion of the project was completed over a 5-week period starting in April and ending in the first week of May. During this period of time 4 tests were conducted in order to verify that the bridge met the design specifications set at the beginning stages of the project. The remainder of Spring quarter was spent incorporating the testing results into the rest of the overall project and condensing the information into presentations.

Issues that arose from the project mainly consisted of logistical issues from remote learning. The weight loading of the bridge was originally planned to be conducted during the sixth week of spring quarter, but it was brought forward two weeks to have the results before the SOURCE presentation was recorded. This schedule change caused the previous procedure to become obsolete due to a location change as the test was meant to be conducted in Everett, but it was instead done in Ellensburg. This also caused an increase in project spending as the supplies to conduct the testing had to be procured. An eyebolt and bucket were purchased in order to secure the loading to the bridge roadway when supplementary items had been identified for the original testing location.

7. Project Management

a. Human Resources

The human resources involved in the production of this project were the principle engineer providing expertise in the structural analysis of the bridge, and the laboratory tech who completed the printing of the pulleys used in the articulation system of the design. The risks associated with the principle engineer was the constraint of time, which was addressed by following a schedule that was designated at for each of the three sections of the project. The risks associated with the laboratory tech was the availability and time that they could dedicate to this project. These constraints were addressed by providing the information for the parts to be printed in early January in the case of a backlog of in parts being printed.

b. Physical Resources

The physical resources that were required for the completion of the were the 3D printer in Hogue Hall, a device consisting of several clamps to construct the trusses of the bridge, a handsaw, and a miter box for the cutting of angles in for the members. The only resource that had a risk associated with it was the availability of the 3D printer and the time constraints that were created by the need of other students to access the machine. These constraints were dealt with by submitting the parts that needed to be 3D printed in early January to ensure the parts would be completed on schedule.

c. Financial Resources

The principle engineer was also the primary source of monetary support for the project. The project budget was expected to be around $100 during the proposal of the project for the materials, with the tools for the construction of the project being provided by friends and family. In the case that the project was expected to exceed the budget that was initially set, the costs of the materials would be recalibrated, and the remaining materials would be adjusted to maximize the remaining budget.

8. DISCUSSION

a. Design

The design of the bridge was altered several times of the course of the designing process. There were variations in the sizing of individual parts, and there were different designs that were considered. There were initially three different designs that were considered for the bridge, and each of those designs had their own method of articulation for the roadway. The design that was chosen was the third design due to the simplicity of the geometry for the parts, and the streamlined manufacturing process presented by that geometry. The other designs utilized more advanced techniques like lamination or k joints, which would have been difficult to accomplish with the tools that were available. As new information became available the previous analysis had to be updated to reflect the new dimensions of the parts to accommodate the design. There was no issue in updating these values as most of the alterations happened in the first few analyses, and the remaining analyses built upon those previous findings.

b. Construction

The manufacturing process had to be altered from the initial plan due to the lack precision equipment when working remotely. The geometry needed to accommodate the overall dimensions of the bridge lead to the tension and compression supports required a miter box which needed to be purchased in a small enough size for the parts and able to cut a thirty degree angle. Due to the small size of many of the parts involved in the bridge the cutting of the parts to size needed to be completed using a fine toothed saw, when the original plan was to use table saw or circular handsaw for the initial rough cuts, then the parts would be sanded down into the specifications set during in the part drawings. Instead, the parts were all the members were cut using the fine-toothed saw because it left a much cleaner surface than a standard hand saw. There was a concern that the parts may fall out of spec during the sanding process if the parts were not secured by the ends of the part receiving uneven pressure leading to an uneven surface. This was checked by measuring the total length of the part at several different points on the finished surfaces to check for variations in the surface. All of the single cut members fell within the tolerances set in the drawings using this process.

While the tension and compression members were being produced several issues arose due to the angle the parts had to be cut at. There were three stages in the manufacturing process of these parts, the cut to initial length which all of the other members received, an angled cut, and a second angled cut that was perpendicular to the previous one. The initial cut to length was completed for all twenty-four of these members without any issues. To solve these issues the initial angled cuts were made using the 30-degree angle on the miter box, then were sanded down. While the parts were being sanded, an issue arose from the parts not receiving an even finish, or the angle was being altered too much causing the parts to fall outside of tolerance. This was addressed by using a thirty-degree steel wedge as a support to maintain the angle during the sanding process. The second angled cut encountered the issue of not fitting inside the miter box that had been used for all of the previous cuts. The plan was to cut using the zero-degree slot on the box and cut perpendicular to the finished surface. Because the part did not fit within the miter box, the part was moved to be against the outside wall of the box, then a composition notebook was used to raise the part to allow the cut to go through the thickness of the part. The same steel block used for the sanding of the previous cut was used for these angled cuts. To check the angle of the surfaces, a protractor was used to verify the angle between the two cuts and the angle of the angle of the surface.

During the assembly process of the side trusses a sample consisting of two of the support members and one cross member was used as a go-no-go gauge to verify that trusses would be similar in height and length. The pieces were constrained using two straight edges and the miter box to ensure a consistent shape. The inside angle of each of these sub-assemblies was checked to verify it was sixty degrees as specified in the design. After the six sub-assemblies were completed for one of the side trusses, the top and bottom beams were laminated onto the truss. The truss was secured using several clamps flat onto a table, but the balsa wood was not in direct contact with the clamps. Straight edged materials were used instead to prevent the balsa from being damaged by the force exerted by the clamps. Approximately twenty pounds of a distributed load was then applied to the truss to prevent the wood from deforming during the gluing process. The glue was then allowed to harden overnight to avoid any flaws that may have occurred by handing the truss before the glue was completely set. Despite these precautions one truss ended up thirty thousandths taller than the other. In order to not reduce the cross-sectional area of the other truss to below the design value, a sixteenth of an inch board was laminated onto the top beam, then sanded down till the two trusses were the same height.

c. Testing

The testing regiment was changed several times as the third phase of the project progressed. The specifications of what was tested remained constant, but the way the tests were procured had several iterations. The first test that was preformed was on the articulation system verifying the height the roadway could reach and that it could maintain that position. Initially a go no go device was going to be manufactured to serve as the way to check the height without directly measuring it. After consideration it was decided that it would be more beneficial to have the actual value the roadway was able to reach directly measured rather than rely on another piece of equipment that would require additional time to manufacture.

The roadway clearance test required a test block to be manufactured which was completed by use of a 3D printer. The block was initially going to be made using left over balsa wood from the construction of the bridge, but in the interest of time it altered to be printed. An additional change was the utilization of a piece of string to move the test block across the roadway. The original testing procedure had the block being moved by the test administrators fingers which was deemed to be difficult on the account of the cross beams above the roadway, along with how narrow the roadway is in relation to the height of the side trusses.

No changes had to be made to the general testing of dimensions and weight of the bridge. The tests that were performed were simple enough that the potential issues could be anticipated and addressed.

The final test that was administered was the weight loading of the bridge. This test had the largest changes in terms of what was initially written into the procedures. The plate that was planned to be used to disperse the weight applied to the bridge was planned to be purchased as a complete unit, but due to time constraints it was purchased as a stock steel plate, then adjusted to fit the dimensions required. This change was both cheaper and faster. Other changes include the abutments being changed to accommodate the change in testing location, due to the bridge being moved to Ellensburg, most of the specifics of the procedure needed to be changed to reflect the equipment available during the testing period.

9. CONCLUSION

The design for this bridge meets all of the standards and requirements that were outlined at the start of this process. The design of the bridge based off of the material specifications of Solid works was at a projected mass of is 55 grams which is well under the maximum mass of 85 grams. The actual mass of the bridge was measured to be 52-54 grams which could not be differentiated due to the resolution of the scale. The articulation system was designed using a drawbridge design with the entire balsa wood portion of the bridge being lifted with a pulley system powered by motors. The verification of this process was to see if the top of the roadway is 140 mm from its original position, and if the two servo motors are able to synchronize to allow for sustained use. The design was able to raise the bridge 153 mm from its resting position and it was able to hold that position for several minutes before the test was ended. The final aspect of the bridge testing that was tested was the weight application test where 45 pounds was to be distributed on a section surrounding the center of the roadway. The projected value was around 220 pounds before failure, but the test was only conducted to 51.4 pounds which exceeded the minimum requirements. The necessary support that was needed to reach these results were the availability of the resources of the school to manufacture some of the parts, and the financial support of the principal engineer. The necessary money to complete fulfil the budget was set aside during the planning phase of the proposal in order to prevent issues during the manufacturing process.

10. ACKNOWLEDGEMENTS

This project would not have been possible without the help and resources provided by Central Washington University and the faculty of the Mechanical Engineering Technology program. In addition to the mentorship and guidance provided by the faculty, they offered frequent feedback on ways to improve the project. Acknowledgement is also extended to the friends and family who helped to provide some of the tools needed to manufacture the parts used in this project. Special Thanks to everyone that was involved in bringing this project to completion:

- Professor Charles Pringle
- Dr. Choi
- Ted Bramble
- Dale Engebretson
- Mark Janice
- Gregory Bertolacci
- Production Plating INC.

References

"Online Materials Information Resource." *MatWeb*, www.matweb.com/.

The material properties for each of the types of materials used in the construction of the bridge were found using this website.

APPENDIX A - Analysis

Appendix A-1 – Cross Section Requirements

Kyle Engebretson | MET 489 | 9/18/20 | 1/3

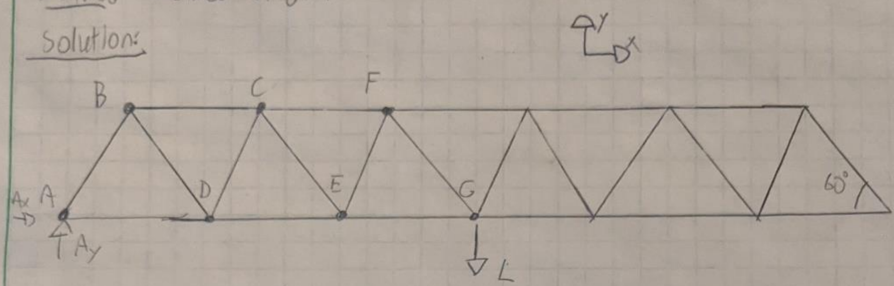
Given: Balsa wood, L = 20 kg

Find: Dimensions of each member

Assumptions: Failure due to direct shear

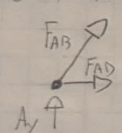
Method: Method of joints

Solution:



$A_y = \frac{1}{2}L = 98.1\,N$

Point A

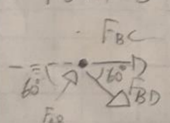


$\Sigma F_y = 0 = A_y + F_{AB}\sin 60° \rightarrow F_{AB} = -\frac{A_y}{\sin 60°} = \frac{98.1N}{\sin 60°} = -113.3\,N$

$\Sigma F_x = 0 = F_{AB}\cos 60° + F_{AD} \rightarrow F_{AD} = -F_{AB}\cos 60° = 56.6\,N$

$F_{AB} = 113.3\,N$ (C)
$F_{AD} = 56.6\,N$ (T)

Point B



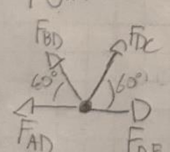
$\Sigma F_y = 0 = F_{AB}\sin 60° - F_{BD}\sin 60° \rightarrow F_{BD} = F_{AD}$

$\Sigma F_x = 0 = F_{AB}\cos 60° + F_{BC} + F_{BD}\cos 60° \rightarrow F_{BC} = 2F_{AD}\cos 30°$

$F_{BC} = -2(113.3\cos 60°) = 113.3\,N$

$F_{BD} = 113.3\,N$ (T)
$F_{BC} = 113.3\,N$ (C)

Point D

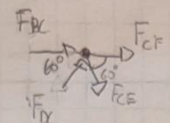


$\Sigma F_y = 0 \quad F_{BD}\sin 60° + F_{DC}\sin 60° \rightarrow F_{DC} = -F_{BC} = -113.3\,N$

$\Sigma F_x = 0 = \sout{F_{BD}\cos 60°} - F_{AD} + \sout{F_{BC}\cos 60°} + F_{DE} \rightarrow F_{AD} = F_{DE} = 56.6\,N$

$F_{DC} = 113.3\,N$ (C)
$F_{DE} = 56.6\,N$ (T)

Point C



$\Sigma F_y = 0 = -F_{DC}\sin 60° - F_{CE}\sin 60° \Rightarrow F_{CE} = -F_{DC} = -113.3\ N$

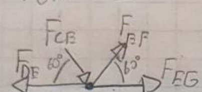
$\Sigma F_x = 0 = F_{CF} + F_{CE}\cos 60° + F_{BC} - F_{DC}\cos 60°$

$F_{CF} = -F_{BC} + F_{DC}\cos 60 - F_{CE}\cos 60° = 113 + 113.3\cos 60° - 113.3\cos 60°$

$F_{CF} = 113.3\ N\ (C)$

$F_{CE} = 113.3\ N\ (T)$
$F_{CF} = 113.3\ N\ (C)$

Point E



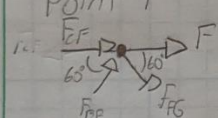
$\Sigma F_y = 0 = F_{EF}\sin 60° - F_{CE}\sin 60° \Rightarrow F_{EF} = 113.3\ N$

$\Sigma F_x = 0 = F_{CE}\cos 60° + F_{EF}\cos 60° + F_{EG} - F_{DE}$

$F_{EG} = -2F_{CE}\cos 60° + F_{DE} = -2(113.3\cos 60°) + 56.6 = 56.6\ N$

$F_{EF} = 113.3\ N\ (C)$
$F_{EG} = 56.6\ N\ (T)$

Point F



$\Sigma F_y = 0 = F_{EF}\sin 60° - F_{FG}\sin 60° \Rightarrow F_{FG} = F_{EF} = 113.3\ N$

$\Sigma F_x = 0 = F_{CF} + F + F_{EF}\cos 60° + F_{FG}\cos 60°$

$F = F_{CF} - 2F_{EF}\cos 60° = -226.6\ N$

$F = -226.6\ N$

$F_{FG} = 113.3\ N\ (T)$
$F = 226.6\ N\ (C)$

4/4

Balsa wood

A safety factor of 5 was applied

$\sigma = F/A$

Tensile strength ultimate axial 7.6 MPa

113.3 N (T) $A = \frac{5 \cdot 113.3N}{7.6 \cdot 10^6 Pa} = 74.54\ mm^2$

56.6 N (T) $A = \frac{5 \cdot 56.6N}{7.6 \cdot 10^6 Pa} = 36.84\ mm^2$

113.3 N (C) $A = \frac{5 \cdot 113.3N}{7.6 \cdot 10^6 Pa} = 74.54\ mm^2$

226.6 N (C) $A = \frac{5 \cdot 226.6N}{7.6 \cdot 10^6 Pa} = 149.08\ mm^2$

Top Beam $A = 149.16\ mm^2$ → 10 mm X 12 mm

Lower Beam $A = 36.84\ mm^2$ → 10 mm X 15 mm See Next sheet

Compression Support $A = 74.5\ mm^2$ → 10 mm X 8 mm

Tension Support $A = 74.5\ mm^2$ → 10 mm X 8 mm

$\sigma_r = 16.6\,MPa$ for bending

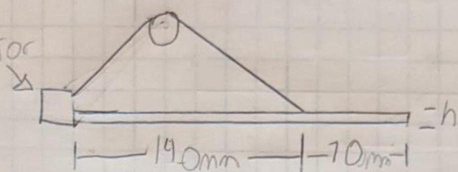
$$\sigma_F = \frac{3FL}{2bd^2} = \frac{3\cdot(9.81 m/s^2)(10\,kg)(408\,mm)}{2(10mm)(15mm)^2} = 26.68\,MPa$$

$\sigma_r < \sigma_F$ there for the dimensions will not fail in bending for the lower beam

Appendix A-2– Articulation Motor Requirements

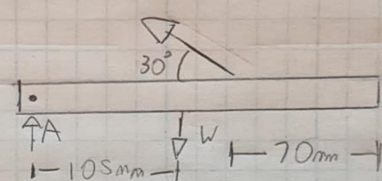
Given: $t = 38mm$
$\rho = 160 kg/m^3$
$h = 1.5mm$

Find: Torque of the motor



Assumptions: The balsa wood is homogenous
Pulley is frictionless
String will not fail
Motor works at constant rate

Solution:



$$W = \rho V g = \rho h t L g = (160 kg/m^3)(1.5 \cdot 10^{-3} m)(38 \cdot 10^{-3} m)(210 \cdot 10^{-3} m)(9.81 m/s^2)$$

$$W = 0.0188 N$$

$$\circlearrowleft + \Sigma M_A = 0 = (140mm)(T)\sin 30° - (105mm)(0.0188 N) \rightarrow T = \frac{(105mm)(0.0188 N)}{(140mm)(\sin 30°)}$$

$$T = 0.02818 N$$

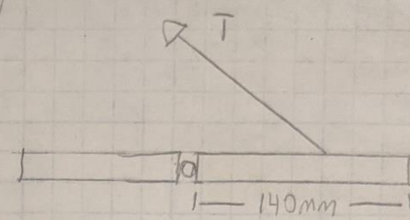
$$Torque = T \cdot r = (0.02818 N)(105 \cdot 10^{-3} m) = 0.00296 Nm$$

Torque = 0.00296 N·m

Appendix A-3 Pivot Pin Diameter

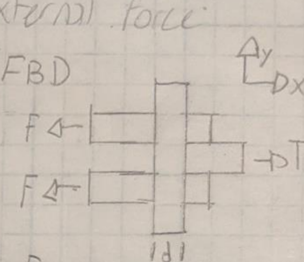
Kyl Engebretson | MET 489 | Analysis 3

Given: Tension in string = 0.02818 N
304 Stainless Steel
Double Shear



Find: Diameter of Pin

Assumptions: Tension in string is only external force



Equations: $\tau = T/A$ $\tau = 0.6\,\sigma_y$

$F = \frac{1}{2} T$

Solution:

$$\tau = F/A \rightarrow 0.6\,\sigma_y = F/A \rightarrow A = \frac{F}{0.6\,\sigma_y}$$

$$A = \frac{\pi}{4} d^2$$

$$\frac{\pi}{4} d^2 = \frac{F}{0.6\,\sigma_y} \rightarrow d = \sqrt{\frac{4F}{0.6\pi\,\sigma_y}} = \sqrt{\frac{(4)(0.1409\,N)}{(0.6\pi)(215\,MPa)}} = 0.0118\,mm$$

$d_{min} = 0.0118\,mm$

A Pin diameter of 2.0mm will be used

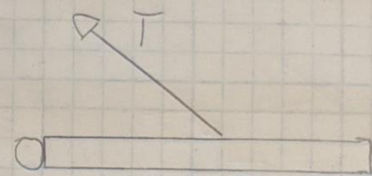
Appendix A-4 Thread Diameter

Kyle Engebretson | MET 489 | Analysis 4

Given: Nylon Thread

$\sigma_y = 40\ MPa$

$T = 0.02818\ N$



Find: Diameter of thread

Assumptions: Homogenous Material

Equations: $\sigma = T/A \qquad A = \pi/4\, d^2$

Solution: $\sigma = T/A \rightarrow A = T/\sigma \rightarrow \pi/4\, d^2 = T/\sigma$

$$d^2 = \frac{4T}{\pi\sigma} \rightarrow d = \sqrt{\frac{4T}{\pi\sigma}} = \sqrt{\frac{4\cdot(0.02818N)}{\pi\,(40\cdot10^6 Pa)}}$$

$d = 0.0299\ mm$

Nylon string #9 will be used which has a diameter of 1.07 mm.

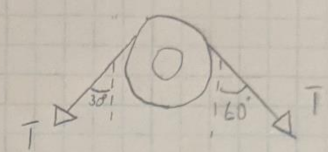
Appendix A-5 Pulley Design

Given: ABS Plastic

$\sigma_{comp} = 65\ MPa$

$T = 0.0282\ N$

$t = 2\ mm$

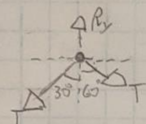


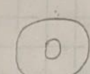
Find: Thickness of the Pulley

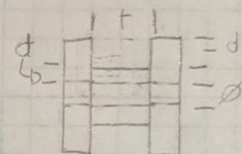
Assumptions: Material is uniform

The forces acting on the pulley can be modeled at a single point

Method: $\sigma_{comp} = \frac{F}{A}$







$\Sigma F_y = 0 \rightarrow R_y - T\cos 30° - T\cos 60°$

$R_y = T\cos 30° + T\cos 60° = 0.0282\,(\cos 30° + \cos 60°)\ N$

$R_y = 0.0385\ N$

$\sigma_{comp} = \frac{F}{A} \rightarrow A = \frac{F}{\sigma_{comp}} \rightarrow dt = \frac{F}{\sigma_{comp}}$

$d = \frac{F}{\sigma_{comp}\, t} = \frac{0.0385\ N}{(65 \cdot 10^{6}\ Pa)(2 \cdot 10^{-3}\ m)} = 0.000296\ mm$

$d = 0.0003\ mm$

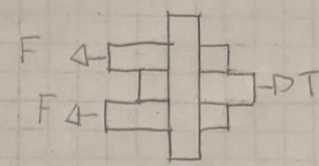
For ease of printing the thickness will be 1.0 mm

Appendix A-6 Bushing Design

Kyle Engebretson | MET 489 | Analysis 6

Given: 304 stainless Steel

Inner diameter = 2 mm

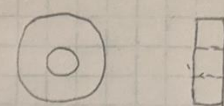


Find: Cross sectional area of bearing

Assumptions: Bearing is frictionless

Bearing will be considered solid for the analysis

Ignore bearing weight



Method: $\sigma = T/A$

Solution:

$$\sigma = T/A \rightarrow A = T/\sigma$$

$$A = \frac{0.0282\ N}{215 \cdot 10^6\ Pa} = 0.000131\ mm^2$$

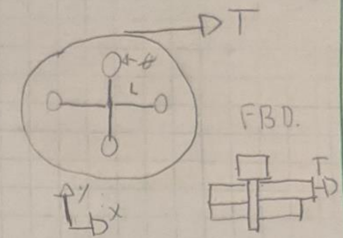
Due to availability the bearing that will be used will have a 2mm inner diameter, 7mm outer diameter, & will be 3.5mm wide

Analysis A-7 Number of Screws

Kyle Engebretson | MET 489 | 10/22/20

Given: L = 6.29 mm   11.85 mm   13.31 mm

ϕ = 0.73 mm



M1 X 12 mm Stainless Steel Screws

Shear modulus = 77.0 GPa

Find: Minimum Number of screws

Assumptions: The diameter used in Area will be 0.75 mm wich is the tap diameter, single shear

Equations: $\tau = \frac{F}{A}$ $F = \frac{T}{n}$

Solution: $\tau = \frac{T}{An} \rightarrow nA\tau = T \rightarrow n = \frac{T}{A\tau}$

$$n = \frac{0.0282N}{\frac{\pi}{4}(0.75 \cdot 10^{-3} m)^2 \cdot (77.0 \cdot 10^9 Pa)} = 9.12 \cdot 10^{-6} \text{ screws}$$

The number of screws used will be 2 to secure the pulley housing to the mounting bracket

Appendix A-8 Motor Shaft

Kyle Engebretson | MET 489 | 10/22/20

Given: $V = 4.8\,V$ minimum

$I = 1.0\,A$ minimum

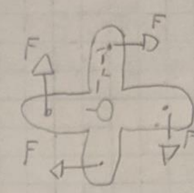
$\omega = 110\,RPM$

$T = 0.0282\,N$

$L = 6.29\,mm$

ABS plastic

shear modulus = 875 MPa

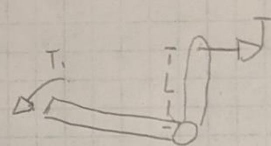


Find: Thickness of the shaft

Assumptions: Mounting bracket can be simplified to a single arm for the calculation

Equations: $P_{wr} = V \cdot I$

$$T_1 = \frac{60 \cdot P_{wr}}{2\pi\, \omega}$$



$$\tau = \frac{Tc}{J}$$

Solution: $P_{wr} = V \cdot I = 4.8\,V \cdot 1.0\,A = 4.8\,W$

$$T_1 = \frac{60 \cdot P_{wr}}{2\pi\, \omega} = \frac{60 \cdot 4.8\,W}{2\pi \cdot 110\,RPM} = 0.4167\,N \cdot m$$

$$T_{net} = T_1 - T \cdot L = 0.4167\,N\cdot m - 0.0282\,N \cdot (6.29 \cdot 10^{-3}\,m)$$

$$T_{net} = 0.4165\,N \cdot m$$

$$\tau = \frac{Tc}{J} \rightarrow \tau = \frac{T\,\frac{D}{2}}{\frac{\pi}{64} \cdot D^4} \rightarrow \frac{\pi}{64} D^3 \tau = T/2 \rightarrow D^3 \frac{\pi}{64} \tau = T/2$$

$$\sqrt[3]{D^3} = \sqrt[3]{\frac{32\,T}{\pi\,\tau}} \rightarrow D = \sqrt[3]{\frac{32 \cdot 0.4165\,N \cdot m}{\pi \cdot 875 \cdot 10^6\,Pa}} = 1.693\,mm$$

The original shaft in the servo motor is a hollow shaft with an outer diameter of 4.52mm & an inner diameter of 1.79mm

$$A = \frac{\pi}{4} D^2$$

$$A_1 = \frac{\pi}{4} (1.693\,mm)^2 = 2.25\,mm^2$$

$$A_2 = \frac{\pi}{4} \left[(4.52\,mm)^2 - (1.79\,mm)^2 \right] = 13.53\,mm^2$$

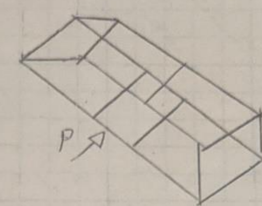
The original shaft will be used

Appendix A-9 Number of cross beams

Kyle Engebretson | MET 439 | 10/28/20

Given: Balsa Wood side Loading of 10 kg
$\sigma = 7.6\,MPa$ $SF = 4$

Find: cross section of cross beams

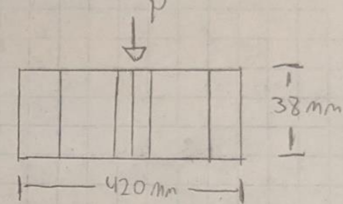


Assumptions: No Flaws in wood

Forces acting through each beam will be the same to make the problem solvable

Method: $n\sigma = \frac{F}{A}$

Solution:



# of beams = 7

$$n\sigma = \frac{F}{A} \rightarrow A = \frac{F}{n\sigma} \rightarrow A = \frac{P \cdot g}{n\sigma} = \frac{4(10\,kg)(9.81\,m/s^2)}{7(7.6 \cdot 10^6\,Pa)}$$

$$A = 7.376\,mm^2$$

1/8 inch square balsa wood sticks will be used the cross sectional Area of these sticks is $10.08\,mm^2$

Appendix A-10 Thickness of road

Kyle Engebretson | MET 489 | 10/30/20

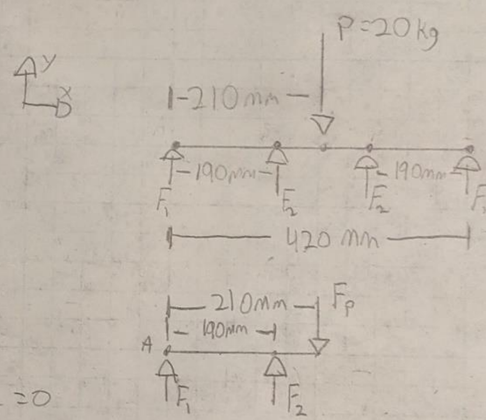
Given: Balsa wood $\sigma = 1.0\,MPa$ Perpendicular to grain

Load is 20 kg

Find: thickness of road

Assumptions: Distributed load by the plate put onto the road can be modeled as point load

Method: $\Sigma M = 0$ $\Sigma F_y = 0$ $\sigma = F/A$



Solution:

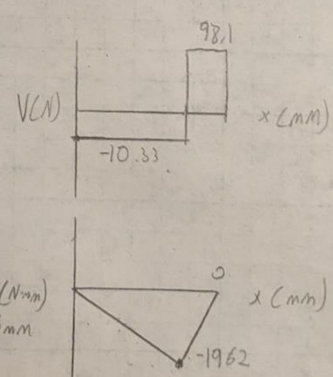
$F_p = \frac{1}{2}P \cdot g = 98.1\,N$

$\circlearrowleft + \Sigma M_A = 210\,mm\,F_p - 190\,mm\,F_2 = 0$

$F_2 = \frac{210}{190} F_p = 108.43\,N$

$\Sigma F_y = 0 = F_1 + F_2 - F_p \rightarrow F_1 = F_p - F_2$

$F_1 = (98.1 - 108.43)\,N = -10.33\,N$



$\sigma = F/A \rightarrow A = \frac{F}{\sigma} \rightarrow wt = \frac{F}{\sigma}$

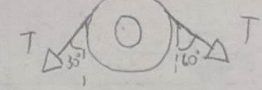
$t = \frac{F}{w\sigma} \rightarrow \frac{98.1\,N}{(38 \cdot 10^{-3}\,m)(1 \cdot 10^{6}\,Pa)} = 0.0026\,mm$

Sheet with thickness of 1mm will be used for the roadway

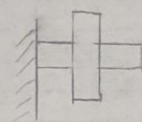
Appendix A-11 Thickness of pulley rod mount

Kyle Engebretson | MET 489 | 11/5/20

Given: stainless steel
Tension in string = 0.02818 N
single shear



Find: Diameter of pin



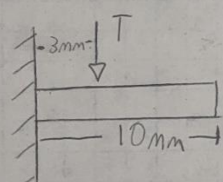
Assumptions Force due to tension on pulley can be modeled as a point load

Method:

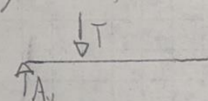
$$\sigma = \frac{F}{A}$$

Solution:

$$F = T\cos 30^\circ + T\cos 60^\circ = T = 0.2818$$



$$\Sigma F_y = 0 = A_y - T \rightarrow A_y = T$$



$$\sigma = \frac{T}{A} \rightarrow A = \frac{T}{\sigma} \rightarrow \frac{\pi}{4}D^2 = T/\sigma \rightarrow D = \sqrt{\frac{4T}{\pi\sigma}}$$

$$D = \sqrt{\frac{(4)(0.02818N)}{\pi \cdot (215 \cdot 10^6 Pa)}} = 0.167 \cdot 10^{-6}\ mm$$

Pin size of 2mm will be used consistencey of other stainless steel rods.

Appendix A-12 Strength of Glue

Given: $F = 226.6\ N$ (c)

Find: Type of glue to use at joints

Assumptions: Calculations will be based off the largest force in a member of the truss

wood members don't fail under this loading

thickness of glue is negligible

Method: $\sigma = F/A$

Solution:

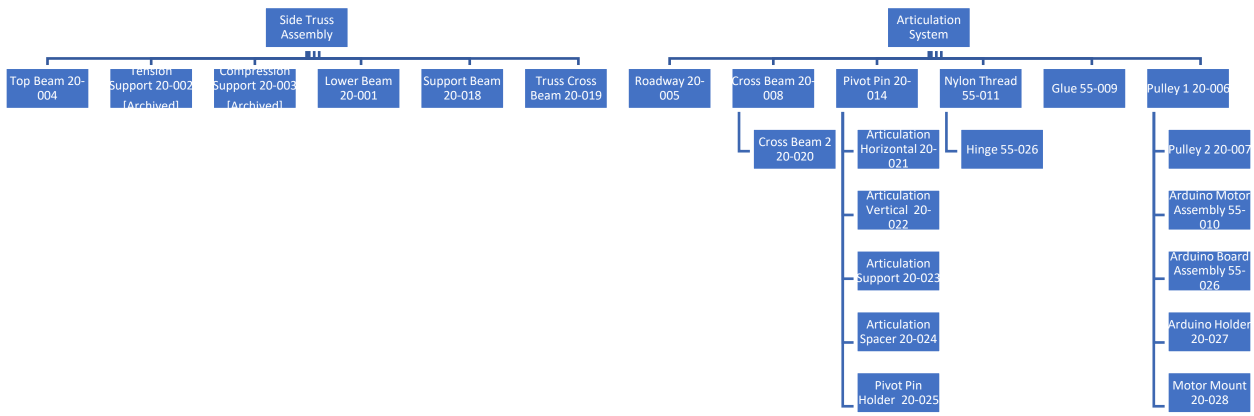
$$\sigma = F/A = \frac{226.6\ N}{10mm \times 15mm} = 1.51\ MPa$$

The average strength of superglue is approximately 24 mPa which is signifigantly higher than the calculated value. Elmer's super glue will be used in the joints.

APPENDIX B - Drawings

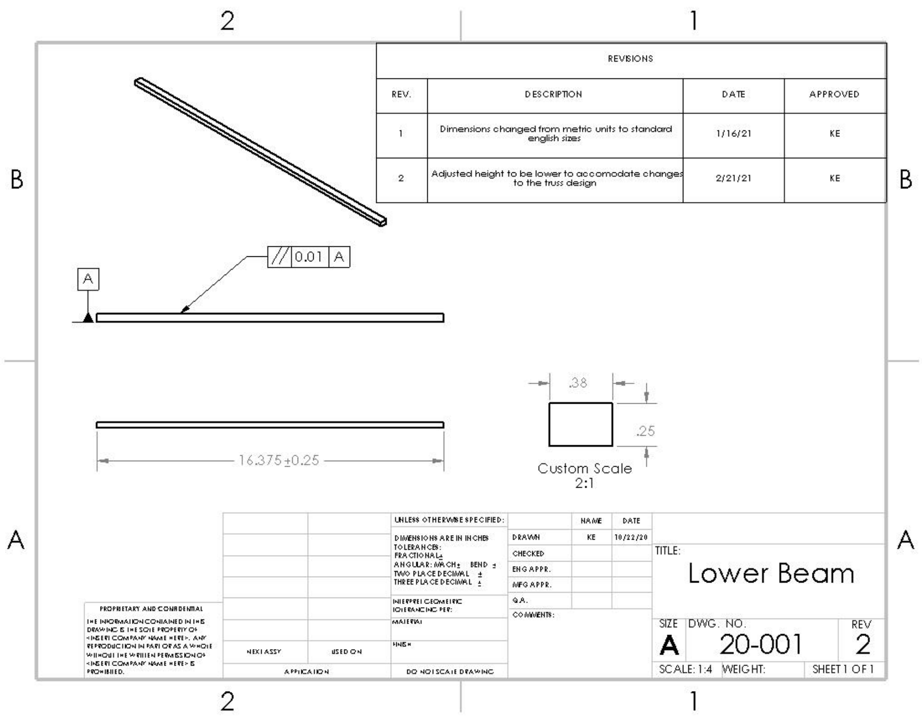
Drawing Tree

Diagram showing the parts that are included in the design of the bridge, and groups them based off of their function.



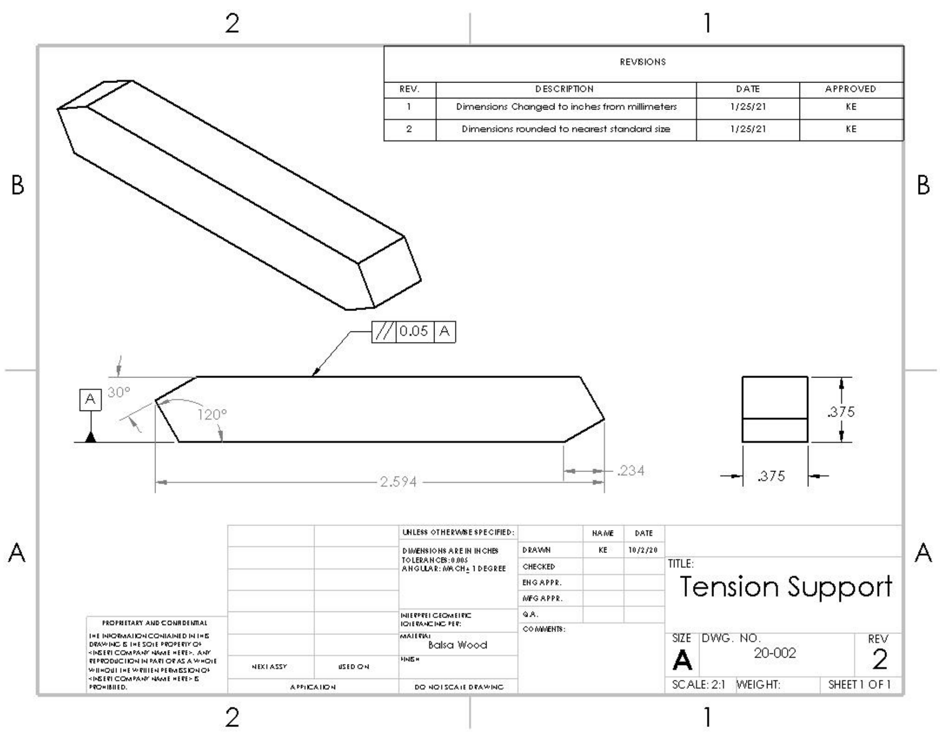
25-001 Lower Beam

This drawing is for the lower support beam that will span the length of the bridge. The analysis for this member can be seen in appendix A-1 as one of the cross-sections calculated. The design was altered to reduce the height of the beam, but in combination with the 20-019 truss cross beam the net cross sectional area is the same.



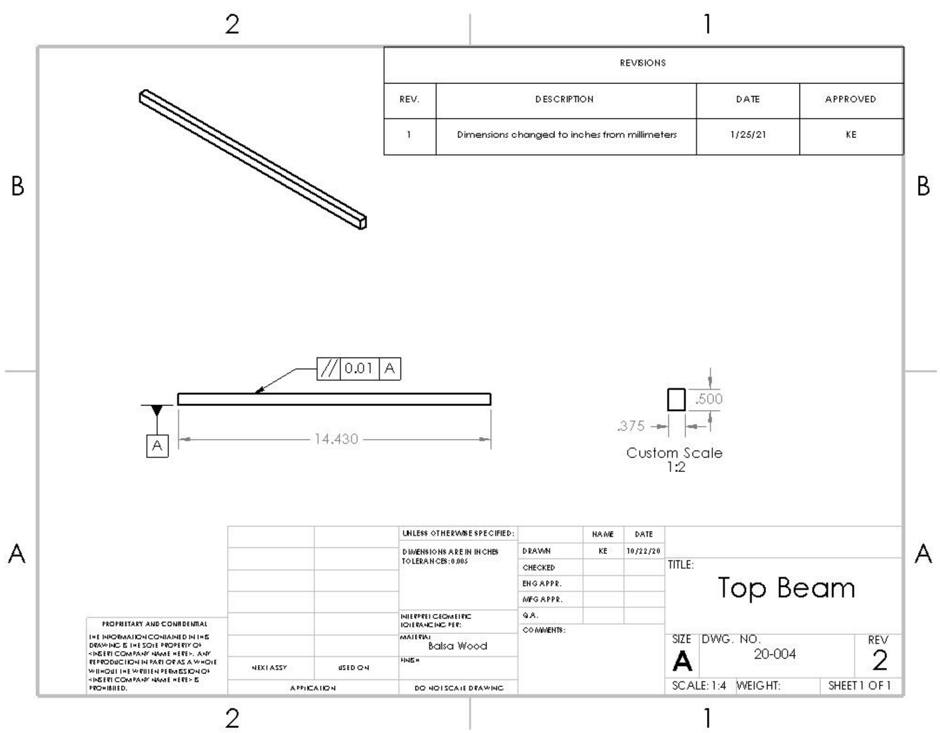
20-002 Tension Support

This is the drawing for the tension support of the bridge truss. The calculations to design for the cross section of this part can be seen in appendix A-1. This part was archived during the manufacturing process due to issues related to tolerancing. It was replaced with part number 20-018.



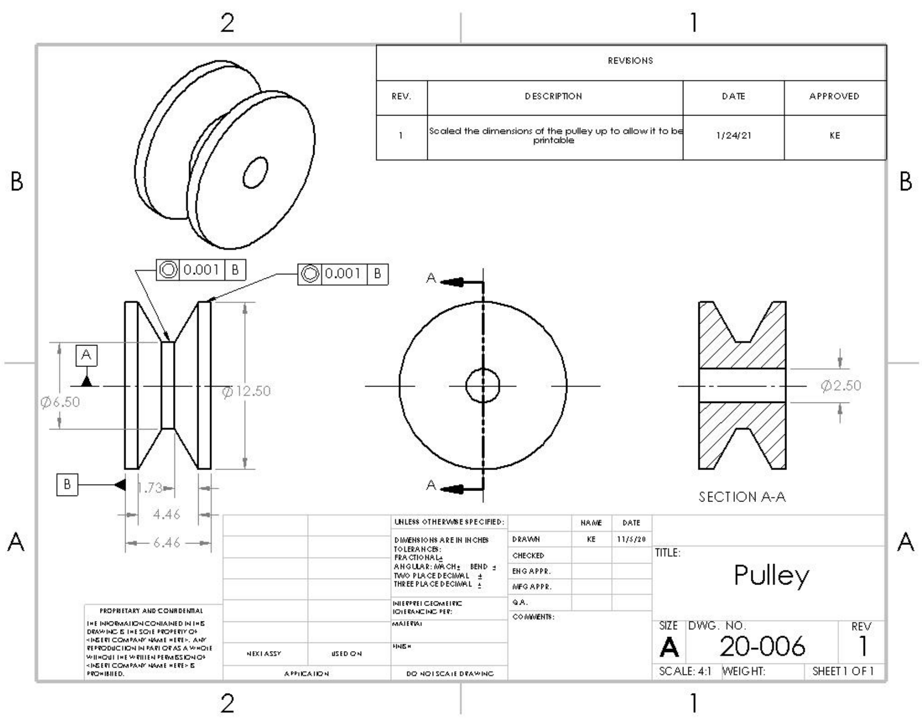
20-004 Top Beam

This is the drawing for the top beam that will span the upper portion of the bridge truss. The calculations used to find the dimensions of the cross-sectional area can be seen in appendix A-1. The part had two changes made to it during the manufacturing phase of the project. The dimensions were changed to English units to make the material easier to obtain and the height was reduced to compensate for changes made elsewhere in the design.



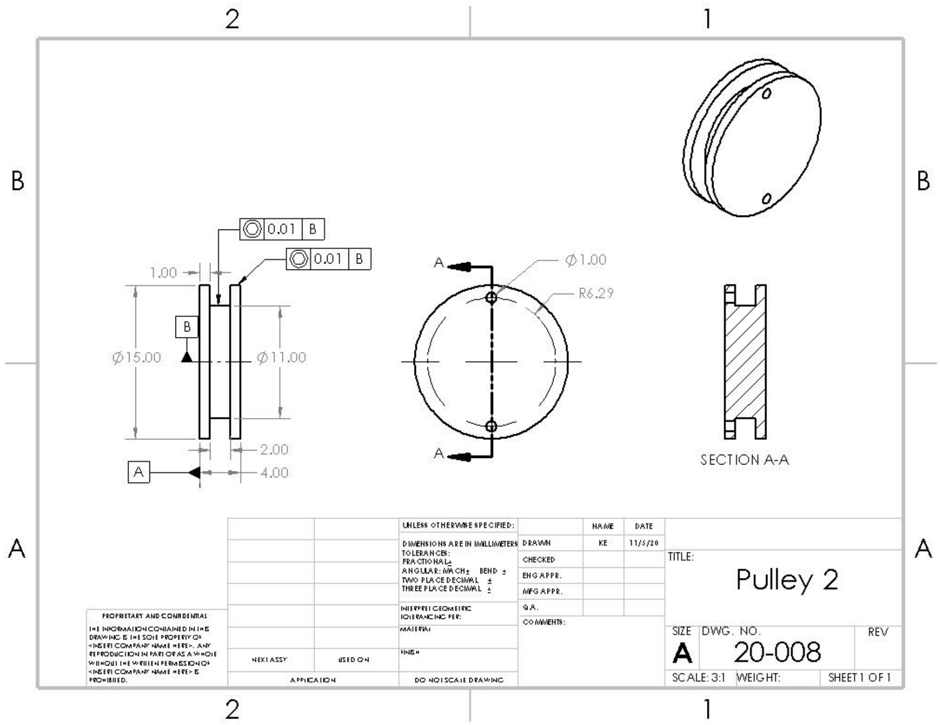
20-006 Pulley 1

This drawing shows the pulley that will be used in the articulation of the bridge. The pulley will be connected to the upper beam of the bridge truss, the calculations for this parts dimensions can be seen in appendix A-5. The dimension were changed to allow the part to be manufactured by the 3D printer that was available.



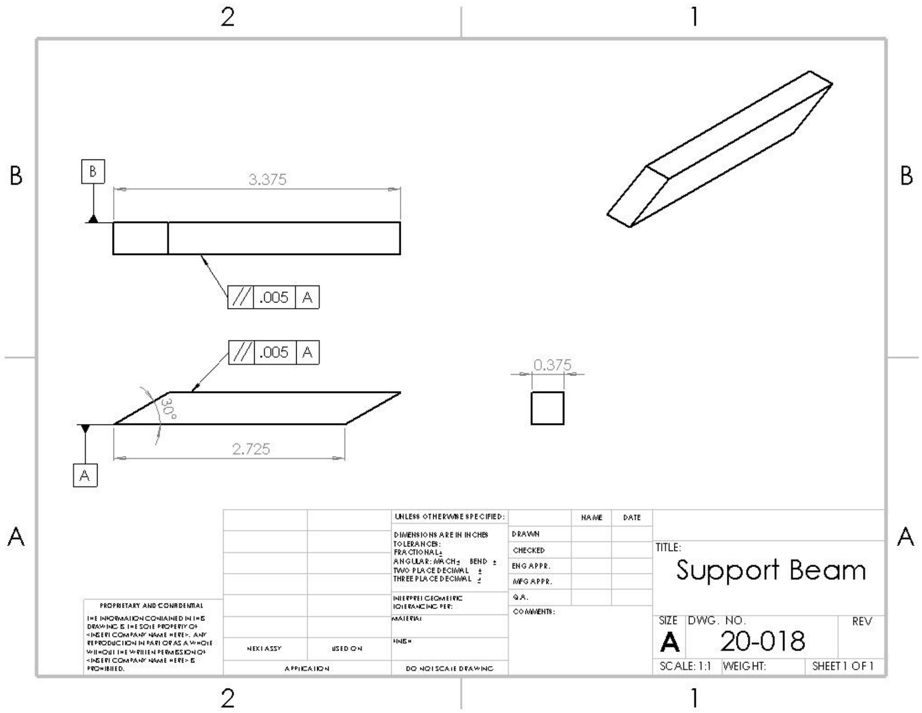
20-008 Pulley 2

This drawing represents the pulley that will be mounted to the Arduino motor and will act as wrap the nylon thread as the roadway is raised. The calculations for some of the dimensions of this drawing can be seen in appendix A-7 and A-5.



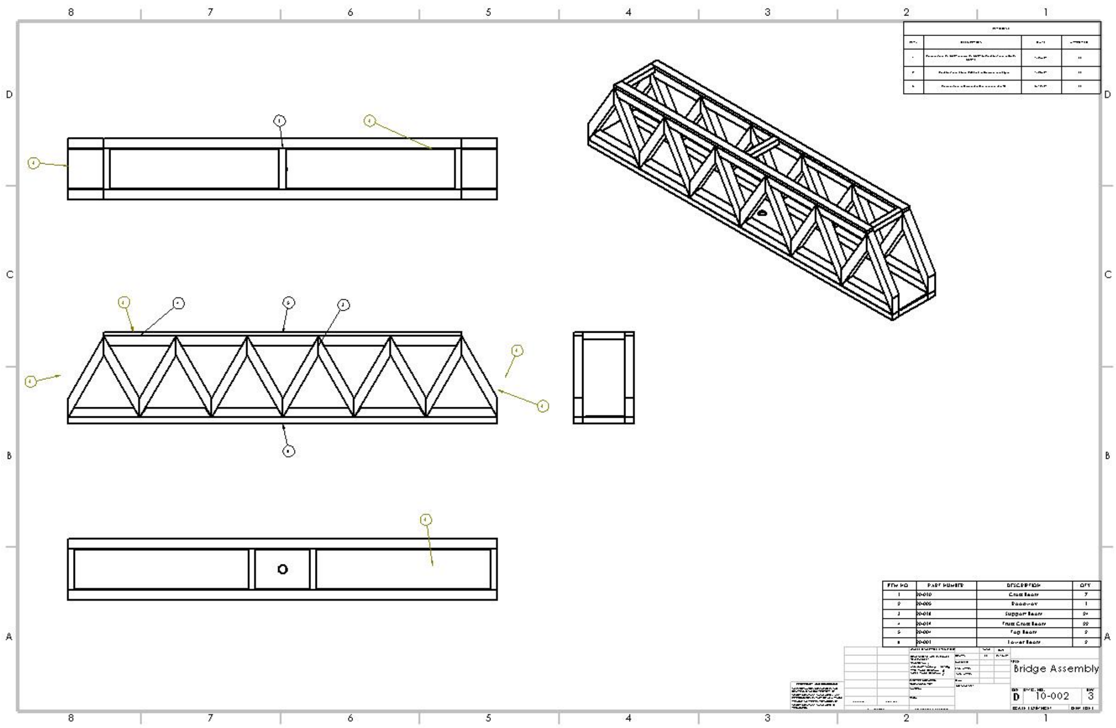
20-017 Support Beam

This is the drawing for the updated member that was used in the bulk of the truss design for the project. This piece replaced all of the existing tension and compression members in the design.



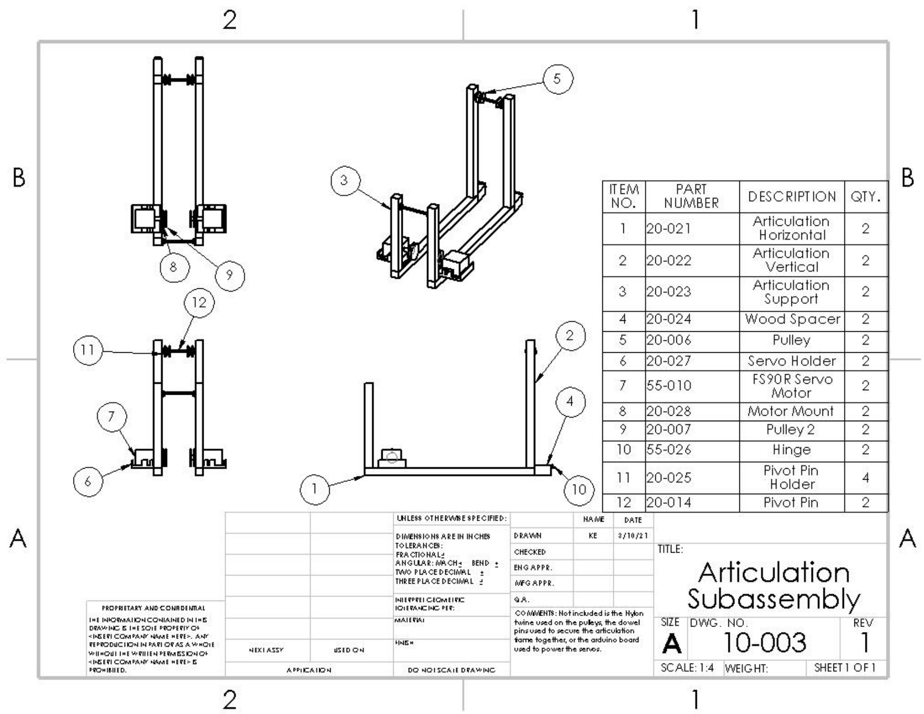
10-002 Bridge Assembly

This drawing is the complete assembly of the bridge. The design underwent several changes during the manufacturing process making this the third revised design.



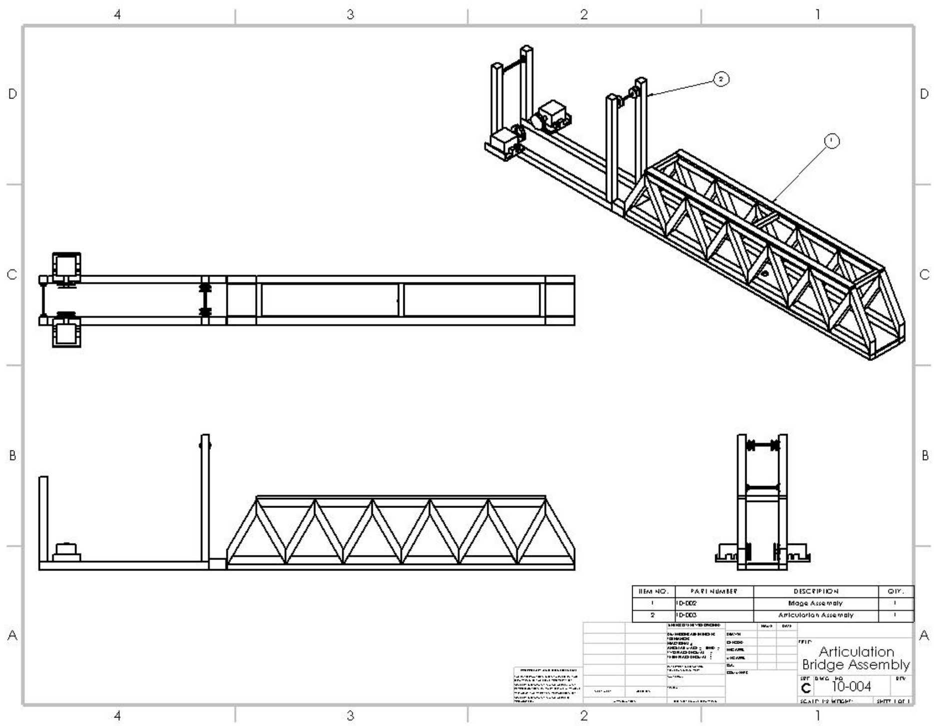
10-003 Articulation Assembly

The drawing below is the articulation system that was designed near the end of the manufacturing phase of the project. The previous design had the articulation system combined within the bridge itself but was altered to fit the intentions of the project parameters.



10-004 Bridge Articulation Assembly

This drawing shows the final iteration of the bridge design with the articulation system. The Arduino board that is used to power the servo motors was not included in the drawing as well as the twine that used to raise the bridge.



Arduino Board Code

```
#include <Servo.h> //Include the code library specific to the servos

Servo myservo1; //Declaring the servos as items for the board
Servo myservo2;

const int Green = 2; //Dessignate the green button as pin 2
const int Red = 4; //Designate the red button as pin 4

int buttonStateRed = 0; // Set the buttons to have no default value
int buttonStateGreen = 0;

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600); // Activate the sevo library
myservo1.attach(10);
myservo2.attach(12);

pinMode(Green, INPUT_PULLUP); //Designate the buttons as input paramters
pinMode(Red, INPUT_PULLUP);
}// end setup
void loop() {
  // put your main code here, to run repeatedly:
buttonStateRed = digitalRead(Red); //Create a variable to read the state of the buttons
buttonStateGreen = digitalRead(Green);

if (buttonStateRed == LOW) // When the red button is pressed
{
  myservo1.writeMicroseconds(1250); //Rotate servo 1 clockwise
  myservo2.writeMicroseconds(1650); //Rotate servo 2 counterclockwise
}
else if (buttonStateGreen == LOW)
{
  myservo1.writeMicroseconds(1650); //Rotate servo 1 counterclockwise
  myservo2.writeMicroseconds(1250); //Rotate servo 2 clockwise
}
else
{
  myservo1.writeMicroseconds(1450); //Servos will not rotate when neither button is pressed
    myservo2.writeMicroseconds(1425);
    //myservo1.detach(10);
   // myservo2.detach(12);
}// end if statement
}// end code
```

APPENDIX C – Parts List and Costs

Item	Qty	Description	Cost	Source
20-001	2	Lower Beam	$2.10/per	ACE Hardware
20-002	12	Tension Member	$1.50/per	ACE Hardware
20-003	12	Compression Member	$1.50/per	ACE Hardware
20-004	2	Top Beam	$2.10/per	ACE Hardware
20-005	2	Roadway	$1.20/per	ACE Hardware
20-006	2	Pulley 1	$0.15/per	CWU
20-007	2	Pulley 2	$0.15/per	CWU
22-008	7	Cross Beam	$0.30/per	ACE Hardware
55-009	1	Glue	$10	Amazon
55-010	2	SG90 Servo Motor	$12/per	Amazon
55-011	2	Nylon Twine	$8	Amazon
55-012	2	Motor Mount	$0.15/per	Amazon
55-013	2	Stainless Steel Bearing	$9/per	Bearings Direct
55-014	4	Stainless Steel Rod	$5/per	Simply Bearings

APPENDIX D – Budget

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The lines of the table marked in red were removed from the project but were included in the initial design of the bridge. The parts included that do not have an expected cost associated with the were added to the project after during the manufacturing process, thus they were not accounted for in the initial budget.

Project Budget for Materials

Item	Qty	Description	ected Cost Per	Actual Cost Per Part	Total Cost	Source
20-001	2	Lower Beam	$2.10/per	$1.00/per	$ 2.00	Hobby Town
20-002	12	Tension Member	$1.50/per	$0.20/per	$ 2.40	Hobby Town
20-003	12	Compression Member	$1.50/per	$0.20/per	$ 2.40	Hobby Town
20-004	2	Top Beam	$2.10/per	$1.00/per	$ 2.00	Hobby Town
20-005	1	Roadway	$1.20/per	$ 2.00	$ 2.00	Hobby Town
20-006	2	Pulley 1	$0.15/per	$ -	$ -	3D Printed
20-007	2	Pulley 2	$0.15/per	$ -	$ -	3D Printed
22-008	7	Cross Beam	$0.30/per	$0.05/per	$ 0.35	Hobby Town
55-009	1	Glue	$ 10.00	$ -	$ -	Donated
55-010	2	FS90R Servo Motor	$12/per	$6.00/per	$ 12.00	Amazon
55-011	2	Nylon Twine	$ 8.00	$ 8.00	$ 8.00	Amazon
55-012	2	Motor Mount	$0.15/per	Included with Servo	$ -	3D Printed
55-013	2	Stainless Steel Bearing	$9/per	$ -	$ -	Not Purchased
20-014	4	Pivot Pin	$5/per	$5.00/per	$ 5.00	Amazon
20-018	24	Support Beam	$ -	$0.15/per	$ 3.60	Hobby Town
20-019	22	Truss Cross Beam	$ -	$0.15/per	$ 3.30	Hobby Town
20-020	2	Cross Beam 2	$ -	$0.05/per	$ 0.10	Hobby Town
20-021	2	Articulation Horizontal	$ -	$5.00/per	$ 10.00	Tacoma Screw
20-022	2	Articulation Vertical	$ -	$5.00/per	$ 10.00	Tacoma Screw
20-023	2	Articulation Support	$ -	$5.00/per	$ 10.00	Tacoma Screw
20-024	2	Articulation Spacer	$ -	$0.10/per	$ 0.20	Hobby Town
20-025	4	Pivot Pin Holder	$ -	$ -	$ -	3D Printed
55-026	1	Arduino Board	$ -	$ -	$ -	3D Printed
20-027	2	Arduino Motor Holder	$ -	$ -	$ -	3D Printed
20-028	2	Motor Mount	$ -	$ -	$ -	3D Printed
20-029	2	Hinge	$5.00/per	$5.00/per	$ 10.00	Amazon
		Total Expected	$ 128.60	Total Spent	$ 83.35	

APPENDIX E - Schedule

SCHEDULE FOR SENIOR PROJECT

PROJECT TITLE: Balsa Bridge
Principal Investigator.: Kyle Engebretson

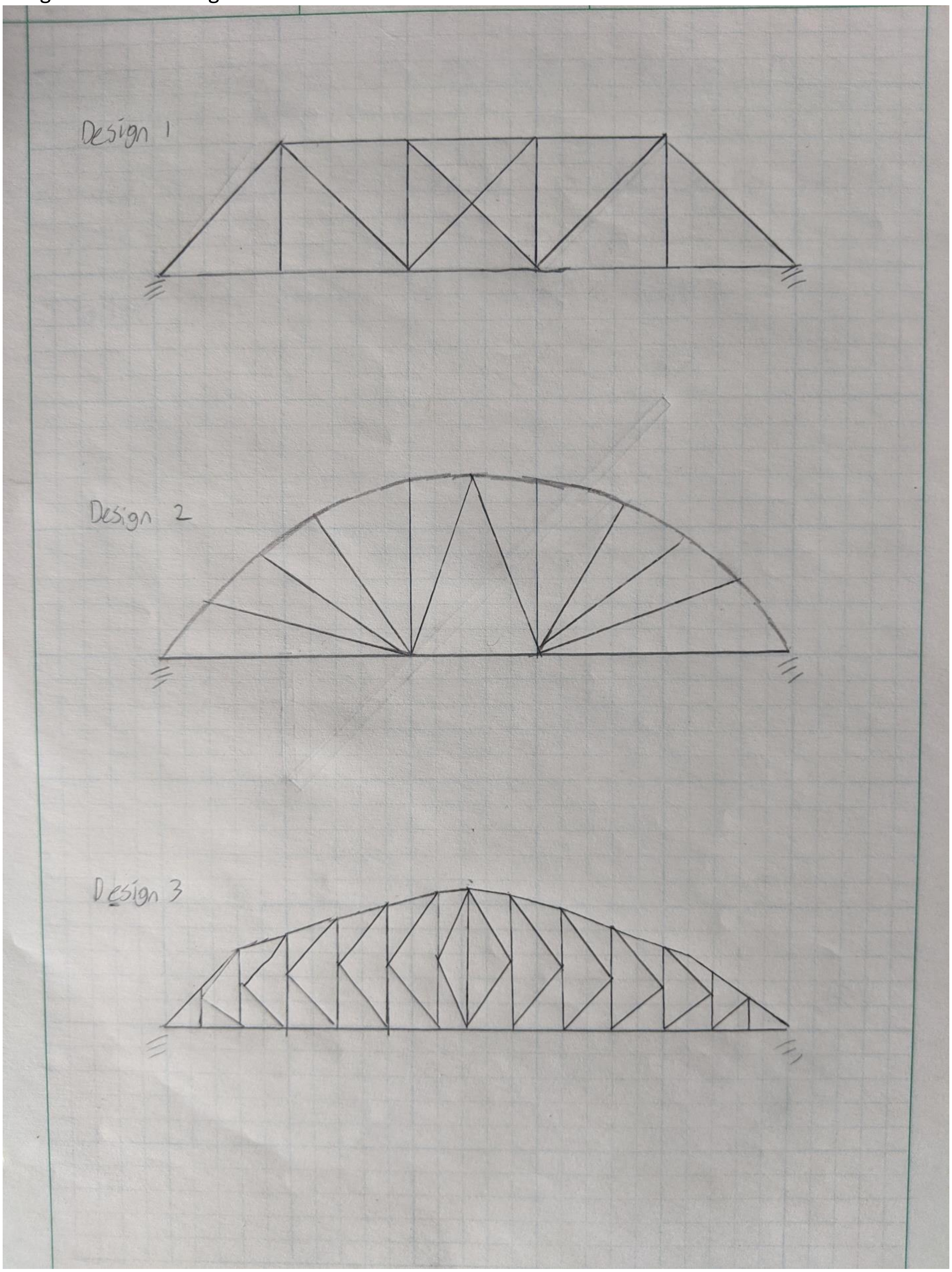
TASK: ID	Description	Duration Est. (hrs)	Actua (hrs)	%Com	Septembe	October	November	Dec.	January	February	March	April	May	June
1	Proposal*													
1a	Outline	2	3											
1b	Intro	1	1											
1c	Analysis	2	3											
1d	Parts and Budget	3	4											
1e	Drawings	1	1											
1f	Schedule	2	2											
1g	Website intro	2	2											
1h	Website population	2	3											
1i	Website Analysis	2	2											
1j	Website Schedule	1	1											
1k	Website Budget	1	2											
1l	Testing Section	3	4											
1m	Website Testing	2	2											
1n	Methods	1	2											
1o	Construction	2	3											
1p	Project Management	2	2											
1q	Conclusion	2	2											
1r	Acknowledgements	1	1											
1s	References	1	1											
	subtotal:	33	41											
2	Analyses													
2a	Internal Forces	2	4											
2b	Articulation Analysis	2	2											
2c	Pivot Pin	1	2											
2d	Articulation String	1	3											
2e	Pulley Dimensions	1	1											
2f	Bearing Thickness	1	1											
2g	Number of Screws	2	3											
2h	Motor Shaft Diameter	2	2											
2i	Cross Beam Thickness	2	2											
2j	Roadway Thickness	2	2											
2k	Pulley Shaft	1	2											
2l	Glue Requirements	1	2											
	subtotal:	18	26											
3	Documentation													
3a	Part 1 Lower Beam Drawing	1	1											
3b	Part 2 Tension Support Drawing	1	3											
3c	Part 3 Upper Beam Drawing	1	1											
3d	Part 4 Pulley	2	2											
3e	Part 5 Pulley 2	2	3											
3f	Bridge Assembly	2	2											
	subtotal:	9	12											
4	Proposal Mods													
4a	Dimmension Changes	4	4											
4b	Methods Changes	1	1											
4c	Construction changes	1	1											
4d	Discusion Changes	2	2											
4e	Website Changes 1	4	4											
4f	Schedule Changes	1	1											
4g	Adjustments to part design	4	6											
4h	Drawing Updates	3	3											
4i	Budget Changes 1	2	2											
4j	Construction 2 Changes	2	2											
4k	Methods 2 Changes	2	2											
4l	Website Changes 2	8	10											
4m	Testing Changes 1	1	1											
4n	Discusion Changes 2	2	2											
4o	Abstract Draft	3	3											
4p	Website Changes 3	5	5											
4q	Testing Changes 2	3	3											
4r	Discussion 3	1	1											
4s	Testing Changes 3	2	2											
4t	Discussion Changes 4	2	2											
4u	Website Changes 4	3	3											
4v	Schedule Changes	2	2											
4w	Budget Changes 2	2	2											
	subtotal:	53	57											
5	Part Construction													
5a	20-001 Lower Beam x 2	1	1											
5b	20-004 Upper Beam x 2	1	1											
5c	20-002 Compression Support x 12	6	7											
5d	20-003 Tension Support x 12	5	7											
5e	20-014 Steel Rod	1	1											
5f	20-008 Cross Beam	2	1											
5g	20-005 Roadway x 2	1	1											
5h	20-002 Support Redesign	6	6											
5i	20-006 Pulley x2	2	2											
5j	20-018 Support Beam x 24	4	4											
5k	20-019 Truss Cross Beam x 22	4	4											
5l	20-007 Pulley 2 x2	2	2											
5m	20-020 Cross Beam 2 x2	1	1											
5n	20-021 Articulation Horizontal x2	3	3											
5o	20-022 Articulation Vertical x2	3	3											
5p	20-023 Articulation Support x2	3	3											
5q	20-024 Articulation Spacer x2	1	1											
5r	20-025 Pivot Pin Holder x4	1	1											
5s	20-027 Motor Mount x2	3	3											
	subtotal:	50	52											
6	Device Construct													
6a	Side Truss 1	7	7											
6b	Side Truss 2	7	7											
6c	Bridge Frame	4	4											
6d	Arduino Circuit	6	6											
6e	Articulation Assembly	4	4											
	subtotal:	28	28											
10	Device Evaluation													
10a	Articulation Testing Procedure	3	3											
10b	Articulation Testing	1	1											
10c	Roadway Clearance Procedure	3	3											
10d	Roadway Clearance Test	1	1											
10e	General Testing Procedure	2	2											
10f	General Testing	1	1											
10g	Weight Testing Procedure	2	2											
10h	Weight Testing	1	1											
10i	Testing Demonstration	3	3											
	subtotal:	17	17											
11	489 Deliverables													
11a	Articulation Testing Results	1	2											
11b	Poster Draft	3	3											
11c	Poster Presentation/Revisions	4	4											
11d	Testing Results	6	6											
11e	Website Presentation Script	4	4											
11f	Website Presentation	3	3											
11g	JumpDrive	4	4											
	subtotal:	25	26											
	Total Est. Hours=	233	259											

APPENDIX F – Expertise and Resources

Table F-1 Decision Matrix

Criterion	Weight	Best Possible	Design #		Design #		Design #	
	1 to 3	3	1	Score x Wt	2	Score x Wt	2	Score x Wt
Cost	3	9	2	6	2	6	2	6
Weight	3	9	3	9	1	3	2	6
Difficulty to build	3	9	3	9	1	3	2	6
Asthetics	1	3	2	2	3	3	2	2
Modularity	2	6	3	6	1	2	3	6
Total	12	36		32		17		26
NORMALIZE THE DATA (muliply by fraction, N)		2.78		88.89		47.22	72.22	Percent
							69.44	Average
							20.97	Std Dev.

Image F-2 Initial Designs



APPENDIX G – Testing Report

Test Report 1 System Articulation

This procedure is a record of the testing trial, recording, and data collection that occurs to verify articulation system of the balsa wood bridge is operating as intended. The testing occurred on Saturday April 3rd, 2021 from 1:00 PM to 1:45 PM in the home of the principal designer of the project. Fifteen minutes was allotted for the set up of testing equipment, fifteen minutes for the testing process and data collection, and the final fifteen minutes were used for cleaning the work area and storing the bridge assembly.

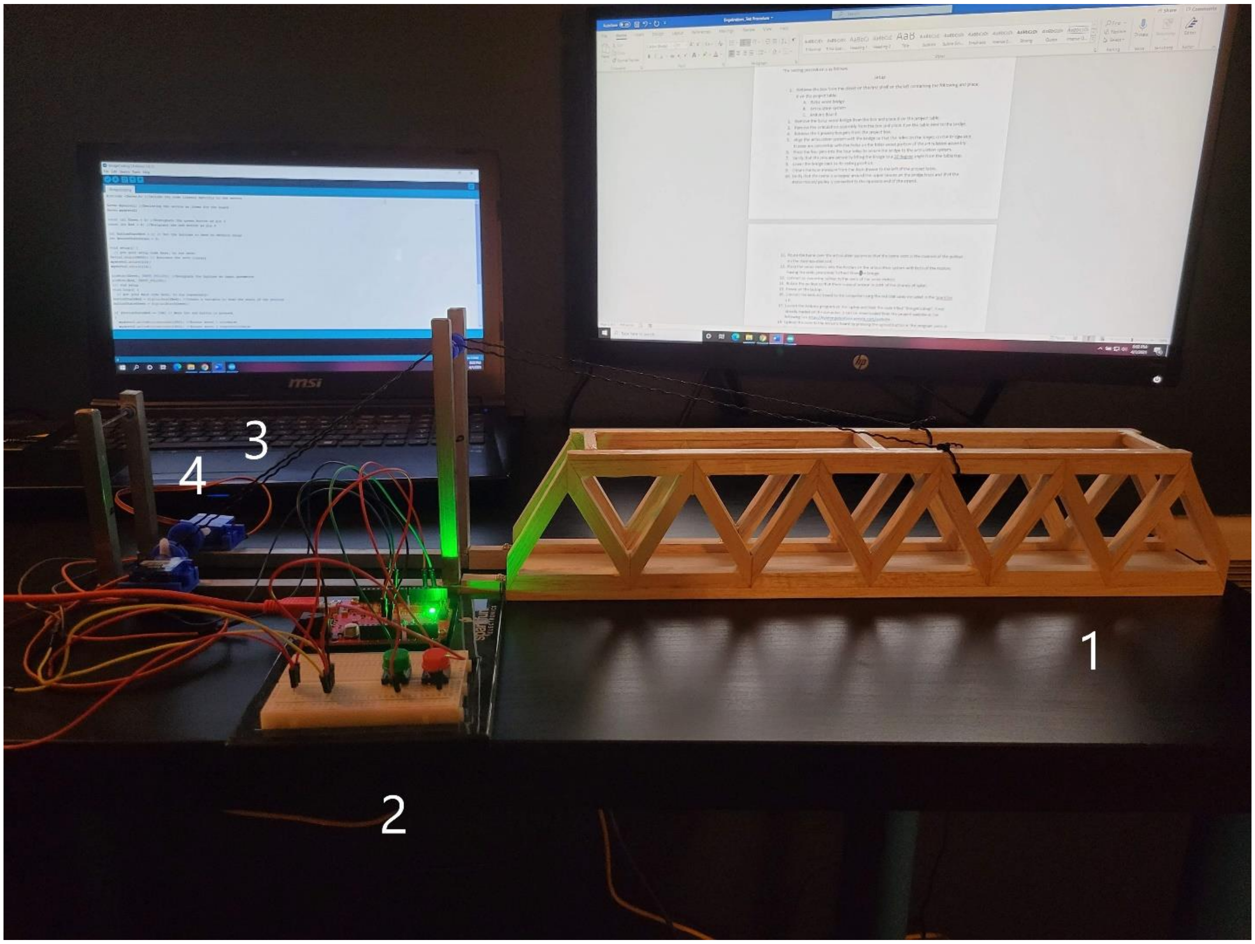
Required Equipment includes:

- Sparkfun Arduino Kit
- 6 male-female pin connection wires
- 12 male-male pin connection wires
- Cellphone with video recording capabilities
- 2 FS90R continuous servo motors
- Table
- Tape measure
- Laptop with Arduino software installed
- Balsa wood bridge with articulation system
- 4 jewelry box pins
- 2 20-inch-long strands of nylon twine size 9

Risk:

The risks associated with the testing procedure are minimal due to the nature of the test being performed. Personal protective equipment was not required for the duration of the test. The primary risks come from damaging the project equipment by not following the testing procedure. No additional personnel are needed for the testing beyond the individual, though they could be on hand as observers or help to film the test.

Figure 1: The whole bridge assembly. 1 is the balsa wood bridge, 2 is the Arduino board, 3 is the articulation system, ad 4 is the servo motors.

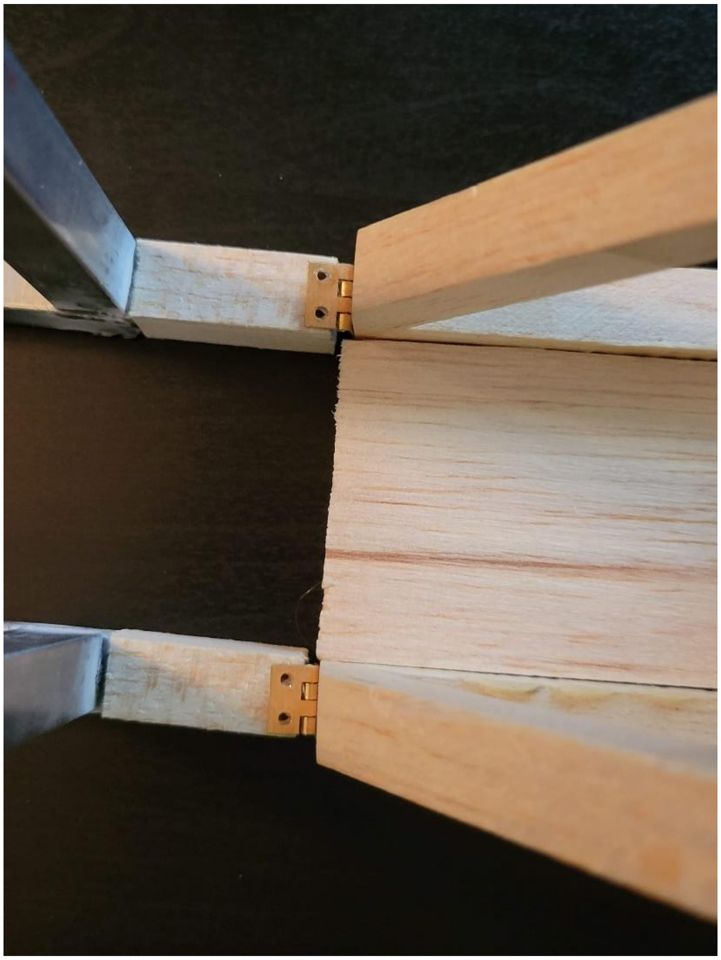


The testing procedure is as follows:

Setup

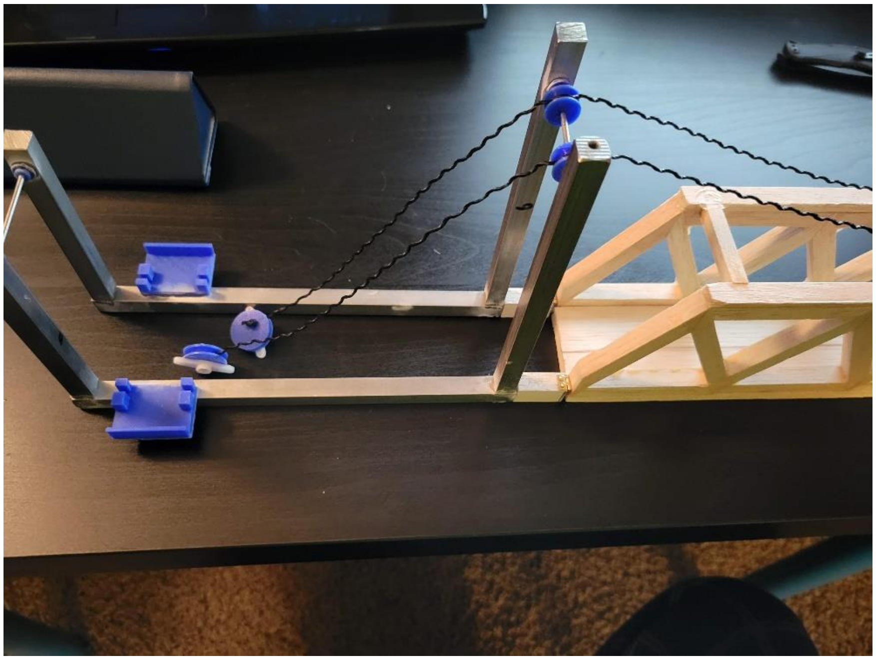
1. Retrieve the box from the closet on the first shelf on the left containing the following and place it on the project table.
    A. Balsa wood bridge
    B. Articulation system
    C. Arduino Board
2. Remove the balsa wood bridge from the box and place it on the project table.
3. Remove the articulation assembly from the box and place it on the table near to the bridge.
4. Retrieve the 4 jewelry box pins from the project box.
5. Align the articulation system with the bridge so that the holes on the hinges on the bridge side trusses are concentric with the holes on the balsa wood portion of the articulation assembly as seen in the figure below.

Figure 2: Hole alignment for hinges and jewelry pins.



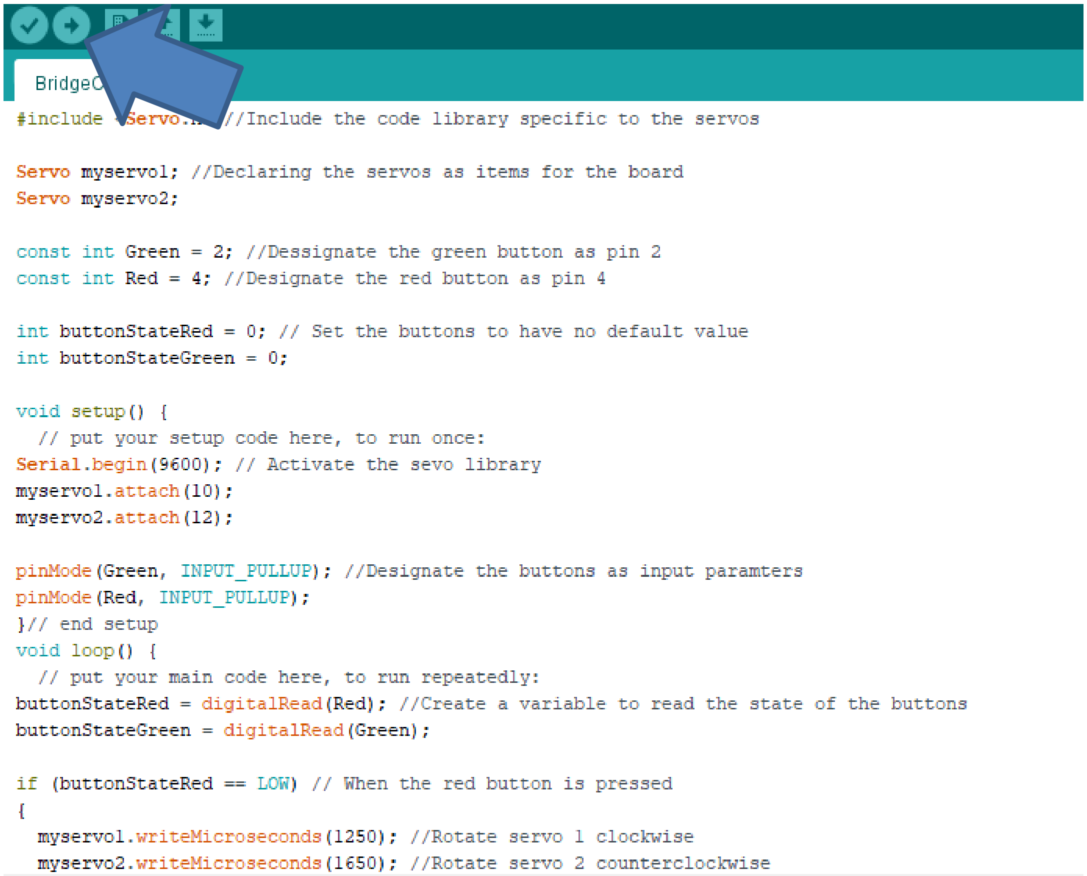
6. Press the four pins into the four holes to secure the bridge to the articulation system.
7. Verify that the pins are secure by lifting the bridge to a 30-degree angle from the table top.
8. Lower the bridge back to its resting position.
9. Obtain the tape measure from the desk drawer to the left of the project table.
10. Verify that the twine is wrapped around the upper beams on the bridge truss and that the motor mount/ pulley is connected to the opposite end of the strand.
11. Route the twine over the articulation system so that the twine rests in the channel of the pulleys on the stainless-steel rod as seen I figure 3.

Figure 3: Image shows how the nylon strands should be routed over the pulleys.



12. Place the servo motors into the holders on the articulation system with both of the motors having the axels positioned furthest from the bridge.
13. Connect to mounting pulleys to the axels of the servo motors.
14. Rotate the pulleys so that there is equal tension in both of the strands of nylon.
15. Power on the laptop.
16. Connect the Arduino board to the computer using the red USB cable included in the Sparkfun kit.
17. Launch the Arduino program on the laptop and load the code titled “BridgeCoding”. If not already loaded on the computer, it can be downloaded from the project website at the following link https://kyletengebretson.wixsite.com/website.

Figure 4: Code for the Arduino board



```
#include <Servo.h> //Include the code library specific to the servos

Servo myservo1; //Declaring the servos as items for the board
Servo myservo2;

const int Green = 2; //Dessignate the green button as pin 2
const int Red = 4; //Designate the red button as pin 4

int buttonStateRed = 0; // Set the buttons to have no default value
int buttonStateGreen = 0;

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600); // Activate the sevo library
myservo1.attach(10);
myservo2.attach(12);

pinMode(Green, INPUT_PULLUP); //Designate the buttons as input paramters
pinMode(Red, INPUT_PULLUP);
}// end setup
void loop() {
  // put your main code here, to run repeatedly:
buttonStateRed = digitalRead(Red); //Create a variable to read the state of the buttons
buttonStateGreen = digitalRead(Green);

if (buttonStateRed == LOW) // When the red button is pressed
{
  myservo1.writeMicroseconds(1250); //Rotate servo 1 clockwise
  myservo2.writeMicroseconds(1650); //Rotate servo 2 counterclockwise
```

18. Upload the code to the Arduino board by pressing the upload button in the program seen in figure 2.
    Figure 4: Code for the Arduino board
19. If the code was uploaded properly then the lights on the servo board should flash.
20. Move the Arduino board near to the front of the table so that the buttons on the breadboard are accessible.
21. Open the camera app on the cellphone that will be used for the recording and swap the setting to video.
22. Position the phone so that the bridge, articulation system, and Arduino board are all within frame.

Testing and Data Collection

23. Start the recording.
24. Press and hold the green button on the breadboard until the upper beam of the bridge contacts the vertical post of the articulation system.
25. Release the button.
26. Use the tape measure to find the height of the top of the road deck to the tabletop. Record the distance.

27. Allow the bridge to stay in the upright position for 10 seconds.
28. Press and hold the red button on the breadboard to lower the bridge.
29. Release the button once the tension in the nylon strands is lost.
30. Measure the height from the top of the roadway to the height of the table. Record the height.
31. Subtract the height from the horizontal bridge from the height measured when the bridge is in the upright position. This calculated value is the articulated height of the roadway from its resting position.
32. If this value is greater than the 14-centimeter requirement then the trial was successful.

Clean Up

33. Disconnect the Arduino board from the laptop by removing the red USB cable from both devices.
34. Remove the mounting pulleys from both of servo motor axels.
35. Remove the jewelry pins from the hinge holding the bridge to the articulation system.
36. Take the servo motors out of the holders on the articulation system.
37. Place the bridge, jewelry pins, and the articulation system back into the project box.
38. Close the Arduino program on the computer and turn off the laptop.
39. Place the Arduino board, red USB cable, and the servo motors back into the project box.
40. Return the tape measure back to the desk drawer to the left of the project table.
41. Move the project box back into the closet on the shelf to the left of the door.

Discussion:

The primary focus of the test was the articulation height of the roadway and the secondary focus was the time held in the articulated position. The only issue that was encountered during the tests was the wrong code being loaded on the Arduino board. The code that was previously loaded on the board did not have the buttons programmed, instead the servos were set to continuously rotate. This was solved by pressing the reset code on the board and loading the correct code and waiting several seconds for the code to load.

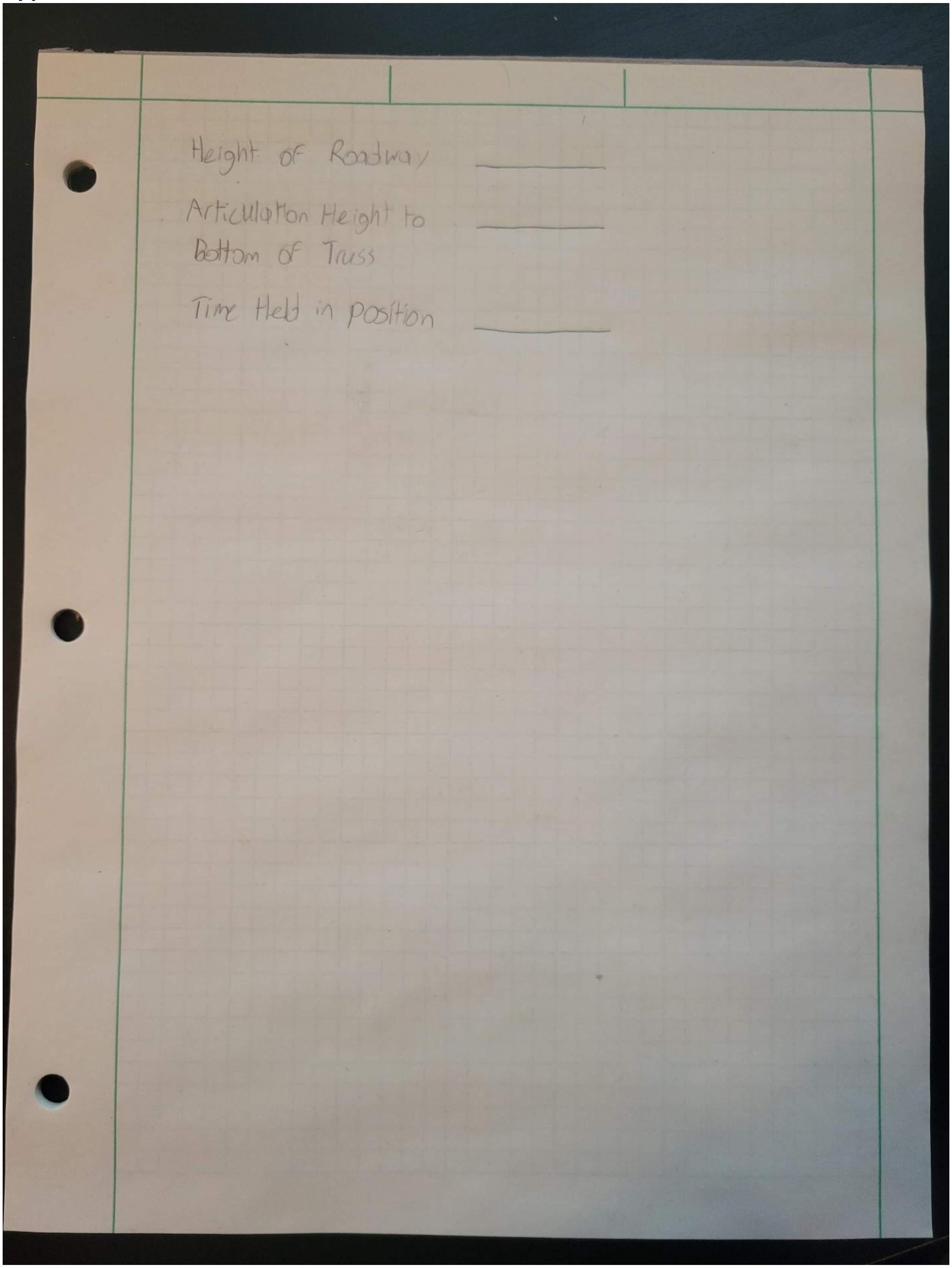
For the test addressing the position being held the test was ended after 60 seconds as it became clear that the bridge would not move from the articulated position unless the buttons were pressed or the board lost power.

Appendix G1.1: Required Items

- Sparkfun Arduino Kit
- 6 male-female pin connection wires
- 12 male-male pin connection wires
- Cellphone with video recording capabilities
- 2 FS90R continuous servo motors

- Table
- Tape measure
- Laptop with Arduino software installed
- Balsa wood bridge with articulation system
- 4 jewelry box pins
- 2 20-inch-long strands of nylon twine size 9

Appendix G1.2: Data Forms

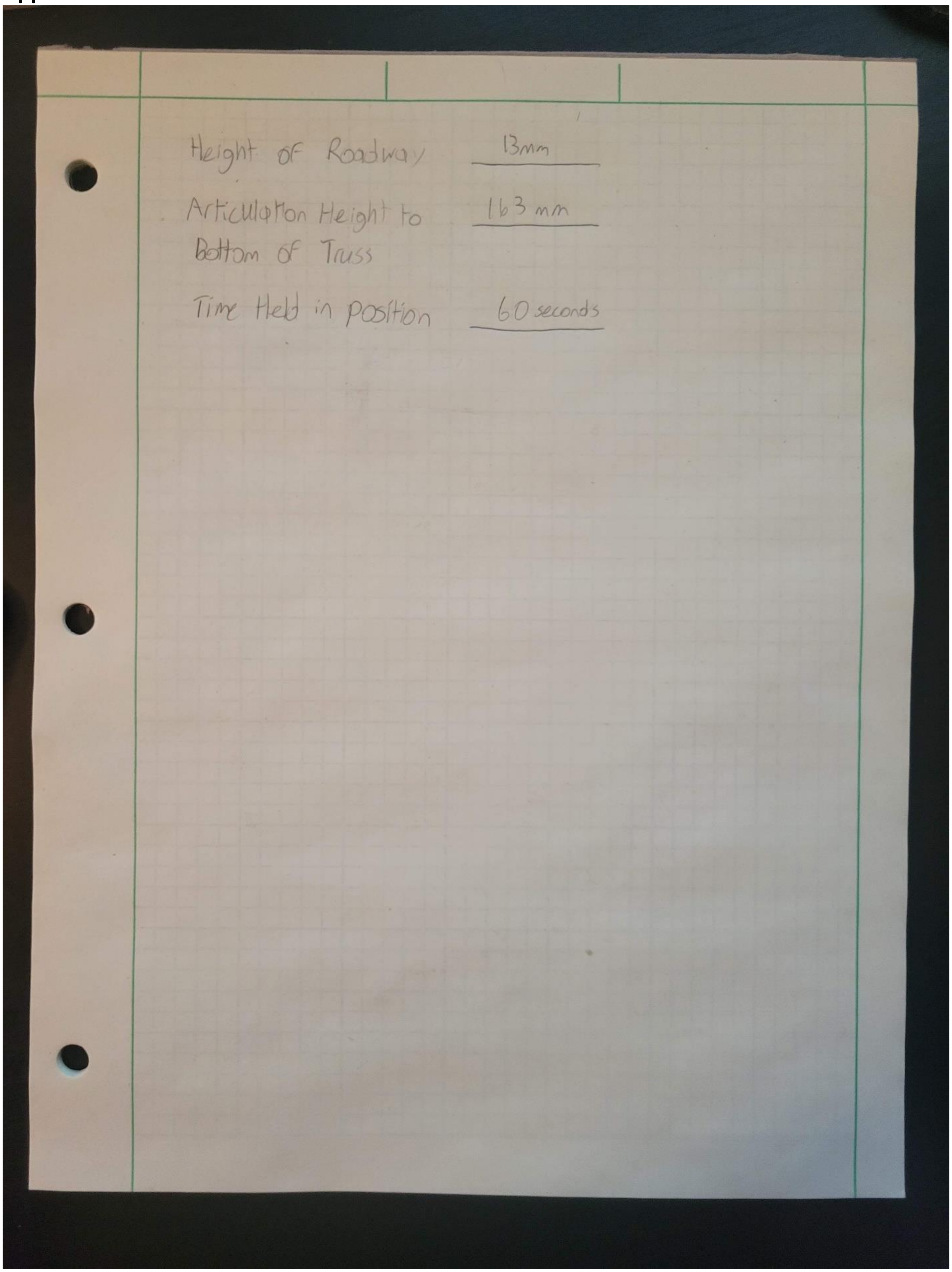


Height of Roadway ________

Articulation Height to
Bottom of Truss ________

Time Held in position ________

Appendix G1.3: Raw Data


Height of Roadway 13mm

Articulation Height to Bottom of Truss 163 mm

Time Held in position 60 seconds

Appendix G1.4: Evaluation Sheet

	Measured/Calc	Required Value
Roadway height from table (mm)	13	-
Height from table to bottom of frame (mm)	167	-
Calculated Articulation Height (mm)	154	140
Time Held in Articulated Position (seconds)	60	10

Test Report 2 Roadway Clearance

This procedure is a recording of the testing trial, recording, and data collection that occurred to verify the roadway clearance of the balsa wood bridge to show that a "car" would be able to cross the bridge unobstructed. The testing occurred on Tuesday April 20th, 2021 between the hours of 6:30 PM and 7:00 PM. Fifteen minutes was allotted for the set up of the testing equipment, five minutes for the testing process, and the remaining ten minutes for the cleanup of the testing area.

Required Equipment includes:

- Calipers
- Table
- Nylon Twine approximately 30 inches in length
- Testing Block
- Balsa Wood Bridge
- Cell Phone with Recording Capabilities

Risk:

The risks associated with the testing procedure are minimal due to the simplicity of the test being performed. No personal protective equipment was required for the testing nor was there any risk to the testing equipment. No additional personnel were required for the test itself, but a second individual was utilized for the recording of the test.

Setup

1. Retrieve the box from the closet on the first shelf on the left containing the following and place it on the project table.
    A. Balsa wood bridge
    B. Testing block
    C. Nylon thread
2. Place the balsa wood bridge on the table and verify that it is disconnected from the articulation system.
3. Place the testing block on the table.
4. Retrieve the calipers from the top drawer next to the project table.
5. Verify that the calipers are zeroed and adjust if necessary.
6. Measure the height of the block and the width of the block on the widest side. Record both measurements.
7. Verify that the height is at least 25 mm and the width is at least 32 mm.

8. Retrieve the nylon string from the project box and thread it through the hole in the test block.
9. Tie a knot in the sting and verify that the knot will prevent the string from being separated from the test block.
10. Place the block onto one end of the roadway with the string running along the top of the roadway.

Testing

11. Begin pulling the string to move the test block across the length of the roadway.
12. Check for any obstructions on the roadway that prevent the block from reaching the other end.

Figure 1: Block Width

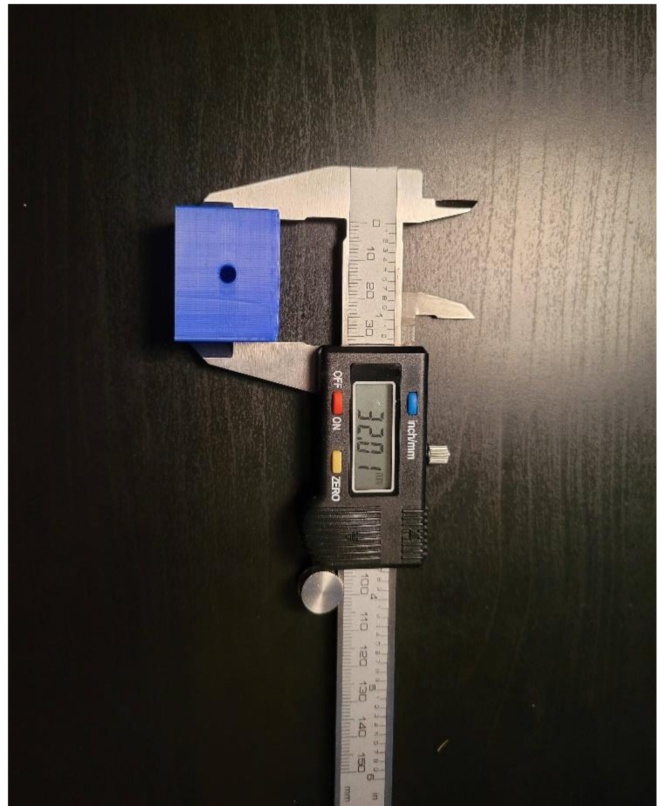
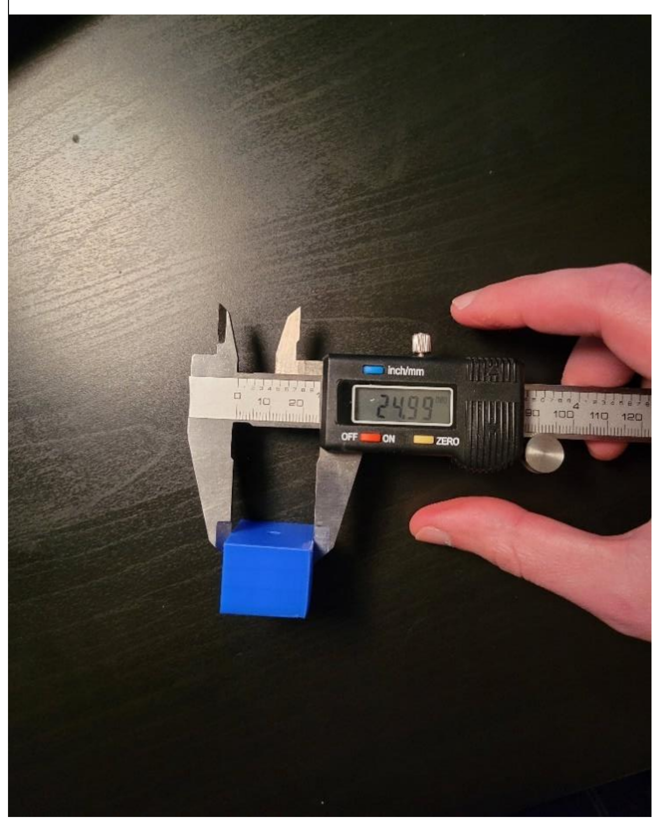


Figure 2: Block Height

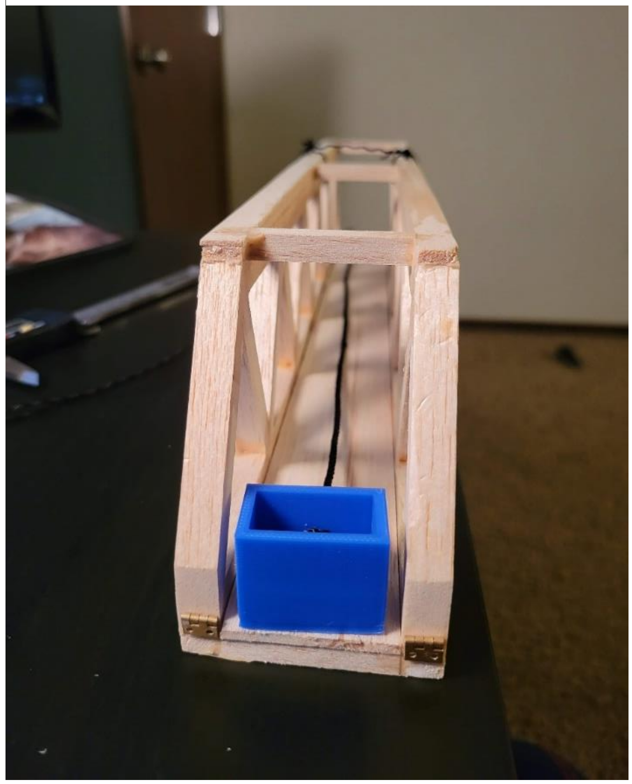


13. Once the block has traveled the length of the bridge record a pass or fail verdict for the test.
14. If any obstructions were encountered repeat the test.

Cleanup

15. Untie the knot from the nylon string and remove it from the testing block.
16. Place the balsa wood bridge, testing block and nylon string back into the project box.
17. Return the testing box back to the closet shelf.
18. Return the calipers to the drawer to the left of the project table.

Figure 3: Test Block on Bridge



Discussion

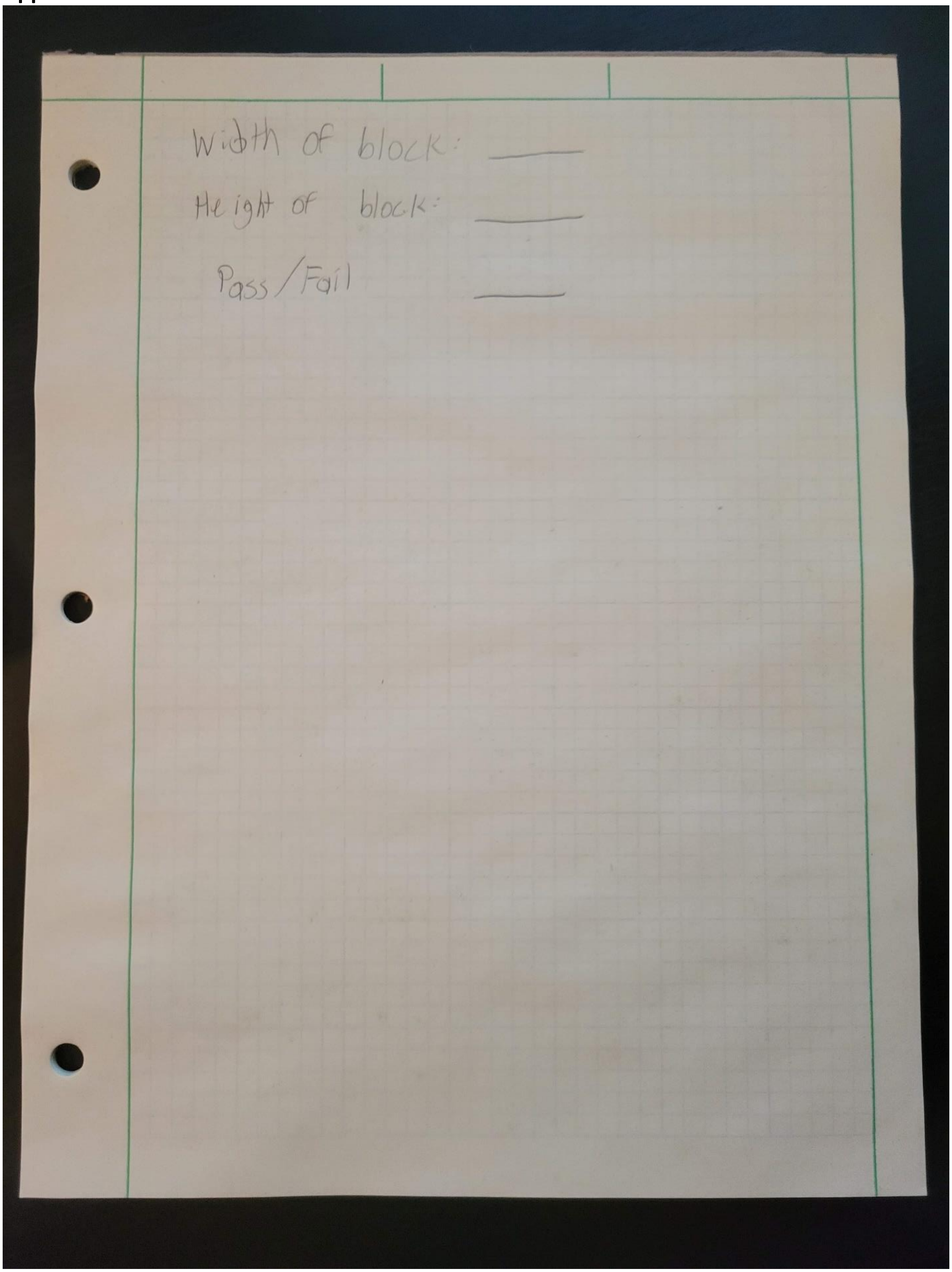
The primary issue with the test performed was the blocks tendency to rotate and hit the side trusses while traveling across the roadway. This was a problem that persisted across multiple attempts and due to how light the test block was in relation to the stiffness of the string used.

The results of the test were that the roadway met the specifications required for the test block to “drive” over the roadway. The block was measured to be 32 mm wide by 24.99 mm tall which were both within the tolerances of the project. Based on the pass-fail criteria, the design was passed.

Appendix G2.1: Required Items

- Calipers
- Table
- Nylon Twine approximately 30 inches in length
- Testing Block
- Balsa Wood Bridge
- Cell Phone with Recording Capabilities

Appendix G2.2: Data Forms

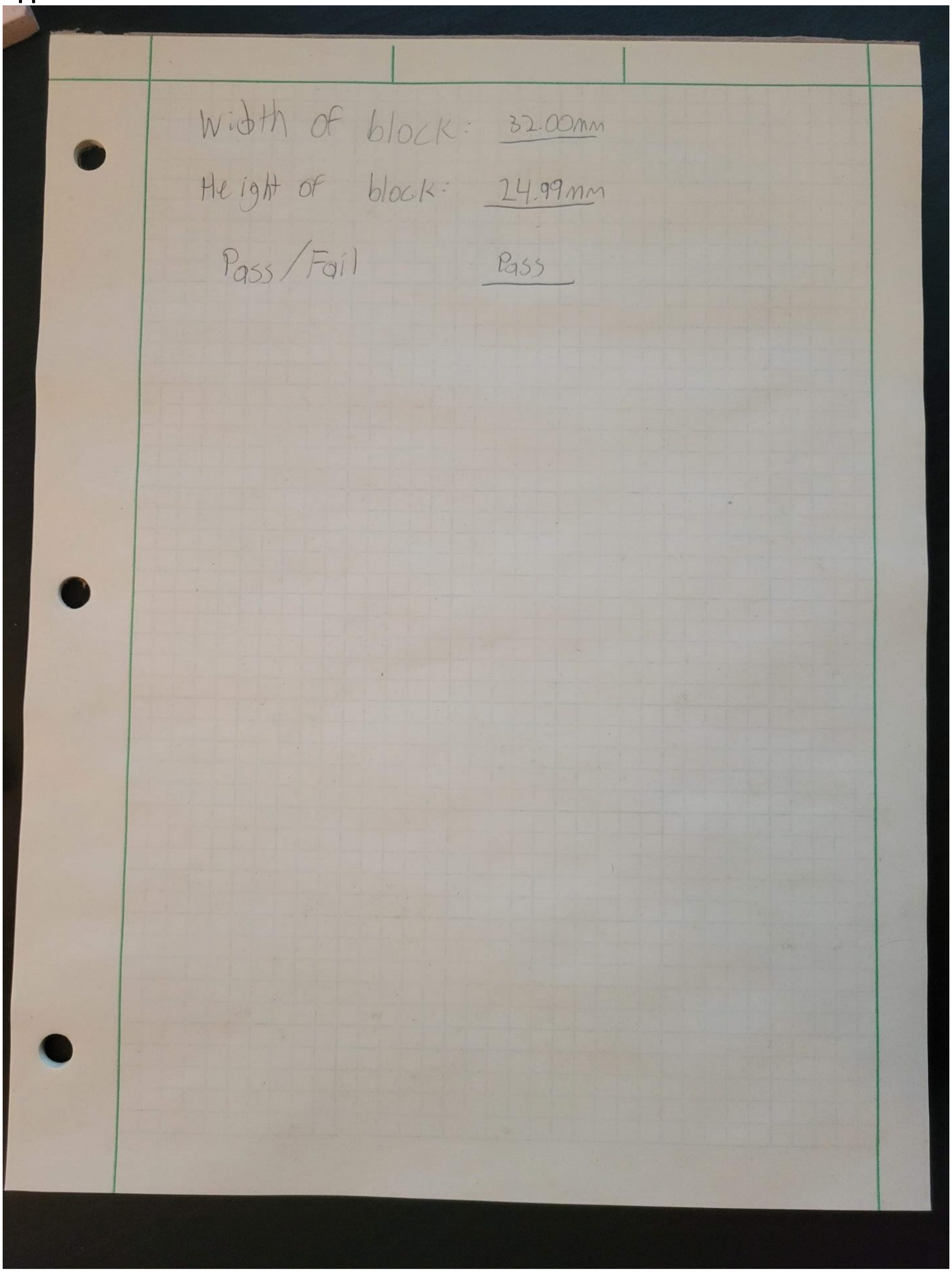


Width of block: ______

Height of block: ______

Pass/Fail ______

Appendix G3.3: Raw Data



Width of block: 32.00mm

Height of block: 24.99mm

Pass/Fail Pass

Test 3 General Project Requirements
This procedure is a collection of several different attributes that the bridge design was required to meet but were not sufficient in complexity on their own to warrant individual testing regiments. These tests will cover specific dimensions of the bridge and the weight of the bridge without the articulation system attached. The Tests occurred on April 23, 2021 between the hours of 8:00 AM and 10:00 AM in the home of the principal engineer.

Required equipment includes:

- Cellphone with video recording capabilities
- Table
- Balsa wood bridge
- Tape measure
- Accuteck digital scale
- Calipers

Risk:
The risks associated with the testing regiment were minimal due to the tests being performed. There was no risk to the person performing the test, but there was the standard risk of damaging the bridge due to mishandling of tools. No additional personnel were utilized for the testing beyond the principal engineer.

The testing procedure is as follows:

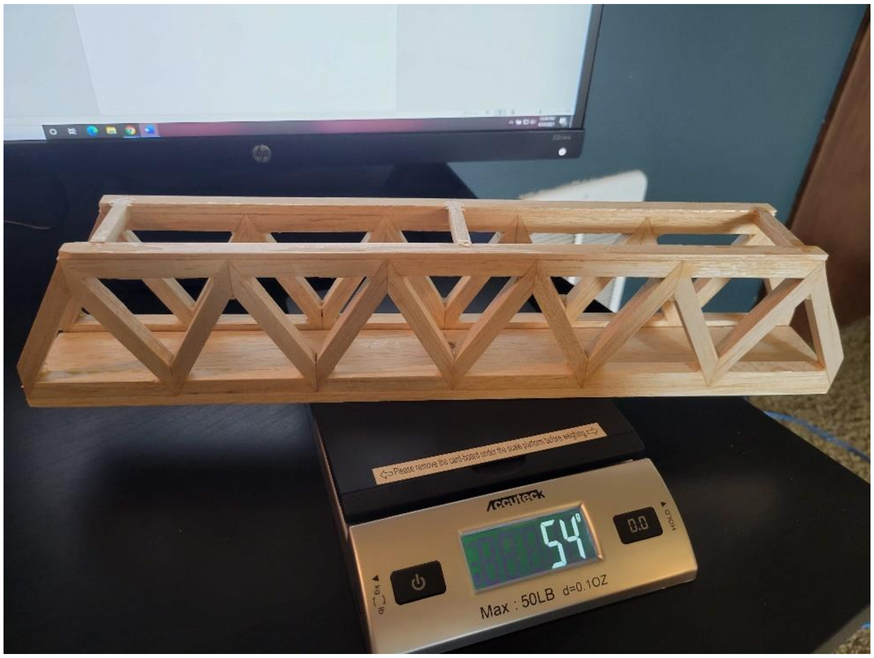
Setup

1. Retrieve the project box from eh first shelf on the left in the closet containing the balsa wood bridge, calipers, and tape measure.
2. Remove the balsa wood bridge, calipers, and tape measure from the box and place them on the project table.
3. Retrieve the Accuteck digital scale from the lower cabinet to the left of the project table.

Weight of the bridge

4. Turn on the digital scale and zero it.
5. Remove the nylon twine from the bridge that is connecting the side trusses to the servo motors.
6. Place the bridge onto the scale and wait till the scale has stabilized on a weight value.
7. If the scale is not already set in grams cycle through the units by pressing the button on the left side of interface.

Figure 1: Bridge on Scale



8. Record the mass displayed on the scale and remove the bridge from the scale.
9. Place the bridge back onto the table.

Length of the bridge

10. Using the tape measure, hook one end of the bridge truss and run the case beyond the other end of the bridge.
11. Record the length in centimeters.
12. Remove the tape measure from the bridge and retract the tape.

Height from abutments

13. Remove the calipers from their case and turn them on.
14. Adjust the calipers so hat the two jaws are touching and zero it.
15. If the calipers were not set to millimeters change the units so they are.
16. Use the depth bar of the calipers with the base of set on the roadway to measure the height to the roadway by extending the depth bar.
17. Record the depth measured by the calipers.

Width of roadway

18. Using the same calipers measure the width of the roadway by checking the portion of the roadway that is extended beyond the end of the truss.
19. Record the width displayed by the calipers.
20. Power off the calipers and return them to their case.
21. Visually inspect the roadway to verify that there are no other holes besides the hole in the center of the roadway for the weight testing.

Figure 2:Roadway Height From Tabletop

Figure 3:Roadway Width Measurement

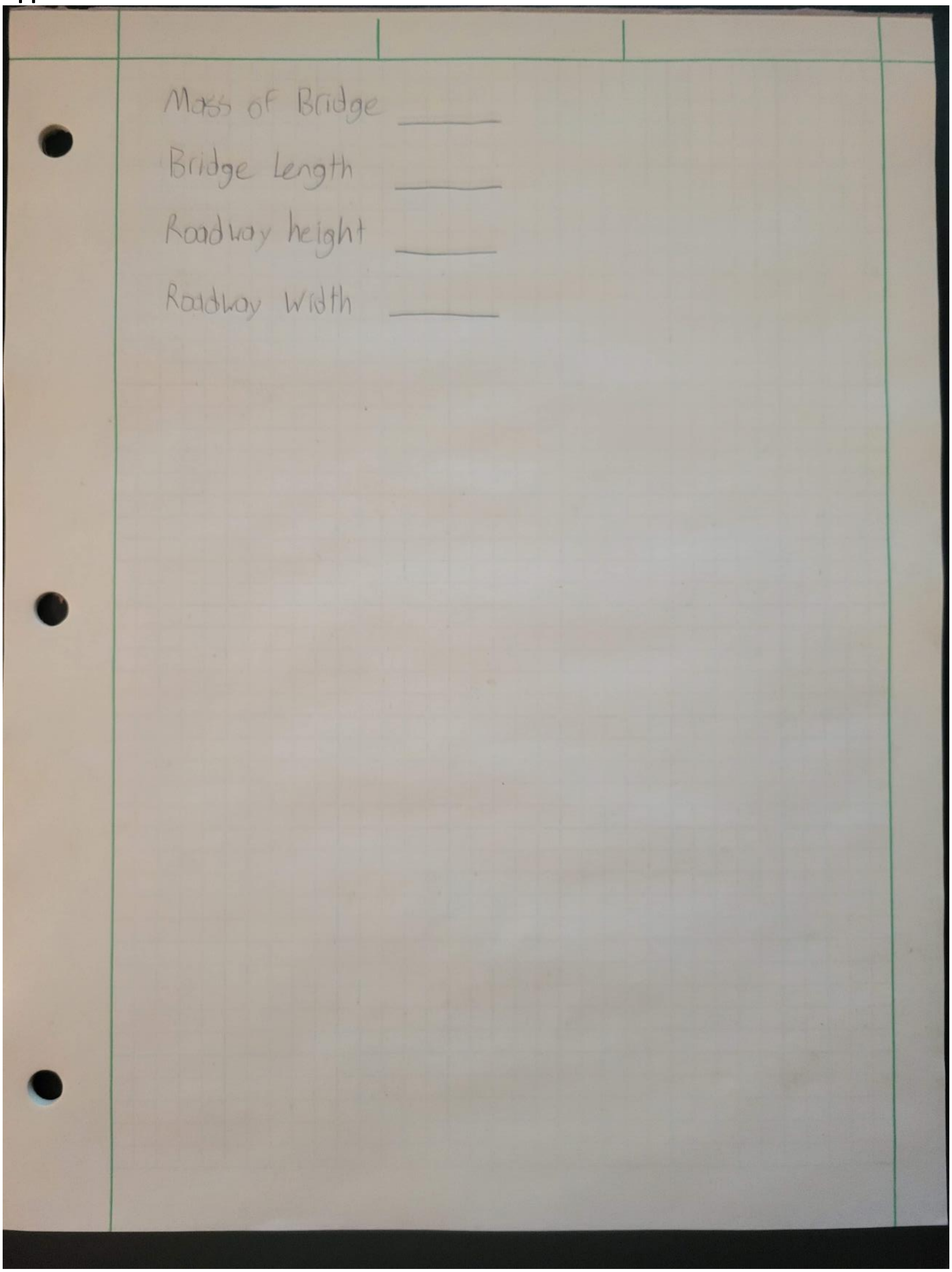
Discussion

The testing had no complications as the tests performed were simplistic with low risks associated. The values were all within the tolerance of the project which was ±1 mm for the dimensions of the testing block.

Appendix G3.1: Required Items

- Cellphone with video recording capabilities
- Table
- Balsa wood bridge
- Tape measure
- Accuteck digital scale
- Calipers

Appendix G3.2: Data Forms

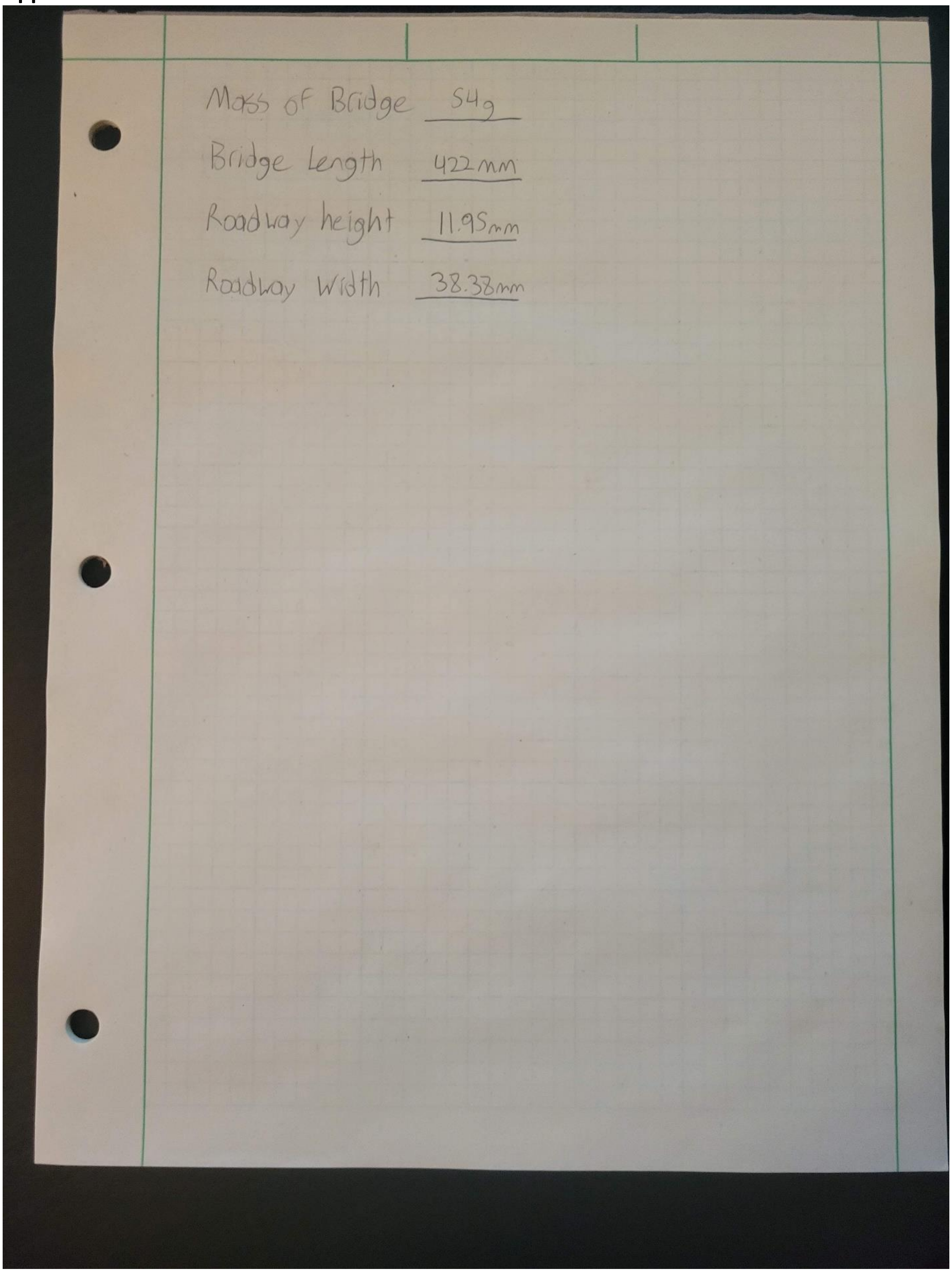

Mass of Bridge ______

Bridge Length ______

Roadway height ______

Roadway Width ______

Appendix G3.3: Raw Data



Mass of Bridge 54g

Bridge Length 422mm

Roadway height 11.95mm

Roadway Width 38.38mm

Test Report 4 Bridge Loading
The following procedure is the record of the testing, and data collection that weas performed to verify the weight loading of the bridge The testing occurred on Saturday April 17th, 2021 from 11:00 AM to 12:30 PM in the home of the principal designer of the project. Approximately 45 minutes were allocated for the set-up of the test, 15 minutes for the testing and data collection, and 30 minutes for the cleanup process.

Required Equipment Includes:

- Balsa wood bridge with articulation system
- Two identical bedside cabinets
- Tape measure
- 5 Gallon bucket with handle
- Test plate
- ¼-20 UNC eyebolt with 3” thread
- ¼-20 UNC nut
- 2” washer
- TV mounting spacer
- 15 Gallon cooler
- 10 Gallons of water
- 2 Gallon Bucket
- 32 oz water bottle
- Digital 50-pound scale

Risk:
The risks associated with the testing were both to the equipment and the personnel performing the test. The risks to the equipment were the bridge breaking and preventing any follow up testing, the water in the bucket spilling and damaging the other equipment or surrounding items, and the articulation system being destroyed if the bridge fractured. The risks to the personnel were splinters in the case of the bridge fracturing and having the bucket fall onto the foot of the tester. No additional personnel were utilized beyond the principal engineer.

Setup

1. Gather the project box from the closet and move it into the downstairs garage. The box includes:
    - Balsa wood bridge with articulation system
    - Tape measure
    - Eyebolt
    - Test plate
    - Washer
    - Nut
    - Spacer

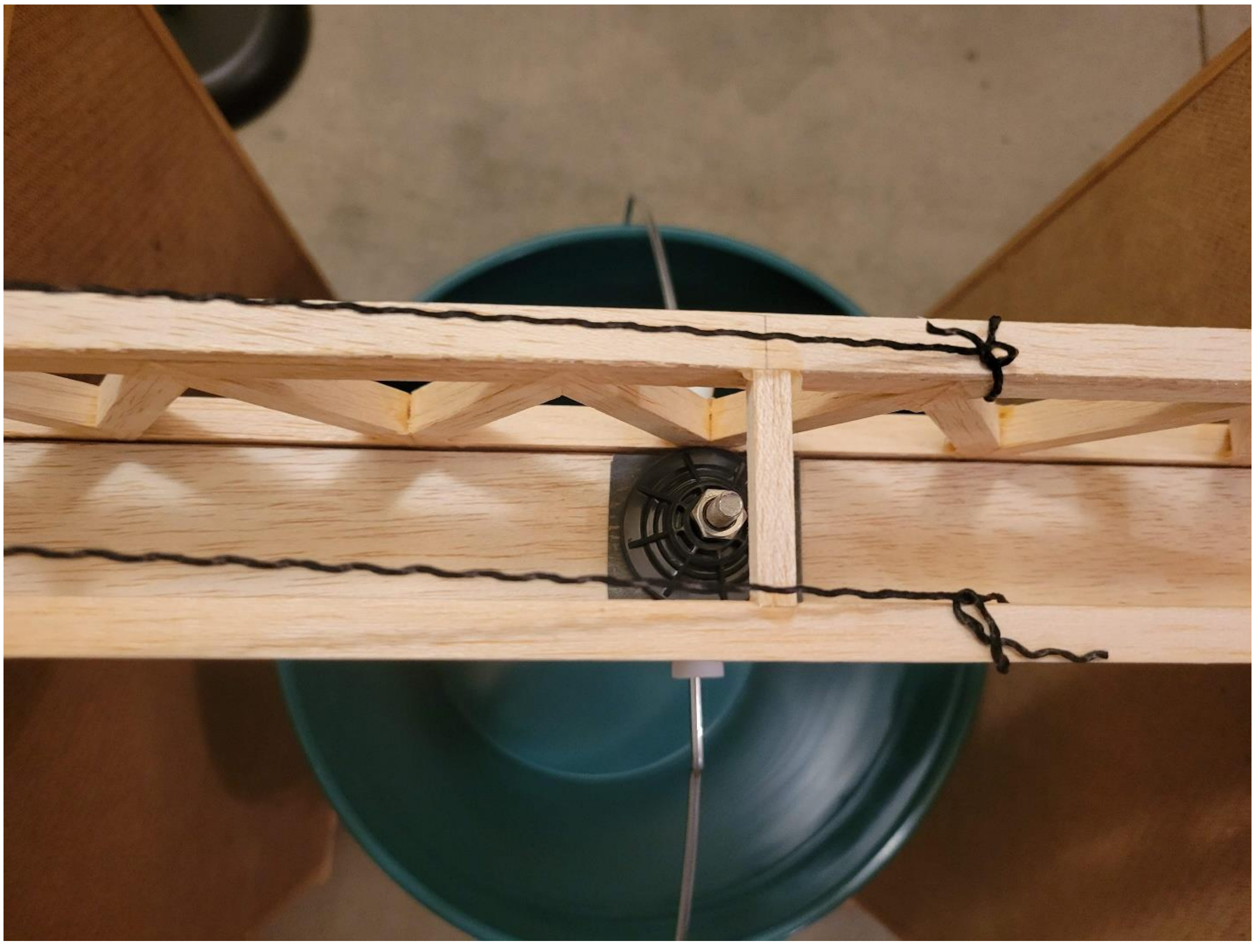
2. Gather the two bedside cabinets from the master bedroom and move them to the garage.
3. Place the cabinets 400 mm apart measured from the inside edge as seen in figure 1. Align them so that they are symmetric about the hole on the bridge roadway. Place the bridge on the top of a cabinet with the opposite end of the bridge resting on the other cabinet.

Figure 1: Bridge on Abutments

4. Retrieve the 5-gallon bucket from the back wall of the garage and release one side of the handle.
5. Using the tape measure the inside height of the bucket and the inner diameter. Record both values.
6. Retrieve the digital scale from the closet in the master bedroom and place it on one of the two cabinets.
7. Power on the scale and zero it. Set the scale to pounds and ounces.
8. Place the eyebolt, test plate, nut, and spacer into the 5-gallon bucket and place it on the digital scale and record the value displayed.
9. Pass the handle through the eyebolt and resecure the handle to the bucket.

10. Place the testing plate on the roadway centered on the hole and stack the washer, then spacer on top.
11. Pass the threads of the eyebolt through all the material till it is visible on the top of the spacer. Thread the nut onto the eyebolt approximately 2 revolutions so the bottom of the bucket is approximately 3 inches from the ground. The result can be seen in the following figure.

Figure 2: Roadway Loading Equipment



12. Take the 2-gallon bucket and fill it in the kitchen sink with tepid water.
13. Once the bucket is full, dump it into the cooler in the garage and repeat 5 more times.
14. Retrieve the 32 oz water bottle from the kitchen.

15. The complete testing setup should match the following figure.

Figure 3: Complete Testing Assembly

Data Collection

16. Using the water bottle pick up water from the cooler and pour it into the 5-gallon bucket hanging below the bridge.
17. 20 bottles full of water is equivalent to 5 gallons so that is the target value.
18. If the bridge does not break under 5 gallons, continue adding water till the bucket is full.

Clean-up

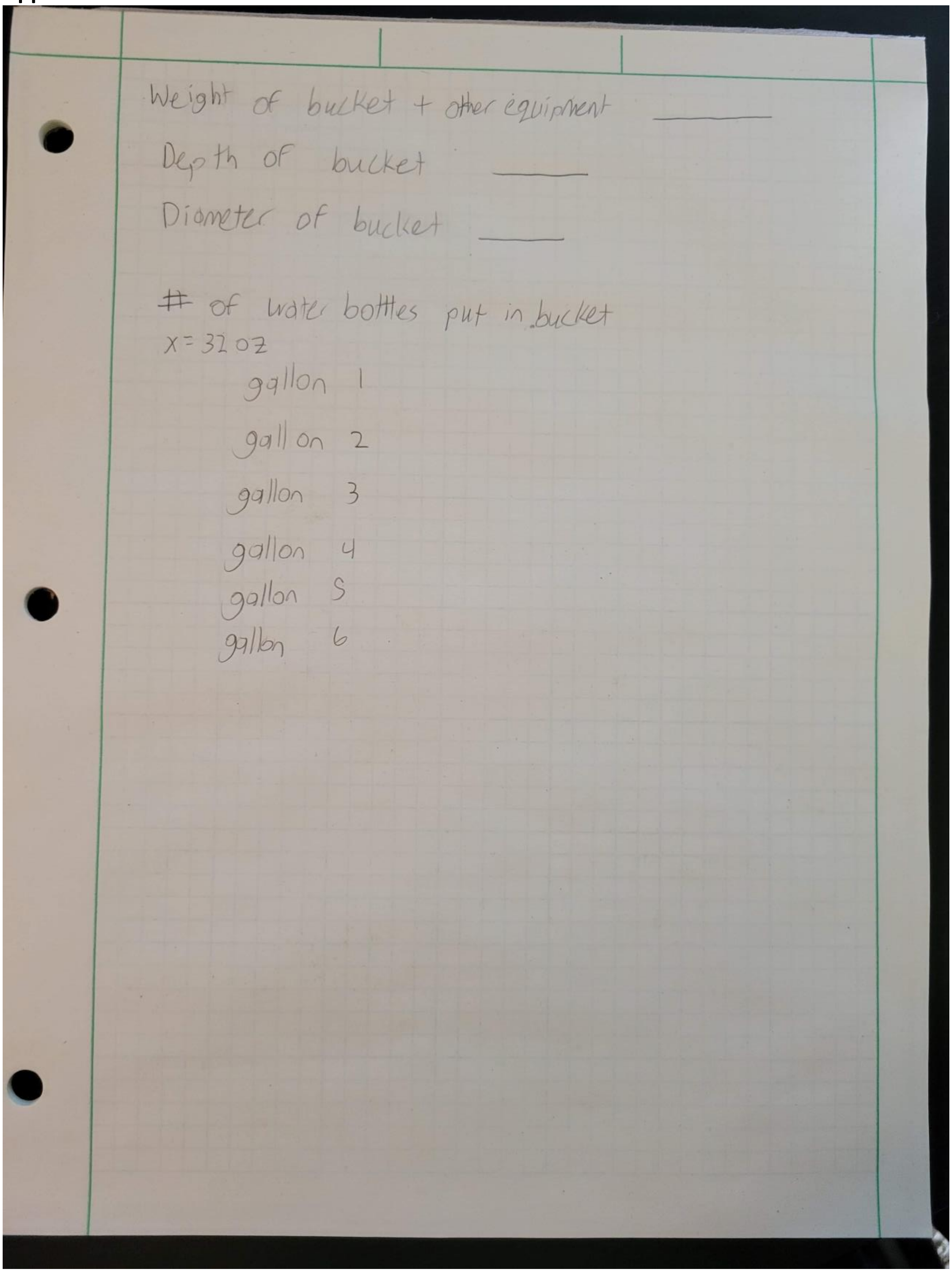
19. Carefully lift the bridge from the abutments by the handle of the bucket.
20. Unthread the nut from the eyebolt and separate the bridge from the bucket.
21. Take the bucket outside and dump the contents into the gravel.
22. Take the cooler outside and dump the contents into the gravel.
23. Unclip the bucket handle and remove the eyebolt.
24. Place the bridge, eyebolt, plate, spacer, and nut back in the project box.
25. Return the water bottle back to the kitchen.
26. Return the cabinets and project box back to the master bedroom.
27. Return the buckets and cooler the to the backwall of the garage.

Discussion
During the testing process the final weight of the water could not be measured directly. The bucket that was purchased was wider than the platform on the scale and could not be balanced when full. Instead the inside dimensions of the bucket were measured to calculate the volume, then using the known density of water, the weight was calculated. The testing procedure also needed to be altered to fit the location as the initial draft was meant for testing in Everett not Ellensburg.
The results of the test were that the bridge was successful at holding the target of 44 pounds. The calculated total weight was found to be 51.4 pounds. There were on signs of buckling or damage on the bridge.

Appendix G4.1: Required Items

- Balsa wood bridge with articulation system
- Two identical bedside cabinets
- Tape measure
- 5 Gallon bucket with handle
- Test plate
- ¼-20 UNC eyebolt with 3” thread
- ¼-20 UNC nut
- 2” washer
- TV mounting spacer
- 15 Gallon cooler
- 10 Gallons of water
- 2 Gallon Bucket
- 32 oz water bottle
- Digital 50-pound scale

Appendix G4.2: Data Forms



Weight of bucket + other equipment ______

Depth of bucket ______

Diameter of bucket ______

\# of water bottles put in bucket
x = 32 oz

gallon 1

gallon 2

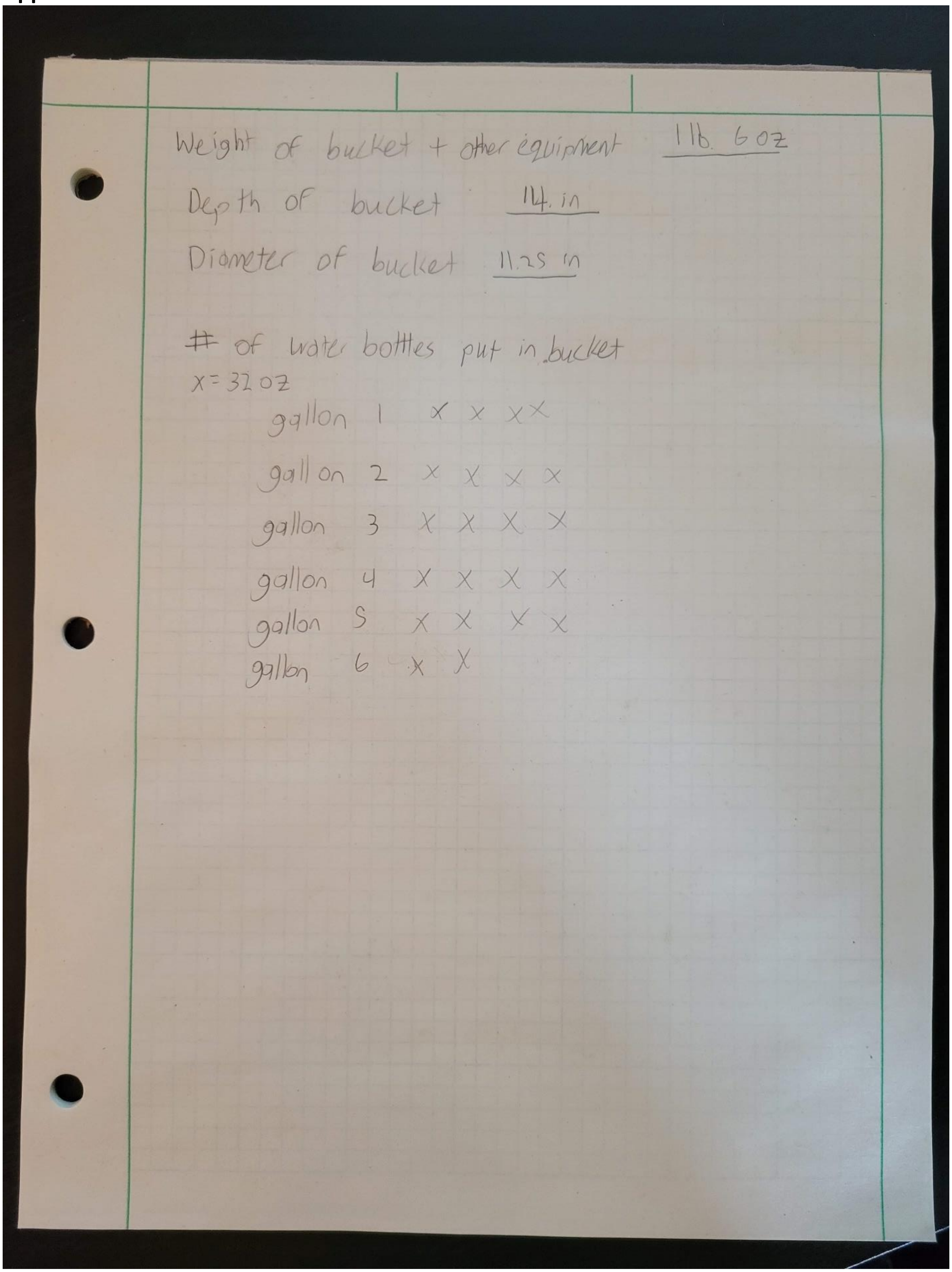
gallon 3

gallon 4

gallon 5

gallon 6

Appendix G4.3: Raw Data


Weight of bucket + other equipment 1 lb. 6 oz

Depth of bucket 14. in

Diameter of bucket 11.25 in

# of water bottles put in bucket

x = 32 oz

gallon 1 x x x x

gallon 2 x x x x

gallon 3 x x x x

gallon 4 x x x x

gallon 5 x x x x

gallon 6 x x

Appendix G4.4: Evaluation Sheet

Height of Bucket (in)	Dimaeter of Bucket (in)	Volume of bucket (ft^3)	Calculated Weight of Water (lb)	Weight Applied (lb)	Weight of Testing equiment (lb)
14	11.25	0.81	50.25	51.62821061	1.375

Appendix G5: Testing Schedule

TASK: ID	Description	Est. (hrs)	Actua (hrs)	%Com	Septembe	October	November	Dec	January	February	March	April	May	June
10	Device Evaluation													
10a	Articulation Testing Procedure	3	3											
10b	Articulation Testing	1	1											
10c	Roadway Clearance Procedure	3	3											
10d	Roadway Clearance Test	1	1											
10e	General Testing Procedure	2	2											
10f	General Testing	1	1											
10g	Weight Testing Procedure	2	2											
10h	Weight Testing	1	1											
10i	Testing Demonstration	3	3											
	subtotal:	17	17											
11	489 Deliverables													
11a	Articulation Testing Results	1	2											
11b	Poster Draft	3	3											
11c	Poster Presentation/Revisions	4	4											
11d	Testing Results	6	6											
	subtotal:	14	15											
	Total:	31	32											

APPENDIX H – Resume

KE

KYLE ENGEBRETSON

11105 26TH AVE SE EVERETT, WA 98208
(425) 345-6144 KYLET.ENGEBRETSON@GMAIL.COM

OBJECTIVE

Seeking employment in the mechanical engineering field that will challenge me and allow me to use my education, skills and experiences in a way that allows for future growth and advancement.

SKILLS

Strong analytical skills, as well as the ability to learn concepts quickly. Excellent communication skills, organized, detail oriented. CWSA Certified.

EXPERIENCE

INCOMING ORDER PROCESSOR/SUPERVISOR • PRODUCTION PLATING • AUGUST 2016 TO PRESENT
Responsible for organizing and processing incoming orders, communicating effectively with other departments and performing duties in a high stress environment while dealing with time constraints. Frequent exposure to engineering drawings.

SOCCER REFEREE • NORTH CHAPTER SOCCER REFEREE ASSOCIATION • SEPTEMBER 2012 TO 2016
Grade 8 soccer referee. Officiated youth games as well as worked multiple state and national championship tournaments. Ensured games are conducted in a safe and orderly manner. Communicated with other officials quickly and efficiently to make decisions.

EDUCATION

CENTRAL WASHINGTON UNIVERSITY • SEPTEMBER 2019 TO PRESENT
Studying mechanical engineering technology. 3.89 cumulative GPA.

EVERETT COMMUNITY COLLEGE • SEPTEMBER 2016 TO 2019
Studying engineering, 3.31 cumulative GPA.

CASCADE HIGH SCHOOL • JUNE 2016 GRADUATE
College in the High School and AP courses. Earned 45 college credits while in high school. Participated in Cascade food drive.