Articulating Balsa Wood Bridge

By

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ABSTRACT

This report describes the design, construction, and testing of a small-scale articulating balsa wood bridge that allowed passage over normally impassable terrain. The bridge was required to span a 400mm gap, while also articulating the midpoint of the bridge 140mm above its resting position. The bridge also needed to support a 20kg (44 lbs.) point load in the center of the bridge, and the bridge and articulation tower together needed to weigh less than 85 (0.19 lbs.) grams.

To construct the bridge, statics and mechanics of materials was used to design a truss that was calculated to support the load with a safety factor of 1.25. An articulation tower was constructed, and string was attached from the bridge to a motor that allowed the bridge to be raised. A switch on the motor allowed the motor to articulate the bridge up and down. All bridge and tower members were constructed using balsa wood and wood glue. The parts were manufactured by measuring and cutting stock balsa wood to length.

Once constructed, the final weight of the bridge was 79.5 grams and spanned 429mm in length. The bridge was able to hold 634.01 N (64.7 kg) before failure. Under a 19.4 kg load none of the truss members experienced fracture. The bridge articulated 155 mm above its resting position and articulated to its max height in 0.97 seconds.

Keywords: bridge, truss, mechanics of materials

Contents

1. INTRODUCTION

a. Description

The problem that was solved in this project was the design and construction of an articulating balsa wood bridge.

b. Motivation

This project was motivated by a need for a device that would allow an engineering student to understand mechanics of materials on a small scale. An interest in architecture and further understanding of the mathematics behind how and why objects are built the way that they are were also motivations as to why this project was chosen. Balsa wood specimens were also tested during lab classes taken concurrent to this course, so a familiarity of the calculations and physical properties of balsa wood contributed to the choosing of this project.

c. Function Statement

The balsa wood bridge must allow passage over a normally impassable terrain.

d. Requirements

1. 32mm by 25mm block must traverse the bridge in under 10 seconds.
2. Midpoint of road deck must be 140mm above horizontal resting position when articulated.
3. Abutments are 60mm wide and made of steel and are 400 mm apart.
4. Bridge must be longer than 400mm to rest on abutments.
5. 38mm wide solid balsa road deck.
6. 10 grams on string allowing for gap for printer paper to slide under bridge.
7. Supports load between 18.9 to 20 kg.
8. Weight of bridge must be 85 grams or less (with articulation hard components removed)
9. Max vertical deflection of 25 mm
10. Ascend/descend of bridge must be done with push of button/lever.
11. Articulation from fully closed to fully open must be done in under 60 seconds.
12. Bridge must be only made from 2 materials: balsa wood and wood glue (excluding articulation components)

e. Engineering Merit

To solve this engineering problem, concepts described and studied throughout Mechanical Engineering Technology classes were used. Statics was used to balance the forces and to calculate the weight distribution. Mechanics of materials was used to calculate deflection, stress equations, and to analyze the material properties under tension/compression, and to determine the forces in the members using the method of joints. And dynamics was used to determine the power of motor given the angular velocity.

f. Scope of Effort

The student was responsible for the design and analysis of the balsa wood bridge; this includes calculations to ensure the bridge meets the requirements. Construction of the bridge was also done by the student after the design was created and drawings of each part were completed. The project report and presentations were also done by the student.

g. Success Criteria

Success for this project was the designing and construction of a balsa wood bridge that allowed travel across the bridge, and articulation that allowed travel under the bridge.

h. Stakeholders

The stakeholders for this project were Professor Pringle, Professor Choi, and Chris Berkshire. Both professors were overseeing all projects in the class, and Berkshire was assisting with the manufacturing aspect for the projects.

2. DESIGN & ANALYSIS

a. Approach: Proposed Solution

The balsa wood bridge had to allow an object to travel the bridge, the bridge had to articulate, and had to be able to support a load from underneath it. One design idea for this bridge was that of a bascule bridge, which was a type of bridge that was split in the middle, and both sides articulate. This design was discarded because having two articulated components was deemed too complicated for the scope of this problem, as well as the fact that if the bridge was split in the middle, it would likely not be able to hold a load effectively.

Two drawbridge designs were also considered: one with a flat road deck and one with a curved road deck. The idea behind the curved road section drawbridge was akin to that of a flatbed for a semitruck; that as the load is applied to the bridge, the curve will level out. This design was discarded based on research of balsa wood, as it did not have much elasticity for the short distance it would be crossing. The drawbridge with the flat road section seemed like the most logical option. A Pratt truss design was chosen because of its overall simplicity and ease of construction. Refer to Appendix F01 for more details on how each design was valued.

b. Design Description

The balsa wood bridge functioned like a drawbridge and incorporated a Pratt truss design. An articulation tower (also made of balsa wood) was placed at one end of the bridge resting on the abutments. String was attached to a motor, led to the top of the tower, and attached to the opposite side of the bridge. This allowed the bridge to articulate.

c. Benchmark

Examples of various balsa wood bridge engineering projects were found on the internet. Specific requirements varied from project to project. One specific balsa wood bridge had a total mass of 85 grams and was able to hold 202 lbs. before failure. Refer to Reference (5).

d. Performance Predictions

The goal was to have the bridge support 20 kg but was calculated to support 25 kg of weight due to any calculation rounding, error, and/or material defects. It was also ideal that the bridge was able to fully open to the vertical height of 140 mm within 15 seconds.

e. Description of Analysis

In the analysis, statics was used to draw free body diagrams, balance the forces, and calculate weight distribution. Mechanics of materials was used to calculate deflection, and to use the method of joints to determine the forces in each beam and determine if the member was in tension or compression. Dynamics was used to determine how the bridge would act under motion.

f. Scope of Testing and Evaluation

The bridge was tested to see if it could support the 20kg load. The bridge was tested to see if it articulates, and that the midpoint of the road deck will rise 140mm above its horizontal resting point.

g. Analysis

i. Analysis 1 – Height of Articulated Midpoint

Section 1d-2 states the midpoint of the road deck must be able to articulate up 140 mm from its original horizontal resting point, and Section 1d-4 states the bridge must span over a 400 mm gap. Trigonometry was used to calculate the predicted height of the midpoint would be 148.5mm when articulated, assuming the bridge articulated 45 degrees above the horizontal. Refer to Appendix A01.

ii. Analysis 2 – Forces in Truss Members

One requirement in Section 1d-7 was that the bridge needed to support a load of 20 kg, so the forces in each of the members of the truss were analyzed. The method of joints was used to analyze the members. It was found that the largest force a member experienced was 367.5 N in both compression and 245 N in tension. MDSolids was used to corroborate the calculations. Refer to Appendix A02 for the calculations.

iii. Analysis 3 – Cross-Sectional Area of Truss Members

The bridge must be able to support a load of 20 kg according to Section 1d-7. Using the forces acting on each member that were calculated in Appendix A02, as well as material properties in Reference (4), it was determined that each truss must have a cross sectional area of 3/8 in. by 3/8 in. (9.525 mm by 9.525 mm). Refer to Appendix A03.

iv. Analysis 4 – Dimensions of Truss Members

The bridge must be longer than 400 mm to rest on abutments (refer to Section 1d-3), as well as able to support 20 kg (refer to Section 1d-7). The cross-sectional area of the trusses was determined in Analysis 3, and using that information, the dimensions of the truss members was found so that drawing of each component of the truss could be created. Each dimension for the truss was calculated using geometry and can be found in Appendix A04.

v. Analysis 5 – Thickness of Road Deck Supports

The bridge road deck must be wide enough for a 32 mm by 25 mm block to traverse (refer to Section 1d-1), the road deck must be 38 mm wide (refer to Section 1d-5), and the bridge must support a 20 kg load (refer to Section 1d-7) Since the truss members are 9.525 mm tall, that same height was assumed for the road deck. Using balsa wood material properties from Reference (4), a height of 9.525mm, and the force of 245 N. It was calculated that the road deck support would need to be 38.1 mm (1.50 in) to support the load. Refer to Appendix A05 for calculations.

vi. Analysis 6 – Shear Strength of Adhesive

The bridge must support a 20 kg load, as stated in Section 1d-7. Therefore, the adhesive selected must be able to support the 245 N load. The shear strength of the adhesive was 27 MPa (refer to Reference (3)). The largest shear force was found by dividing the 245 N load by the smallest cross-sectional area of the truss and road deck supports. This was determined to be 2.7 MPa, meaning the adhesive can support the 20 kg load. Refer to Appendix A06.

vii. Analysis 7 – Power to Articulate Bridge

According to Section 1d-11, the bridge must full ascend/descend in under 60 seconds, and therefore the motor had to be able to handle the power it takes to articulate the bridge. Using the specifications of the motor in Refence (1), the power of the motor was found to be 1.59 Watts, and the bridge was found to need 0.0069 Watts to articulate, meaning the motor selected has the power to articulate the bridge in 1.26 seconds when factoring in friction. Refer to Appendix A07.

viii. Analysis 8 – Deflection of Truss

Section 1d-9 required a max vertical deflection of 25 mm. Using the dimensions of the truss, material properties from Reference (2), and a point load of 245 being applied to the bottom center of the truss, the deflection of the truss was calculated using the virtual work method. The truss was calculated to deflect 0.726 mm. Refer to Appendix A08 for detailed calculations.

ix. Analysis 9 – Total Mass of Bridge

The total mass of the bridge had to be less than 85 grams, according to Section 1d-8. The total volume of the truss members and road deck was calculated and using the density of balsa wood from Reference (4) the total mass of the bridge was calculated to be 55 grams. Refer to appendix A09.

x. Analysis 10 – Articulation Tower Dimensions

Section 1d-2 stated that the bridge must articulate 140mm above horizontal resting position. To allow for this, an articulation tower was designed, and the dimensions of the members in the articulation tower were calculated. For simplicity, the tower members had the same cross-sectional area as the bridge members. All dimensions and calculations can be found in Appendix A10.

xi. Analysis 11 – Fatigue on Road Deck

Section 1d-1 requires a 32mm by 25mm block to traverse the bridge. This can be assumed to be a model car. A fatigue analysis using the Goodman equation was calculated. The road was calculated to withstand 145 cycles on the block traversing the bridge. Refer to Appendix A11 for details on calculations.

xii. Analysis 12 – Minimum Weight to Lift Bridge

When 10 gram is placed on the articulation string on the bridge, the bridge must raise enough such that a sheet of standard printer paper can slide under the bridge, according to section 1d-6. A calculation of the weight required to lift the bridge was done using the torque equation, assuming the mass of the bridge was 55 grams, and the length of the bridge was 430 mm. The bridge was calculated to lift at a weight of 28 grams. Refer to appendix A12.

h. Device: Parts, Shapes, and Conformation

After researching various truss designs on the internet, a Pratt truss design was chosen because of its overall simplicity and 45-degree angles for the truss members, which allowed for easy construction of the bridge. A load of 25kg from the middle of the truss was used for analysis. This allowed for a safety factor of 1.25 for the required 20kg the bridge had to support. This tolerance was to account for the mass of the bridge which must not exceed a mass of 85g, as well as any potential defects in the balsa wood. An issue with kinematics was that both the articulation tower and bridge needed to be constructed out of balsa wood, this created concern that the tower would be lighter than the bridge and would not be able to support the articulation. This issue was solved by having to motor be attached to the articulation tower, weighing the articulation tower down. The ergonomic issue was ensuring the bridge would not give the user splinters; however, balsa wood is a soft wood, and therefore does not cause splinters.

i. Device Assembly

A balsa wood bridge was constructed to span the distance this connecting two abutments. The bridge design consisted of a Pratt truss design, made of two web bays per side. The design was symmetrical down the center of the bridge. The bridge was wide enough to allow a 32mm by 25mm block to traverse the roadway, and the roadway spanned the length and width of the bridge. The bridge also articulated to allow tall objects to pass that would otherwise not be able to when the bridge was in the horizontal position. The articulation was incorporated into the assembly by two nails being pushed into the balsa wood at the intersection of the end of the bridge and the bottom of the articulation tower. A motor and shaft were attached to string, which used the tower as a means of supporting the string and was attached to the middle support on the top of the bridge. When the motor was turned on, it pulled the string and articulated the bridge upward, and the opposite was done to lower the bridge. When resting in the horizontal position, the string provided no tension onto the bridge, as per the requirements.

j. Technical Risk Analysis

The bridge components had the least amount of mass possible, while still conforming to the safety factor of 1.25. To reduce weight, adhesive was used conservatively. Further analyses were done to determine the size of the members of the truss such that the load supported, as well as confirmed that the adhesive could support the shear strength of the bridge. A Technik M-Motor was used to raise and lower the bridge. A motor mount design was conceived so that the motor could be attached to the device to allow articulation while simultaneously weighing the articulation tower down.

k. Failure Mode Analysis

The bridge was most likely to fail when the 20 kg point load was applied to the center of the bridge. Balsa wood was considered a brittle material, so a failure in a member of the truss was possible. Failure was also likely to occur in the road deck, as that was what the point load was applied from, and the bending stress could cause failure.

l. Operation Limits and Safety

Although there was a safety factor, bridge was designed to hold a load of 20 kg, and therefore a load weighing more than 20 kg should not be applied to the bridge. The bridge was not designed to articulate with a load as well, and therefore all loads should be removed before the bridge is articulated.

3. METHODS & CONSTRUCTION

a. Methods

This project was conceived, analyzed, and designed at CWU. Working within the constraints of university resources, parts were manufactured by using simple resources. Due to the small and simple size of the components in the project, part manufacturing was done with a hand saw and wood glue. Access to the table saw in the Central Washington University wood shop was provided by the Mechanical Engineering Technology department if needed for more complicated parts.

i. Process Decisions

Manufacturing methods mostly consisted of measuring and cutting balsa wood strips to length and using adhesive to assemble them. The parts of the bridge that needed to be manufactured were the trusses, road deck, road deck supports, and the tower used to support the articulation. Appendix F, Table F02 used a decision matrix to determine whether hand tools, such as wood knifes, or mechanical tools, such as a circular saw, should be used. The time, precision, availability, manufacturability, and cost of both were analyzed, and the hand tools were selected due to their high precision and the simplicity of the parts. Hand tools also allowed the project to be constructed at home, so additional time in the woodshop was not needed.

Although initially the plan was to use a carving knife to manufacture parts, during manufacturing the carving knife was not strong enough to cut the balsa wood at a reasonable speed. The carving knife also caused the wood to split while it was being cut. A hobby hacksaw was used to manufacture the pieces instead. The hacksaw manufactured parts quicker, cut the balsa wood cleaner, and left straighter finishes on the ends of the manufactured pieces.

Although the bridge and tower could only be made from balsa wood, the brand of adhesive used to construct the project could be selected based on preference. Research on various wood glue brands was done. Another decision matrix was created to determine the wood glue brand to be used for the project, and can be seen in Table F03 in Appendix F. The cost, availability, spec sheet, strength, and cure times were compared between the three brands, and although Gorilla Wood Glue was not valued as the highest adhesive of the three being compared, it was selected based on familiarity with the product, as well as the fact that it had the highest shear strength out of the brands chosen.

The string that assists in the articulation of the bridge rests upon a part of the tower, and it was analyzed in Appendix F, Table F04 whether it the string should rest on the balsa wood, a 3D printed element, or a pully. The time, cost, likelihood of friction, and the manufacturability of each of the three was compared, and it was determined that the string should rest on a pully, as it would alleviate any friction on the balsa wood and would not be as time consuming as designing and 3D printing a new part.

Upon further designing, it was decided that a pulley was not to be used in the final design of the articulation tower. Adding a pulley unnecessarily complicated the design of the articulation tower and could've led to the project being delayed if a 3D print was required or a pulley needed to be purchased. The decision was instead to use a round piece of balsa wood to pivot the string for articulating the bridge. This design was much easier to manufacture, cost effective, and less complicated than a pulley.

The methods used to construct the device did not significantly change throughout the entire manufacturing process. Parts were manufactured by cutting the stock balsa wood to length using a hobby hacksaw, and wood adhesive was used to construct the bridge and truss. The process was straightforward and did not require any major changes or modifications during manufacturing.

One small issue with the aforementioned manufacturing process was that occasionally the manufactured parts would end up with an uneven finish on the side it was cut from. Modifications to prevent this issue were that the wood was measured and marked from multiple sides before cutting. While cutting, the wood was rotated to ensure the cuts followed the measurement marks and left an even finish. This also helped prevent the wood from splitting during manufacturing, which was a less common but still seemingly random issue. If the manufactured part still had an uneven finish, the part would be remeasured and the excess wood would be cut, leaving the part with an even finish.

b. Construction

i. Description

This project was made from 15 parts and 3 sub-assemblies. All parts were made from raw materials purchased from retailers, which for this project was balsa wood and wood glue. The parts were manufactured at CWU. Since all parts were cut from balsa wood, each part was cut using a wood carving knife. The sub-assemblies were the truss, the bridge and the articulation tower. All three sub-assemblies were created by using wood glue to combine the parts to form the respective sub-assembly.

ii. Drawing Tree, Drawing ID's

The drawing tree in Appendix B01 showed the sub-assemblies and parts needed for each sub-assembly. The full assembly was made of 3 sub-assemblies and could be seen in detail in Appendix B03. The truss sub-assembly could be seen in Appendix B05, the bridge sub-assembly could be seen in Appendix B04, and the articulation tower sub-assembly could be seen in Appendix B06. Appendix B01 was the drawing tree, which detailed how many of each part was required to construct the sub-assemblies and full assembly.

iii. Parts

Fall:

One process group included the balsa wood members that were used to create the bridge and articulation tower. The raw balsa wood was purchased in bulk (refer to Appendix C) and was cut to length by using carving knifes or the table saw, depending on the complexity of the shape. Another process group was the motor, which was purchased and did not require modification (refer to Appendix C). Another process group included 3D printed parts. Although the project was limited to balsa wood and wood glue, there were occasional times where other materials could be used. 3D printed piece was created to securely attach the motor to the articulation tower. Weights could also be added to the articulation tower to add stability during articulation, and these were determined to be coins or other small metal objects.

Winter:

As manufacturing began in Winter, the process groups stayed the same, with only slight parts being added or removed from the process groups based on slight redesigns. The balsa wood process group was still present, as the entirety of the project was manufactured from balsa wood. Every balsa wood part was cut using a hobby hacksaw. The motor was also a process group that was still present during Winter manufacturing. The 3D printed parts process group was also used during Winter manufacturing. Only two parts were in this process group; the axle that attached the articulation cord to the motor, and the motor mount, which attached the motor to the articulation tower. Refer to Appendix C for further details.

iv. Manufacturing Issues

Fall:

Risks with manufacturing the project included having access to the machinery to manufacture the parts. As the wood shop lab time is limited, and the machinery in the lab is shared between other students using them for other projects or classes. Effective time management while in class and labs mitigated this risk. Another risk was potential supply chain issues; if the necessary resources to manufacture the parts were unable to be purchased from retailers, then it would cause a delay in manufacturing. This risk was mitigated by purchasing resources immediately after analyses and drawings were completed. Time management and quality of the parts was another risk, as using a knife to manufacture the parts took time, and often caused fractures, angled beam ends, or other defects in the parts that caused them to be unusable. This required delicate manufacturing of parts as to not waste time or resources, and caused the manufacturing portion of the project to take more time to manufacture than was originally anticipated.

Winter:

The risk of having access to machinery was not an issue during manufacturing due to the use of the hobby hacksaw to manufacture all parts. This allowed parts to be manufactured whenever convenient in nearly any location, mitigating the need of relying on the limited open lab hours or needing to share lab resources with other students. Supply chain issues were also not present during manufacturing. All stock balsa wood and the motor were purchased before

Winter quarter began, which allowed for manufacturing to begin and largely be completed during Winter without any delays or issues. Time management was not an issue during Winter. As mentioned previously, the hacksaw allowed parts to be manufactured effectively and at the convenience of the manufacturer. Most of the parts were manufactured in one sitting since part manufacturing was straightforward. All manufacturing methods were appropriate for manufacturing each part to the specifications.

v. Discussion of Assembly

When constructing the device, wood glue was applied to the parts being attached together, and they were held together with tape until the glue had set roughly 24 hours later. The first sub-assembly that was constructed was the Truss Assembly (NJH-10-003) in Appendix B05. Two of these sub-assemblies were constructed. These sub-assemblies were then used to construct the Bridge Assembly (NJH-10-002) in Appendix B04. The next sub-assembly was the Tower Assembly (NJH-10-004). The Bridge Assembly and Tower Assembly were used to construct the final device, the Bridge and Tower Assembly (NJH-10-001) in Appendix B03. This order of assembly can be seen in the drawing tree in Appendix B01. The final assembly was operated using a switch. When the switch was in the neutral position the bridge wouldn't articulate, when activated in one direction the bridge would articulate up, and when activated in the other direction the bridge would articulate down. The remaining functions of the bridge did not require user operation. The final assembly met the project benchmarks; the size of the bridge met the requirements of the project. The cost to create the project was relatively low (refer to Section 5), and the final assembly manufacturing was straightforward was time efficient.

4. TESTING

a. Introduction

There were various requirements that the balsa wood bridge had to meet to consider the project successful. To determine if these requirements were met, various tests were conducted.

To test if the balsa wood bridge was able to support the required load, 20 kg (45 lbs.) was hung from the bridge. If the bridge can support the load without failure, it will be successful. Based on the calculations, analyses, and research, the bridge in this project was expected to pass this test. The bridge had to also weigh 85 grams or less. This project was predicted to pass this test.

To determine if the bridge passed the articulation requirements, the full articulation of the bridge was timed If the bridge articulates in less than 60 seconds, it will be successful. The bridge was also predicted to articulate in less than 30 seconds. Once the bridge is fully articulated, the distance from the midpoint of the road deck to the original horizontal resting position was measured. It had to measure 140mm or greater to pass this test, which the bridge was predicted to reach.

b. Method/Approach

To conduct the load test, a hole was drilled in the center of the road deck as per the instructions listed on Canvas. A 38 mm square by 6 mm thick steel plate (or round weld nut and washer) was placed on the center of the road deck. The bridge was then positioned on the abutments and a 6 mm diameter rod was threaded through a hole in the center of the steel plate and connected to the weights. The weights in this instance would be a bucket full of weights whose total mass is equal to 20 kg.

To conduct the weight test, the bridge was measured on a scale.

For the articulation test, a stopwatch, such as one on a phone, was used to determine the time it takes the bridge to fully ascend to its max vertical position. A ruler was used to measure if the midpoint of the road deck to the original horizontal resting position.

Updates to the testing included the inclusion of a tensile test, which tested how much weight could be added to the articulation string to slide a sheet of printer paper underneath the bridge. This replaced the weight test, as no “pass/fail” tests could be included in the report. One issue with the tensile test was that there were no weights present in Hogue that were light enough to conduct the test since the weights needed to be in grams. Therefore, the test was updated to be conducted by filling a Ziplock bag with popsicle sticks to act as the weight added to the string. This change was needed because a weight needed to be hung from the string to conduct the test. The load test was also updated to be conducted using the Instron. The Instron was used because it reported accurate loading and deflection values for the bridge. The articulation test largely remained the same.

c. Test Process

For the load test, the bridge was placed in the Instron, and a plate and washer were secured in the 8mm hole in the center of the road deck. The Instron then applied a load to the bridge.

For the weight test, a scale was used. There are numerous scales provided by CWU that can be used for this test.

For the articulation test, all loads were removed from the bridge. A stopwatch and the button to articulate the bridge were started simultaneously. When the bridge reached its maximum height, the stopwatch was stopped. The same procedure was used when articulating the bridge down.

d. Deliverables

All data will be recorded in Microsoft Word, and the data will be available in Appendix G. Pictures and videos will be taken and documented as needed. To determine if deliverables appropriately met the project requirements listed in Section 1d, the requirement will be listed, and after testing the deliverable will be documented.

For the articulation test, three deliverables are to be recorded: the max height of the center of the road deck, if the bridge articulates via a button, and the time it takes for the bridge to articulate. Refer to Section 1d-2, 1d-10, and 1d-11 respectively.

For the load test, two deliverables will be recorded: if the bridge supports a 20kg load, and that the deflection of the road deck under the load is less than 25 mm. Refer to Section 1d-7 and 1d-9 respectively.

For the weight test, one deliverable will be recorded: the total weight of the bridge and articulation tower (with articulation hard components removed). Refer to Section 1d-8.

The bridge itself also has four deliverables: if it allows a 25mm x 32mm block to traverse the bridge, the length of the bridge, the width of the road deck, and the materials the bridge is made from. Refer to Section 1d-1, 1d-4, 1d-5, and 1d-12 respectively.

For the articulation test, two requirements were that the midpoint of road deck must be 140mm above horizontal resting position when articulated and the bridge needed to articulate open within 60 seconds. Refer to Section 1d-2 and 1d-11 respectively. The predicted time to articulate the bridge was 1.26 seconds (refer to Appendix A07) and the predicted height of the road deck was 148.5 mm (refer to Appendix A01). The actual time it took to fully articulate the bridge open was 0.77 sec, 1.03 sec, and 1.11 sec for three trials, leading to an average of 0.97 seconds. The actual height of the road deck was 156 mm, 154mm, and 156 mm for three trials, leading to an average of 155.3 mm. Refer to Appendix G01 for data sheet. One issue that was encountered during testing was that the speed of the motor was too fast, and the momentum of the articulation caused the articulation tower to lift off the ground on the side that was connected to the bridge. Since there was no way to change the speed of the motor, this issue was resolved by holding down the articulation tower during testing. If the motor was able to be slowed, the bridge would be more stable when articulating up and down.

5. BUDGET

a. Parts

Balsa wood was ordered as 3/8" square 36" long strips, which were available at a variety of online retailers. These strips were used to construct the entirety of the truss of the bridge. The truss members were held together by wood glue, also widely available at various retailers. Specific descriptions and costs of the parts can be found in Appendix C.

b. Outsourcing

No parts were outsourced on this project. All parts were manufactured at CWU.

c. Labor

To manufacture the bridge, it is estimated that a total of 20 hours will be needed to assemble the bridge along with its articulation components. Assuming a labor cost of $18/hour, the labor cost would total $360. However, parts were manufactured by the author of this report, who donated time, and thus the total labor cost was $0.

d. Estimated Total Project Cost

The estimated total project cost was not expected to exceed $75.00, after tax and shipping fees. Refer to Appendix D for further details.

e. Funding Source

This project was funded out of pocket by the author of the report.

f. Winter Updates

5a: As anticipated, the cost of the materials for the project was relatively inexpensive. Although there were slight design changes for the articulation tower between Fall and Winter quarter, that did not affect the amount of material that was purchased since extra raw materials were present after manufacturing. Although small mistakes were occasionally made during part manufacturing, there was plenty of excess balsa wood that was used to construct a new part if needed. The total cost of the project was $72.88 including tax and shipping. Manufacturing issues were not present, so the manufacturing did not affect the budget.

5b: No change to statement made in Fall quarter for Section 5b.

5c: No change to statement made in Fall quarter for Section 5c.

g. Spring Updates

5a: There were no costs due to errors or mistakes during testing. The bridge was successfully tested without any damage to the project or additional resource costs.

5c: All testing was done by the author of this report, who donated the time. There were no labor costs due to testing.

5d: Testing did not impact the overall budget for the project. The project remained under the initial $75 budget. Although some mistakes were made during the testing, they only impacted the number of trials that had to be conducted and did not impact the budget. There were missing resources were present during testing, but alternative solutions were created and proved to be successful (refer to Section 8c). For future reference, determining what resources are available in Hogue should be done before planning the testing procedures.

6. SCHEDULE

a. Design

Fall:

During Fall quarter, the design and project proposal began. One motivation for completing the project was staying up to date with tasks regarding the project and not falling behind. Throughout the project, several of the sections and analyses had to be revised due to comments made by the instructors. It was difficult to keep up with the current task at hand while still revising previous tasks. As shown in the Gantt Chart in Appendix E, several tasks took longer than estimated, which caused delay in getting work done efficiently.

b. Construction

Fall:

After analyses were done to determine the base, height, and length of the balsa wood trusses and road deck, balsa wood was purchased to that base and height. Wood glue was also purchased to hold the balsa wood together, and a motor for the articulation tower was purchased as well. Due to the overall simplicity of the project and bridge design, construction was predicted to be a short task.

Winter:

Construction tasks were started and completed during winter quarter. Prior to Winter quarter, eight 3/8" x 3/8" x 36" stock pieces of balsa wood were purchased for the project, as well as wood glue and a motor, all of which was documented in Appendix C. This allowed the construction of the project to begin on schedule in Winter quarter, and there was no delay in manufacturing due to waiting for materials to ship. As per the Gantt Chart in Appendix E, most of the part construction was done by cutting the balsa wood to length, and most of the device construction was done by gluing the parts together to form the bridge and articulation tower. Manufacturing each part was not time consuming, which allowed the project to stay on schedule. There were three major milestones for the manufacturing of the project: constructing the bridge, constructing the articulation tower, and constructing the final project. Each of these milestones were met on time, which can be seen on the Gantt chart section 5 in Appendix E.

Once again referring to the Gantt chart sections 4 and 5 in Appendix E, the estimated amount of time to manufacture each part was similar to the actual amount of time it took to manufacture parts. Almost all of the parts were manufactured in a few days due to the simplicity of the parts, and each part took roughly 0.5 hours to fully manufacture.

A risk associated with the manufacturing and construction schedule was that there was little room for error when manufacturing parts. If a part was manufactured incorrectly and there were no remaining resources to manufacture a replacement, the project would risk falling behind schedule as the additional resources were being received. This risk was mitigated by being precise when manufacturing parts and double-checking measurements before cutting.

c. Testing

Fall:

Testing would consist of various trials to ensure the bridge met the requirements. This included, but was not limited to, hanging 20 kg from the road deck, weighing the bridge, timing how long it takes to articulate, and measuring the fully articulated bridge height.

Spring:

There were 5 testing evaluations done during April and the beginning of May. The first two tests were conducted on April 3rd and consisted of measuring the dimensions of the bridge and testing the articulation of the bridge. The next test measured the tensile strength of the articulation cord and was conducted on April 19th. The last two tests were conducted on May 3rd and measured the final mass of the bridge and the load the bridge could withstand.

Ideally the tests would've been conducted during the same week, however the final schedule did not cause any delays on the project. The tests were conducted over various weeks due to the instruction of the mentors. The tests were also simple and straightforward, which allowed each test to be completed within less than one hour. Each test was conducted during class time and completed on time with the schedule.

The load test was the last test conducted since there was a chance the bridge could've been permanently damaged during the test, which would've impacted the other tests. The load test also required the use of the Instron and a custom piece to hold the bridge during the test, both of which required the instructor, who wanted to conduct the load test for all bridge projects on the same day. Hence why the load test was conducted almost an entire month after the first tests were conducted. Despite the load test being conducted so late, it did not impact any other task on the schedule.

Refer to the Gantt Chart in Appendix E for specific schedule dates.

7. PROJECT MANAGEMENT

Risks of this project included time management, failure of the final product, and supply chain issues leading to lack of materials and resources. Time management required additional attention because as a student, responsibilities from other classes, work, or extracurricular activities took time away from the project. Since the project had a strict deadline and only a set amount of months to complete in its entirety, managing time effectively was essential in completing the project. To control this risk, a schedule was created and strictly followed (refer to Appendix E), and tasks assigned by the instructors were completed on time. This project will succeed due to the availability of appropriate technical expertise and resources.

a. Human Resources

The project designer provided expertise in stress equations, material property analysis, and truss analysis, and their resume is shown in Appendix H. The mentors also provided additional knowledge from experience of mechanics of materials, as well as clarification on what was expected from the project. A risk with the mentors was time, as they had their own schedules to attend to, as well as the fact that their attention was divided up by all the other projects that were being simultaneously worked on by other engineering students. This risk was mitigated by using class time efficiently and coming to class prepared if assistance was needed from the instructors.

b. Physical Resources

Physical resources that were required for this project was a hobby hacksaw to cut the balsa wood to the desired lengths. A risk associated with this manufacturing method was that it would not leave the best finish on the balsa wood when compared to a table saw. This risk was mitigated by carefully manufacturing each part during construction.

c. Soft Resources

Soft resources for this project include Microsoft Word to document the project report, Excel for data, graphs, and calculations, and Project to ensure the project was on schedule. SolidWorks was a soft resource that allowed for the creation of 3D models of the parts, along with their accompanying drawings. MDSolids allowed for verification on mechanics of materials analyses. Risks with these soft resources include time availability, since SolidWorks was only reliable in the computer lab, but using class and open lab time efficiently allowed for this to not be an issue. Another risk was software crashes, which were addressed by constantly saving documents as they were being worked on.

d. Financial Resources

No grants or donations were provided by outside sources for this project. The risk of going over budget was possible. However, due to the low cost of the resources needed to manufacture this project, additional funds will be paid out of pocket by the project designer, if needed.

8. DISCUSSION

a. Design

The initial design that was drafted for the bridge was not largely changed as the project progressed; the bridge retained the same basic design throughout the design phase. However, the dimensions were slightly changed. As the two-dimensional free body diagram was translated to three dimensions, some of the initial dimensions had to be updated and adjusted to account for the conversion. However, the articulation tower had several potential designs before the final design was finally chosen. The final tower design was chosen based on remaining materials from the bridge and simplicity of construction.

One risk for the project was time management. Between other classes, homework, work, and extracurricular activities, ensuring enough time was dedicated to the project was vital. To overcome this risk, specific time throughout the week was dedicated to the project. This included the class time provided and weekend afternoons were specifically used to work on the project. For the design portion of this project, most tasks were met on time, and there was ample time to work on those that were not completed on time or required revisions.

Another risk was the overall design of the bridge. If the bridge failed, meaning it didn't span the required length and articulate, the entire project, including analyses, drawings, and construction had to be completely redone. To overcome this, research on various balsa wood bridge projects was done before even choosing the final design. Other college courses taken alongside this project also provided laboratory experiments that involved balsa wood, allowing for a hands-on understanding of both calculated and physical balsa wood properties.

Something unsuccessful with this project was the majority of the initial analyses. Many of the analyses that were completed were deemed irrelevant as the project went along, such as dimension changes that caused an analysis that calculated the total mass of the bridge to be updated. The constant need to update and occasionally redo an analysis entirely caused delays on the project and took time away from progressing on the project. Although all the analyses have all been completed for this project, for future projects it's important to note that extra time should be allotted to account for any adjustments to be made on the analyses. The analyses can bring about complete design changes, and therefore it's vital to ensure each analysis does not impact the validity of the others. Another way to remedy this would be to have rough analyses that corroborate a design, then to refine those analysis in a legible from, that way there is some form of direction before work on the analyses even starts.

A success of the project was completing all of the work assigned by the mentors on time and going back and revising the project based off of feedback from the mentors as they provided comments. This allowed the project to be completed in a timely manner, and therefore allowed for ample time to revise and edit the project.

b. Construction

The manufacturing process changed slightly after the first two parts were manufactured. Initially, the parts were manufactured using a precision knife, however this process was more time consuming than initially anticipated. The precision knife also did not leave a good finish on the balsa that it cut, which was unacceptable for the project considering several of those cut surfaces would end up mating with other parts. Due to this, remaining parts were manufactured using a hobby hacksaw. Not only did the hacksaw allow parts to be manufactured more efficiently and in less time, but also left a better finish on the manufactured parts.

A risk with manufacturing was ensuring all parts were manufactured without wasting any purchased materials. Since the project was on a budget, it was imperative that each part was manufactured properly the first time and did not require excess attempts at manufacturing and wasting materials. This was also difficult due to the softness of balsa wood, as it would occasionally split while it was being cut. This risk was mitigated by measuring the balsa wood accurately before manufacturing, and cutting the wood gently enough so the wood did not split or chip while being cut. On occasion parts were deemed unusable after being manufactured, however there was a surplus of balsa wood that allowed for a few parts to be manufactured again.

As mentioned above, an unsuccessful part of manufacturing was realizing that the precision knife was not a reliable way to manufacture parts. Another unsuccessful part of the project was the precision of the drawings. The drawings were precise to the hundredths of a millimeter, which for the scope of this project was unrealistic to manufacture to without spending an unreasonable amount of time manufacturing each part, since a total of over 60 total pieces needed to be manufactured for the bridge and articulation tower. To address this, parts were manufactured to a tenth of a millimeter instead. This allowed parts to be manufactured in a reasonable amount of time.

A success of manufacturing was the speed that the parts were manufactured at after purchasing the hobby hacksaw. Roughly half of the parts were manufactured within an hour and a half, which was roughly the amount of time it was estimated the parts would be manufactured. Another success was staying within the budget for the project. Refer to Section 5 for further information.

c. Testing

During the articulation test there was only one modification to the testing procedure, which was the method at which the bridge articulation cycle was timed. Initially, a stopwatch was planned to be used to measure the bridge articulation time, however trying to simultaneously start and stop both the articulation button and the stopwatch was thought not give precise data. Since many of the testing processes needed to be recorded for the project webpage, it was decided that was going to be the way to measure the time.

There were little risks during the articulation test since the test only consisted of articulating the bridge, which was a feature that it was designed to do. No modifications were required for the project, and the only change to the procedure was the change from stopwatch to recording that was mentioned above.

Successes were that the articulation test was successfully conducted. All necessary data was retrieved during testing, and the bridge was able to meet the requirements of the project. There were no failures during the articulation test, as the test was completed successfully.

One issue during the tensile test was finding an appropriate weight that would be applied to the articulation component. Initially, a slotted weight with hanger was going to be hung from the articulation cord. However, there were no weights that could be found in Hogue at the time of testing. To resolve this issue, popsicle sticks were placed in a Ziplock bag, which was then hung from the articulation cord. The popsicle sticks and Ziplock bag makeshift weight was weighted on a scale to determine its weight. If the weight needed to be increased, additional popsicle sticks were added to the makeshift weight. The test was ultimately conducted successfully, and the bridge lifted 0.1 mm under a 15-gram mass such that one sheet of standard printer paper was slid under the bridge (refer to Appendix G2.3).

9. CONCLUSION

a. Design

This project was the articulating balsa wood bridge. The balsa wood bridge must allow passage over a normally impassable terrain. An important analysis was Analysis 2 – Forces in Truss Members, which determined the force in each of the members of the truss for the bridge, and Analysis 3 – Cross-Sectional Area of Truss Members, which determined the cross-sectional area of the truss members for the bridge. The design met all the requirements, and this can be seen in each of the analyses. To meet each of these requirements, engineering merit in statics, mechanics of materials, and dynamics was required. All resources needed to complete the project were available. Success for this project was the designing, construction and manufacturing, and successful testing of the balsa wood bridge. A model has been conceived, analyzed, and designed that meet the requirements defined in Section 1d. Parts have been specified, sourced, and budgeted for acquisition. With this information, the model is ready to be created.

b. Construction

The articulating balsa wood bridge used a Pratt Truss as its design with a tower to help with articulation. The project was manufactured using a hobby hacksaw to cut balsa wood members and wood glue was used to construct the bridge and articulation tower. Modifications that were applied to the manufacturing process was changing from a precision knife to a hobby hacksaw to manufacture parts, which allowed for efficient and timely manufacturing. Another manufacturing modification was measuring and marking multiple sides of the raw material before cutting. This allowed each part to have a better finish and verify that the length of the part being manufactured was as accurate as possible. Refer to Section 8b for further details. The manufacturing process was successful. The project was fully manufactured in Winter quarter.

c. Testing

The articulating balsa wood bridge was overall a success in both performance and design. It showed success in the four areas of design. The bridge articulated open in 0.97 seconds on average, lower than the predicted 1.26 seconds and the requirement of 60 seconds. The midpoint of the bridge articulated to 155 mm on average, above the predicted 148.5 mm and the required 140 mm. The bridge withstood a load of 19.4 kg without permanent damage, meeting the requirement of 18.9 kg. The bridge was designed to withstand a 25 kg load. The final weight of the bridge was 79.5 grams, below the maximum allowed 85 grams.

The bridge was a failure in one area of design. The bridge articulated when 15 grams was applied to the articulation component, passing the prediction of 28 grams but not meeting the requirement of 10 grams.

10. ACKNOWLEDGEMENTS

This project would like to acknowledge Professor Pringle and Professor Choi for their mentorship on the project and presentations, as well as the other professors in the Mechanical Engineering Technologies program at Central Washington University for their instruction and guidance on the various engineering methods and calculations taught during lectures and labs.

This project also acknowledges other engineering students who were working on an articulating balsa wood bridge project of their own, as they corroborated to further understand project requirements and milestones.

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APPENDIX A – Analysis

Appendix A01 – Height of Articulated Midpoint

Nate Harris | MET 489a | 10/3/2023

Given:
- Midpoint of road deck must be 140mm above original resting position.
- Bridge must be longer then 400mm to rest on abutments

Find: height of midpoint of road deck when articulated

Assume: bridge is 420mm long
bridge articulates 45°

Method: trig

Solution

$$\sin \theta = \frac{opp}{hyp}$$

$$opp = hyp \sin \theta$$

$$x = (210\ mm)(\sin 45)$$

$$\boxed{x = 148.5\ mm}$$

midpoint of bridge will reach 148.5mm if bridge articulates 45°

Appendix A02 – Forces in Truss Members

Given: Truss must support 20 Kg load

Find: Reactions in all joints

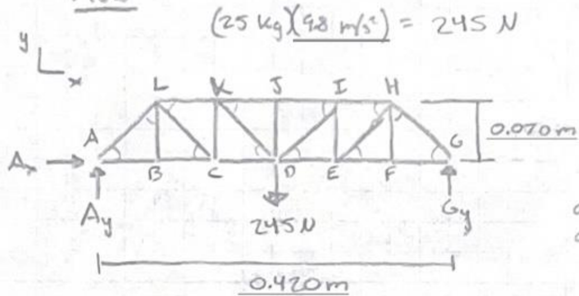
Assume: Pratt Truss Design
25 Kg load
Beams are weightless
Road deck is 420 mm long
All angles are 45°

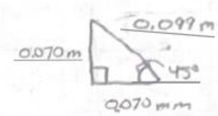
Method: Equilibrium, Method of Joints

Solution:

FBD

$(25\ kg)(9.8\ m/s^2) = 245\ N$





all angles are 45°

Equilibrium

$\circlearrowleft + \Sigma M_A = 0 = 245\ N(0.210\ m) + G_y(0.420\ m)$

$Bg(0.420) = 51.45$

$\boxed{G_y = 122.5\ N}$

$\Sigma F_y = 0 = A_y - 245 + G_y$

$A_y = 245 - 122.5$

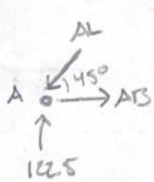
$\boxed{A_y = 122.5\ N}$

$\Sigma F_x = 0 = A_x$

$\boxed{A_x = 0}$

Method of Joints

Point A FBD



$\Sigma F_y = 0 = 122.5 + AL \sin 45°$

$AL \sin 45 = -122.5$

$AL = -173.2\ N$

$\boxed{AL = 173.2\ N\ (C)}$

$\Sigma F_x = 0 = AB + (-173.2 \cos 45°)$

$0 = AB - 122.5\ N$

$\boxed{AB = 122.5\ N\ (T)}$

Appendix A02 – Forces in Truss Members

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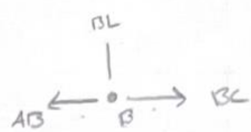
Point B FBD



$\Sigma F_x = 0 = AB + BC$

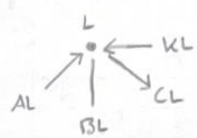
$0 = -122.5 + BC$

$\boxed{BC = 122.5\ N\ (T)}$

$\Sigma F_y = 0 = BL$

$\boxed{BL = 0\ N}$

Point L FBD



$\Sigma F_y = 0 = AL \sin 45 + CL \sin 45 + BL$

$0 = 173.2 \sin 45 + CL \sin 45 + 0$

$CL \sin 45 = -173.5 \sin 45$

$CL = -173.2$

$\boxed{CL = 173.2\ N\ (T)}$

$\Sigma F_x = 0 = AL \cos 45 + CL \cos 45 + KL$

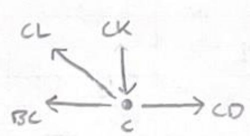
$0 = 173.2 \cos 45 + 173.5 \cos 45 + KL$

$0 = 122.5 + 122.5 + KL$

$KL = -245\ N$

$\boxed{KL = 245\ N\ (C)}$

Point C FBD



$\Sigma F_y = 0 = CL \sin 45 + CK$

$0 = 173.2 \sin 45 + CK$

$CK = -122.5$

$\boxed{CK = 122.5\ N\ (C)}$

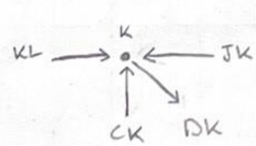
$\Sigma F_x = 0 = CL \cos 45 + BC + CD$

$0 = -173.2 \cos 45 - 122.5 + CD$

$0 = -122.5 - 122.5 + CD$

$\boxed{CD = 245\ N\ (T)}$

Point K FBD



$\Sigma F_y = 0 = CK + DK \sin 45$

$0 = 122.5 + DK \sin 45$

$-122.5 = DK \sin 45$

$DK = -173.2$

$\boxed{DK = 173.2\ N\ (T)}$

$\Sigma F_x = 0 = KL + JK + DK \cos 45$

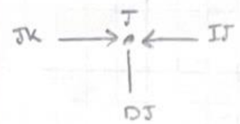
$0 = 245 + JK + 173.2 \cos 45$

$JK = -367.5$

$\boxed{JK = 367.5\ N\ (C)}$

Appendix A02 – Forces in Truss Members

Point J FBD



$\Sigma F_x = 0 = JK + IJ$

$0 = 367.5 + IJ$

$IJ = -367.5$

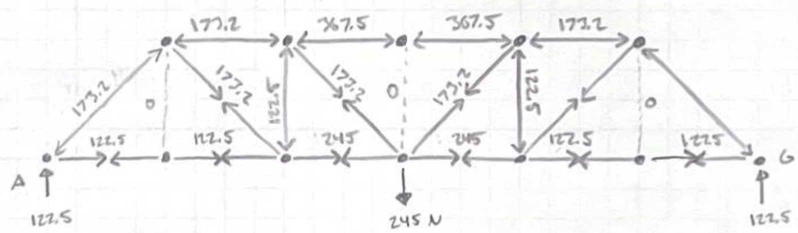
IJ = 367.5 (C) N

$\Sigma F_y = 0 = DJ$

DJ = 0 N

Truss is symmetrical about DJ, therefore

AB = FG = 122.5 N (T)
AL = GH = 173.2 N (C)
BL = FH = 0 N
KL = HI = 245 N (C)
BC = EF = 122.5 N (T)
CL = EH = 173.2 N (T)
CK = EI = 122.5 N (C)
CD = DE = 245 N (T)
DK = DI = 173.5 N (C)
JK = IJ = 367.5 N (C)
DK = 0 N



Appendix A02 – Forces in Truss Members

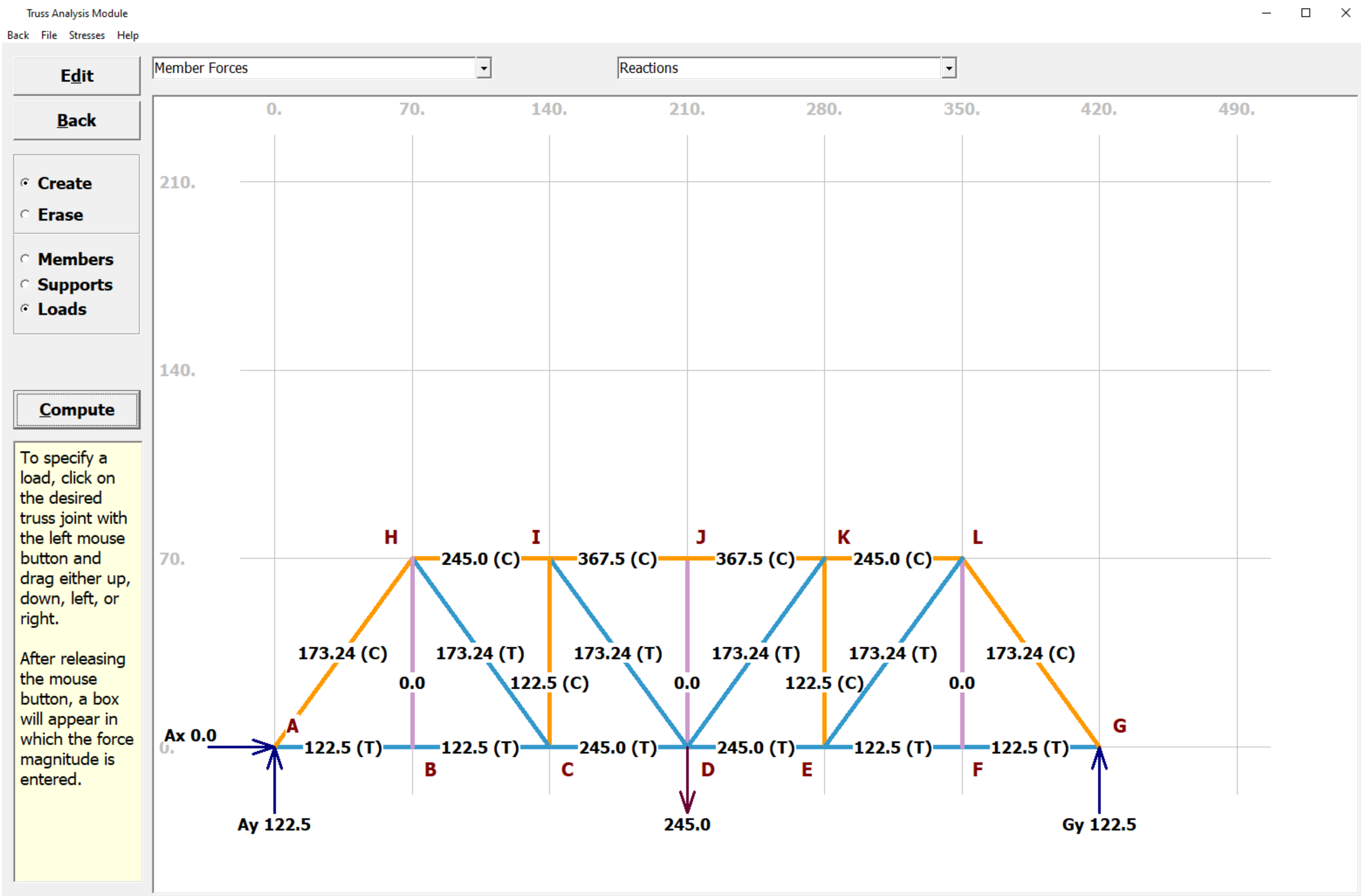


Figure 1: Screenshot of member force analysis done on MDSolids.

Appendix A03 – Cross-Sectional Area of Truss Members

Given: forces applied to members (Appendix A02)

Find: Cross-sectional area of truss to support load.

Assume: axial loading
no mass in member
Truss has square cross-sectional area
max tension is 245 N
max compression is 367.5 N

Method: apply safety factor,
solve stress equation for tension and compression

Solution:

Material Properties of Balsa Wood from MatWeb

Ultimate Tensile Strength = 73.0 MPa (Axial)
Compressive Strength = 6.90 - 9.00 MPa (Parallel to Grain)

FBD Compressed

$$\text{Safety Factor} = \frac{\sigma_{max}}{\sigma}$$

$$\sigma = \frac{\sigma_{max}}{\text{safety factor}} = \frac{6.9\ MPa}{1.25} = 5.52\ MPa$$

$$\sigma = \frac{F}{A} = \frac{F}{b^2}$$

$$b = \sqrt{\frac{F}{\sigma}} = \sqrt{\frac{367.5\ N}{5.52 \times 10^6\ Pa}} = \underline{0.00816\ m} = \underline{8.16\ mm}$$

Appendix A03 – Cross-Sectional Area of Truss Members

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Confirm tensile will not require larger than 8.16mm

FBD Tensile

$$\sigma = \frac{\sigma_{max}}{\text{Safety Factor}} = \frac{73.0\ MPa}{1.25} = 58.4\ MPa$$

$$b = \sqrt{\frac{F}{\sigma}} = \sqrt{\frac{245\ N}{58.4 \times 10^6\ Pa}} = \underline{0.00205\ m} = \underline{2.05\ mm}$$

$b_{compression} > b_{tensile}$

$\underline{8.16\ mm} > \underline{2.05\ mm}$

Therefore, each member in truss must be at least 8.16 mm × $\underline{8.16\ mm}$

Standard Size

$\underline{8.16\ mm} \approx 0.321$ in

The nearest standard size (rounding up) is 3/8 in (0.375 in)

All balsa wood truss members should have a cross sectional area of 3/8" × 3/8" to support load.

Appendix A04 – Dimensions of Truss Members

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Given: truss FBD

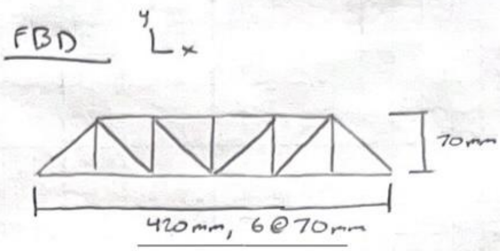
Find: dimensions of truss members

Assume: FBD is centroid of beam

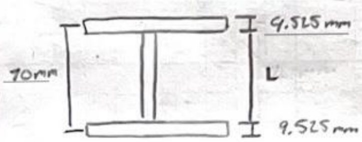
Method: geometry

Solution:

FBD

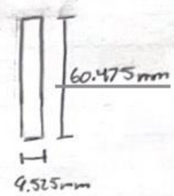


Vertical Trusses

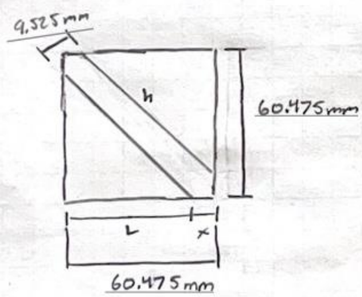


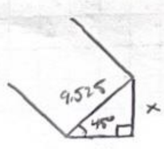
$L = 70 - 2(\frac{1}{2} \cdot 9.525)$

$L = 60.475$



Interior Angled Trusses





$\cos \Theta = \frac{adj}{hyp}$

$x = hyp \cos \Theta$

$= 9.525 \cos 45$

$x = 6.735$

Appendix A04 – Dimensions of Truss Members

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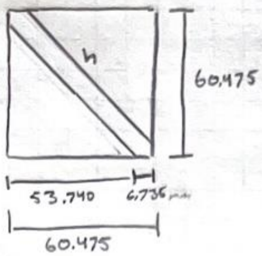
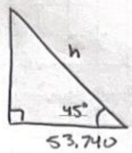


$L + x = 60.475$

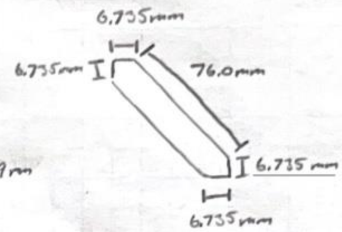
$L = 60.475 - 6.735$

$L = 53.740$ mm

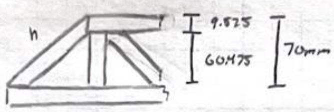


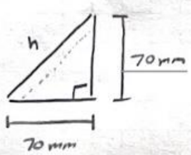
$\cos \theta = \frac{adj}{hyp}$

$h = \frac{adj}{\cos \theta} = \frac{53.740}{\cos 45} = 75.999$ mm



Exterior Angled Truss



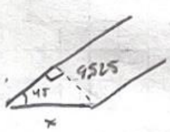


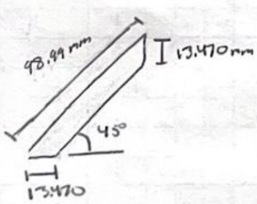
$\sin \theta = \frac{opp}{adj}$

$h = \frac{opp}{\sin \theta} = \frac{70}{\sin 45} = 98.99$ mm

$\sin \theta = \frac{opp}{hyp}$

$x = \frac{opp}{\sin \theta} = \frac{9.525}{\sin 45} = 13.470$ mm





Appendix A05 – Thickness of Road Deck Support

Nate Harris | MET 489 | 11/05/2023 | 1/1

Given: reactions of truss members

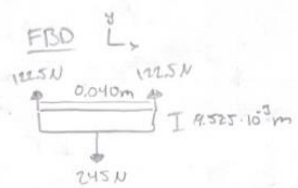
Find: width of road deck support

Assume: $\sigma_{balsa} = 1.10$ MPa
Length = 40 mm
height = 9.525 mm

Method: stress equation

Solution:

FBD



$$\text{safety factor} = \frac{\sigma_{max}}{\sigma}$$

$$\sigma = \frac{\sigma_{max}}{SF} = \frac{1.10 \text{ MPa}}{1.25} = \underline{\sigma = 0.88 \text{ MPa}}$$

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

$$w = \frac{F}{h\sigma} = \frac{245 \text{ N}}{(9.525 \times 10^{-3} \text{ m})(0.88 \times 10^{6} \text{ Pa})} = 0.02922 \text{ m} = \boxed{w = 29.2 \text{ mm}}$$

$$29.2 \text{ mm} \approx 1.150 \text{ in} \xrightarrow{\text{standard size}} 1.50 \text{ in}$$

road deck supports must be 3/8" × 1.5" (9.525 mm × 38.1 mm) to support loading.

Appendix A06 – Shear Strength of Adhesive

Nate Harris	MET 489	11/05/2023	1/1

Given: reactions on truss members
reactions on road deck support

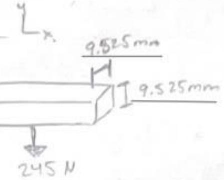
Find: if adhesive can support shear stress

Assume: adhesive shear strength = 27 MPa
max shear force on bridge is 245 N
smallest cross sectional area = 9.525 mm × 9.525 mm

Method: shear stress equation

Solution:

FBD



$$\tau = \frac{F}{A} = \frac{245}{(9.525\times10^{-3}\,m)^2} = 2700450\ Pa = \tau = 2.7\ MPa$$

$\tau_{adhesive} > \tau_{bridge}$
27 MPa > 2.7 MPa

The adhesive can support the shear force on the bridge.

Appendix A07 – Power to Articulate Bridge

Nate Harris	MET 489	11/10/2023	1/1

Given: bridge must articulate in under 60 s
motor torque: 40 mNm
motor angular velocity: 380 rpm

Find: if motor power can support articulating bridge in 60 s

Assume: bridge weight: 85 g
distance string travels to lift bridge is 0.5 m

Method: power equations

Solution:

Power of motor

$T = 40\ mNm = 0.040\ Nm$

$\omega = 380\ rpm \cdot \left(\frac{2\pi\ rad}{1\ rev}\right)\left(\frac{1\ min}{60\ s}\right) = 39.79\ rad/s$

$P_{motor} = T\omega$

$= (0.040\ Nm)(39.79\ rad/s)$

$P_{motor} = 1.59\ W$

Power required to lift bridge

$F = (0.085\ kg)(9.8\ m/s^2) = 0.833\ N$

$d = 0.5\ m$

$t = 60\ s$

$P_{bridge} = \frac{Fd}{t} = \frac{(0.833\ N)(0.5\ m)}{60\ s} = P_{bridge} = 0.0069\ W$

$P_{motor} > P_{bridge}$

$1.59\ W > 0.0069\ W$

The motor has the power to articulate the bridge in 60 s.

Time to articulate bridge

$P_{motor} = \frac{Fd}{t} \Rightarrow t = \frac{Fd}{P_{motor}} = \frac{(0.833\ N)(0.5\ m)}{(1.59\ W)} = 0.26\ s$

add 1.00 s for acceleration of motor, friction, and error in calculations

$t_{predicted} = 1.26\ s$

Appendix A08 – Deflection of Truss

Nate Harris	MET 489	11/11/2023	1/2

Given: max deflection ≤ 25 mm
truss dimensions

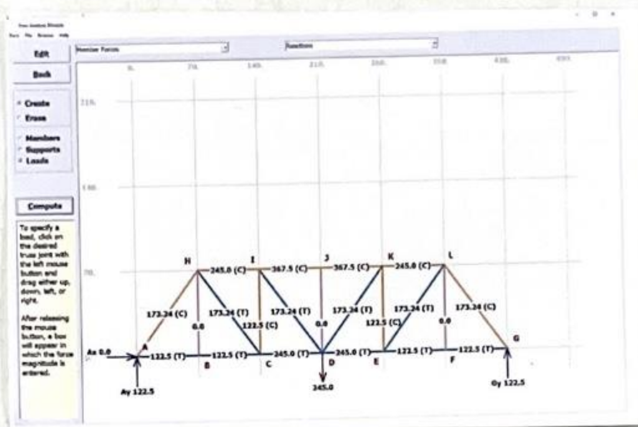
Find: deflection of truss

Assume: E = 3.71 GPa
all member's cross-sectional area = 9.53 mm × 9.53 mm

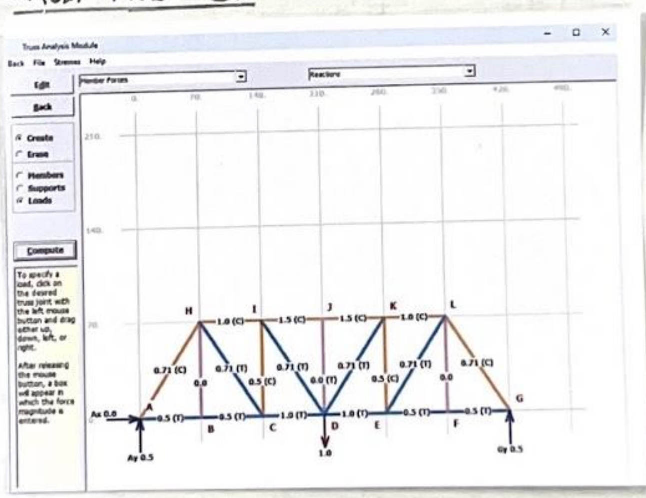
Method: MD Solids
Virtual Work

Solution:

Real FBD $\overset{\text{?}}{L}_x$



Virtual FBD $\overset{\text{?}}{L}_x$



Appendix A08 – Deflection of Truss

Nate Harris	MET 489	11/11/2023	2/2

Deflection at Point D

Member	N (N)	n (N)	L (m)	NnL (N^2m)
IJ	367.5	1.5	0.070	38.59
JK	367.5	1.5	0.070	38.59
CD	245	1.0	0.070	17.15
DE	245	1.0	0.070	17.15
KL	245	1.0	0.070	17.15
HI	245	1.0	0.070	17.15
AL	173.2	0.71	0.099	12.17
GH	173.2	0.71	0.099	12.17
CL	173.2	0.71	0.099	12.17
EH	173.2	0.71	0.099	12.17
DK	173.2	0.71	0.099	12.17
DI	173.2	0.71	0.099	12.17
AB	122.5	0.50	0.070	4.29
FG	122.5	0.50	0.070	4.29
BC	122.5	0.50	0.070	4.29
EF	122.5	0.50	0.070	4.29
CI	122.5	0.50	0.070	4.29
EK	122.5	0.50	0.070	4.29
BL	0	0	0.070	0.00
FH	0	0	0.070	0.00
DK	0	0	0.070	0.00
			Sum NnL	244.55

$A = (9.53\ mm)(9.53\ mm) = 9.08 \times 10^{-5}\ m^2$

$E = 3.71 \times 10^{9}\ Pa$

$$(1\ N)\ \delta_D = \frac{\Sigma NnL}{AE}$$

$$= \frac{(244.55\ N^2 m)}{(9.08 \times 10^{-5}\ m^2)(3.71 \times 10^{9}\ Pa)}$$

$$= 0.0007258\ m$$

$$\boxed{\delta_D = 0.726\ mm}$$

Appendix A09 – Total Mass of Bridge

Nate Harris	MET 489	11/11/2023	1/1

Given: dimensions of bridge members

Find: total mass of bridge

Assume: neglect mass of adhesive.

Method: $V = bhl$

Solution:

Bottom Hori. Member Volume (2 total)

$V = 2\,bhl$
$= 2(9.53\text{ mm})(9.53\text{ mm})(429.53\text{ mm}) = 78{,}021\text{ mm}^3$

Top Hori. Member Volume (2 total)

$V = 2\,bhl$
$= 2(9.53\text{ mm})(9.53\text{ mm})(289.53\text{ mm}) = 52{,}591\text{ mm}^3$

Vert. Member (10 total)

$V = 10\,bhl$
$= 10(9.53\text{ mm})(9.53\text{ mm})(60.48\text{ mm}) = 54{,}928\text{ mm}^3$

Exterior Angled Truss (4 total)

$V = 4\,bhl$
$= 4(9.53\text{ mm})(9.53\text{ mm})(98.90\text{ mm}) = 35{,}929\text{ mm}^3$

Interior Angled Truss (8 total)

$V = 8\,bhl$
$= 8(9.53\text{ mm})(9.53\text{ mm})(85.53\text{ mm}) = 62{,}143\text{ mm}^3$

Road Deck Support (9 total)

$V = 9\,bhl$
$= 9(9.53\text{ mm})(9.53\text{ mm})(40.00\text{ mm}) = 32{,}696\text{ mm}^3$

Road Deck (1 total)

$V = bhl$
$= (1.59\text{ mm})(40.00\text{ mm})(429.53\text{ mm}) = 27{,}318\text{ mm}^3$

Total Volume

$V_{total} = 343626\text{ mm}^3$
$= 343.626\text{ cm}^3$

Total Mass

Balsa Wood Density $= 0.160\text{ g/cm}^3$

$M_{total} = V_{total} D$
$= (343.626\text{ cm}^3)(0.160\text{ g/cm}^3)$

$\boxed{M_{total} = 54.98\text{ g}}$

Appendix A10 – Articulation Tower Dimensions

Nate Harris | MET 489 | 11/11/2023 | 1/2

Given: bridge midpoint must articulate 140 mm above horizontal

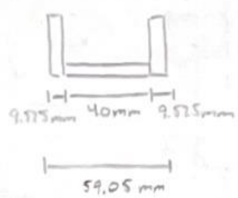
Find: dimensions of articulation tower

Assume: 3/8" x 3/8" (9.525 mm x 9.525 mm) balsa wood will be used to construct articulation tower

Method: geometry

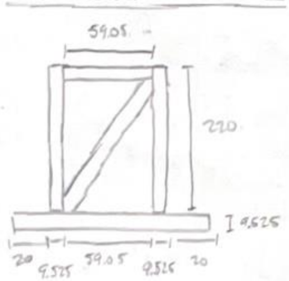
Solution:

FBD Bridge Front

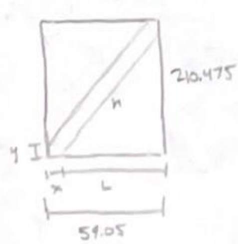


articulation tower must be 59.05 mm wide
length will be 59.05 mm to keep tower square

FBD Tower Side



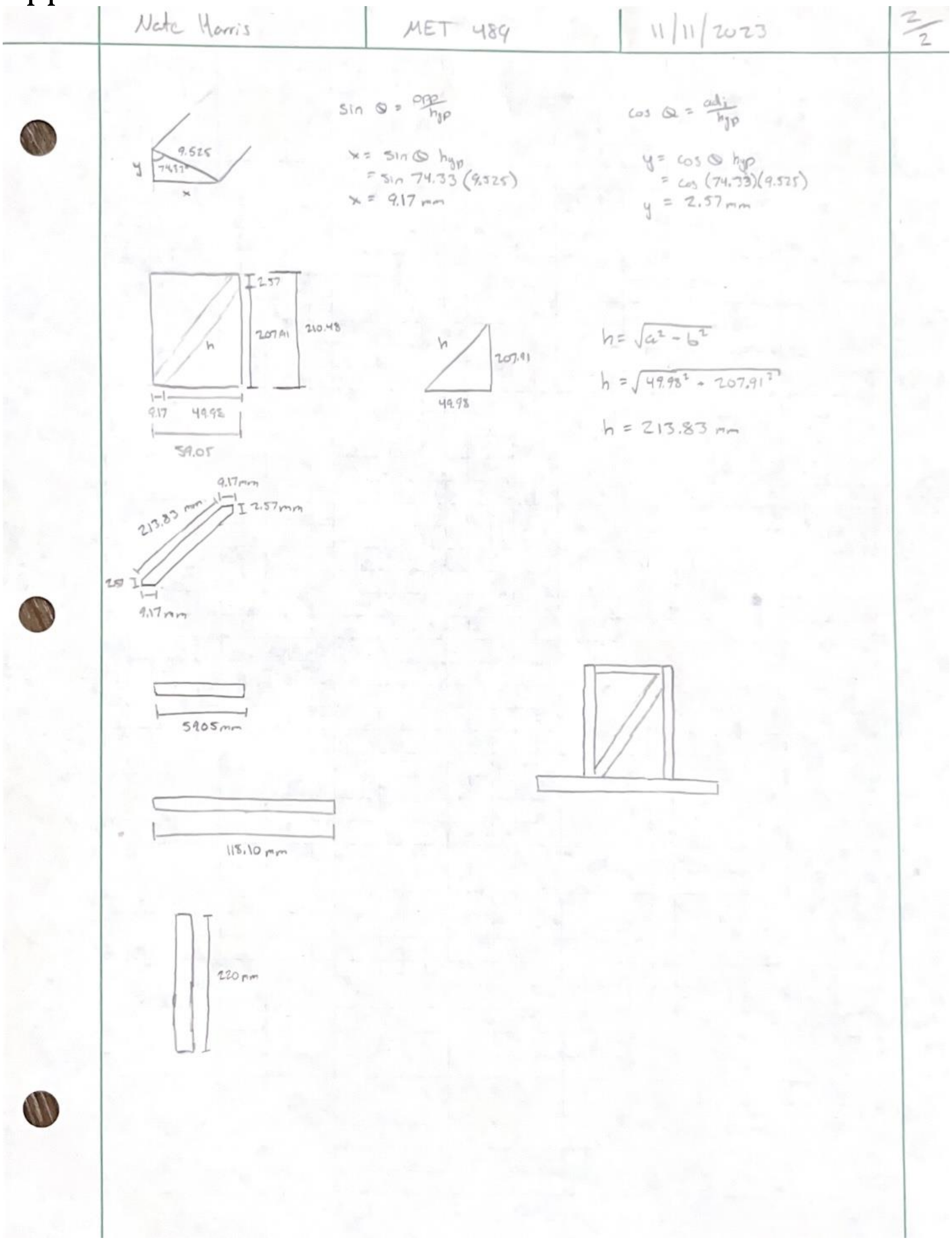
to lift the bridge 140 mm, a height of 220 mm will be estimated



$\tan\theta = \frac{opp}{adj}$

$\theta = \tan^{-1}\left(\frac{210.475}{59.05}\right) = 74.33°$

Appendix A10 – Articulation Tower Dimensions



Appendix A11 – Fatigue on Road Deck

Nate Harris | MET 489 | 12/2/2023 | 1/1

Given: road deck cross section 40 mm × 1.59 mm
material properties of balsa

Find: number of times model car can traverse over balsa bridge.

Assume: model car = 35 g
neglect road deck supports

Method: Fatigue analysis - Goodman Equation

Solution:

$$\sigma_{min} = \frac{(0\ kg)(9.8\ m/s^2)}{(0.04\ m)(0.00159\ m)} = 0\ Pa$$

$$\sigma_{max} = \frac{(0.035\ kg)(9.8\ m/s^2)}{(0.04\ m)(0.00159\ m)} = 5393\ Pa$$

$$\sigma_m = (\sigma_{max} + \sigma_{min})/2 = 2697\ Pa$$

$$\sigma_a = (\sigma_{max} - \sigma_{min})/2 = 2697\ Pa$$

K_t = solid, uniform = 1.0

S_u = 1 MPa (perpendicular to grain)
S_n = no data found, assume $S_n = S_u$

C_m = no data found; assume 1.0
C_{st} = 0.8 (bending stress)
C_R = 0.81 (desired 0.99 reliability)

$$D_e = 0.808\sqrt{bh} = 0.808\sqrt{(40\ mm)(1.59\ mm)} = 6.44\ mm$$

C_s = 1.0

$$S'_n = S_n C_m C_{st} C_R C_s = (1\ MPa)(1.0)(0.8)(0.81)(1.0) = 0.648\ MPa$$

Goodman Eq

$$\frac{K_t \sigma_a}{S'_n} + \frac{\sigma_m}{S_u} = \frac{1}{N}$$

$$\frac{(1.0)(2697\ Pa)}{648000\ Pa} + \frac{(2697\ Pa)}{1000000\ Pa} = \frac{1}{N}$$

$$0.00416 + 0.00269 = \frac{1}{N}$$

N = 145 cycles

Appendix A12 – Minimum Weight to Lift Bridge

Nate Harris | MET 489 | 1/5/2024 | 1/1

Given: bridge length = 430 mm

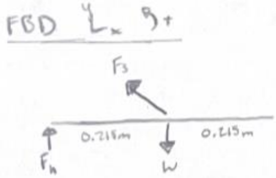
Find: mass to lift bridge

Assume: center of mass in center of bridge
bridge mass = 55g
angle of string = 45°

Method: Torque equation

Solution:

FBD



$\Sigma T = 0 = T_s - T_B$

$T_s = T_B$

$r_s F_s \sin\theta = r_w F_w \sin\theta$

$\frac{F_s}{F_w} = \frac{r_w}{r_s} = \frac{0.215}{0.430} = \frac{1}{2}$

$\frac{1}{2}W = F_h$

$\frac{1}{2}W = F_s$

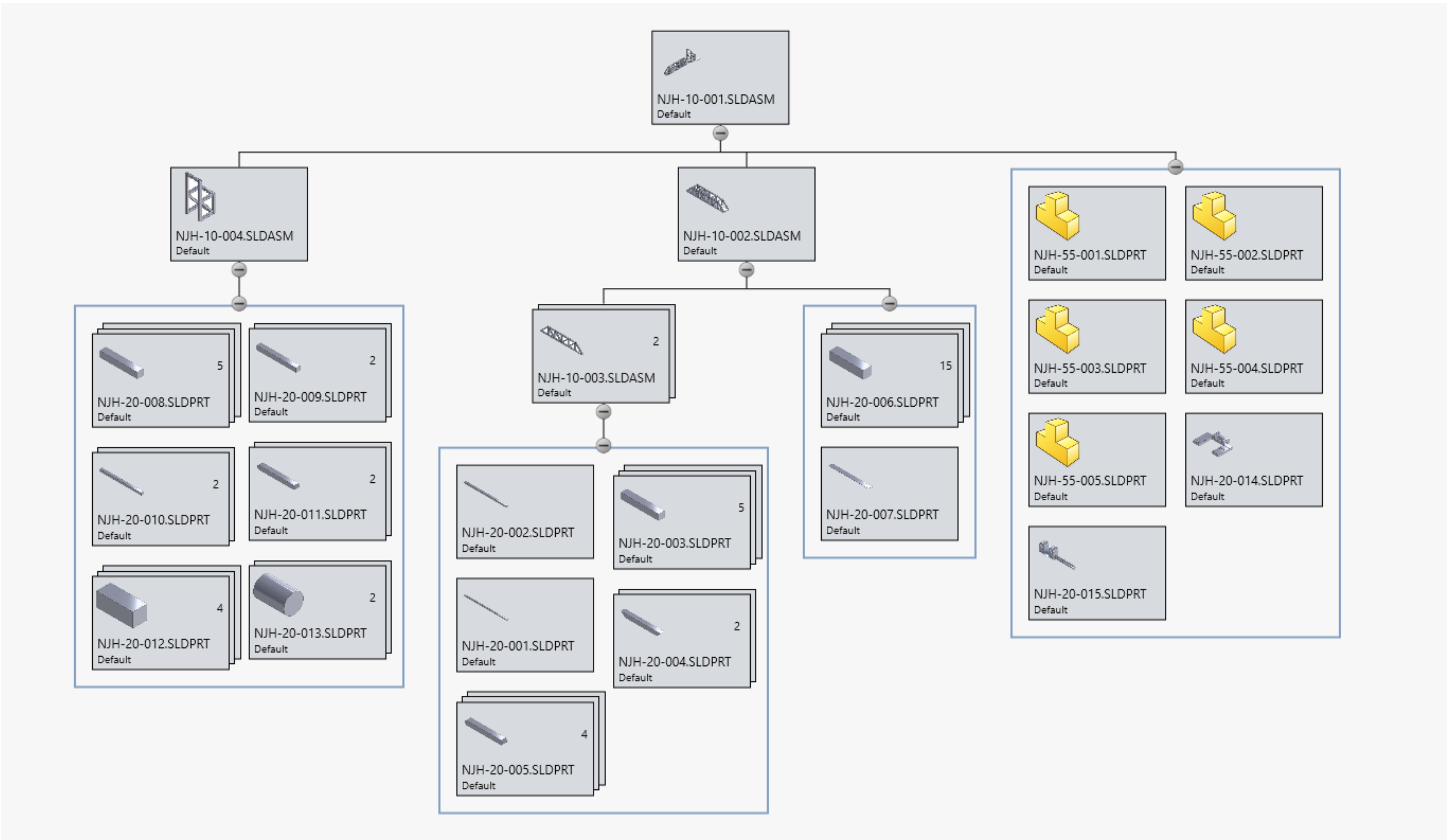
$\frac{1}{2}(0.055\ kg)(9.8\ m/s^2) = F_s$

$0.2695\ N = F_s$

$\frac{0.2695\ N}{9.8\ m/s^2} = 0.0275\ kg = \boxed{28\ g}$

APPENDIX B – Drawings

Appendix B01 – Drawing Tree



Appendix B01 – Drawing Log

DWG Number and filename	Description	DateCreated	ByWhom
NJH-10-001	Bridge and Tower Assembly	1/5/2024	Nate Harris
NJH-10-002	Bridge Assembly	11/28/2023	Nate Harris
NJH-10-003	Truss Assembly	11/28/2023	Nate Harris
NJH-10-004	Tower Assembly	1/5/2024	Nate Harris

DWG Number and filename	Description	DateCreated	ByWhom
NJH-20-001	Bottom Horizontal Truss Member	10/11/2023	Nate Harris
NJH-20-002	Top Horizontal Truss Member	10/18/2023	Nate Harris
NJH-20-003	Vertical Truss Member	10/25/2023	Nate Harris
NJH-20-004	Exterior Angled Truss	10/25/2023	Nate Harris
NJH-20-005	Interior Angled Truss	11/1/2023	Nate Harris
NJH-20-006	Road Deck Support	11/1/2023	Nate Harris
NJH-20-007	Road Deck	11/6/2023	Nate Harris
NJH-20-008	Tower Horizontal Support	1/4/2024	Nate Harris
NJH-20-009	Tower Vertical Short Support	1/4/2024	Nate Harris
NJH-20-010	Tower Vertical Tall Support	1/4/2024	Nate Harris
NJH-20-011	Tower Angled Support	1/4/2024	Nate Harris
NJH-20-012	Tower String Pivot Support	1/4/2024	Nate Harris
NJH-20-013	Tower String Pivot	1/4/2024	Nate Harris
NJH-20-014	Motor Mount	4/22/2024	Nate Harris
NJH-20-015	Axle	4/22/2024	Nate Harris

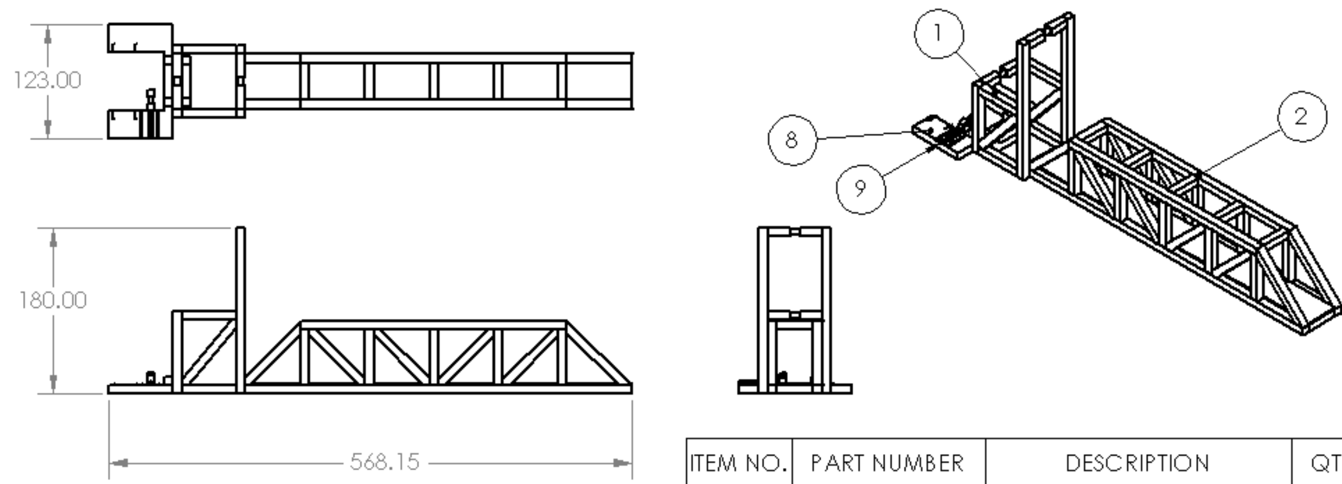
DWG Number and filename	Description	DateCreated	ByWhom	Vendor	Vendor Part#	Mfg.	Mfg. Part#	Link (If applicable)
NJH-55-00	Gorilla 4oz Wood Glue	1/19/2024	Nate Harris	Target	081-22-4242	The Gorilla Glue Company	Not on Mfg Website	N/A
NJH-55-00	Technic M-Motor and Battery Bo	1/19/2024	Nate Harris	Amazon	B0C1MQDJYL	iLeworlder	8881 8883 8293	https://www.amazon.com/gp/product/B0C1MQDJYL/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1
NJH-55-00	Max Alkaline AA Batteries - 8 Pac	3/1/2024	Nate Harris	Fred Meyer	UPC: 00039800107	Energizer	Not on Mfg Website	https://www.fredmeyer.com/p/energizer-max-alkaline-aa-batteries-8-pack/0003980010797
NJH-55-00	Cotton Craft Cord	3/1/2024	Nate Harris	Hobby Lobby	SKU: 2316248	Hobby Lobby	Not on Mfg Website	https://www.hobbylobby.com/Crafts-Hobbies/Basic-Crafts/Macrame/Cora-s-Cotton-Craft-Cord-Value-Pack/p/81152156
NJH-55-00	Nails	3/1/2024	Nate Harris	Ace Hardware	Item # 53228	Hillman	Mfr # 122561	https://www.acehardware.com/departments/hardware/nails-and-staples/nails/53228

Appendix B02 – Drawing Index

Table B02. Drawing Index

Drawing Assignment Num.	**Drawing #(s)**	**Date Submitted**
Upload: DWG 1	NJH-20-001	10/11/2023
Upload: DWG 2	NJH-20-002	10/18/2023
Upload: DWG 3 & 4	NJH-20-003, NJH-20-004	10/25/2023
Upload: DWG 5 & 6	NJH-20-005, NJH-20-006	11/01/2023
Upload: DWG 7 & 8	NJH-20-007, NJH-20-008	11/06/2023
Upload: DWG 9 & 10	NJH-20-009, NJH-20-010	11/13/2023
DWG 11	NJH-20-011	11/27/2023
ASSY 2, ASSY 3	NJH-10-002, NJH-10-003	11/28/2023
DWG 12, DWG 13	NJH-20-012, NJH-20-013	1/4/2024
ASSY 1, ASSY 4	NJH-10-001, NJH-10-004	1/5/2024
DWG 14, DWG 15	NJH-20-014, NJH-20-015	3/2/2024

Appendix B03 – NJH-10-001 – Bridge and Tower Assembly



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	NJH-10-004	Tower Assembly	1
2	NJH-10-002	Bridge Assembly	1
3	NJH-55-001	Wood Glue	1
4	NJH-55-002	Motor	1
5	NJH-55-003	AA Batteries	6
6	NJH-55-004	Cotton Craft Cord	1
7	NJH-55-005	Pins	2
8	NJH-20-014	Motor Mount	1
9	NJH-20-015	Axle	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	NJH	1/5/24
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY | USED ON
APPLICATION

PROPRIETARY AND CONFIDENTIAL
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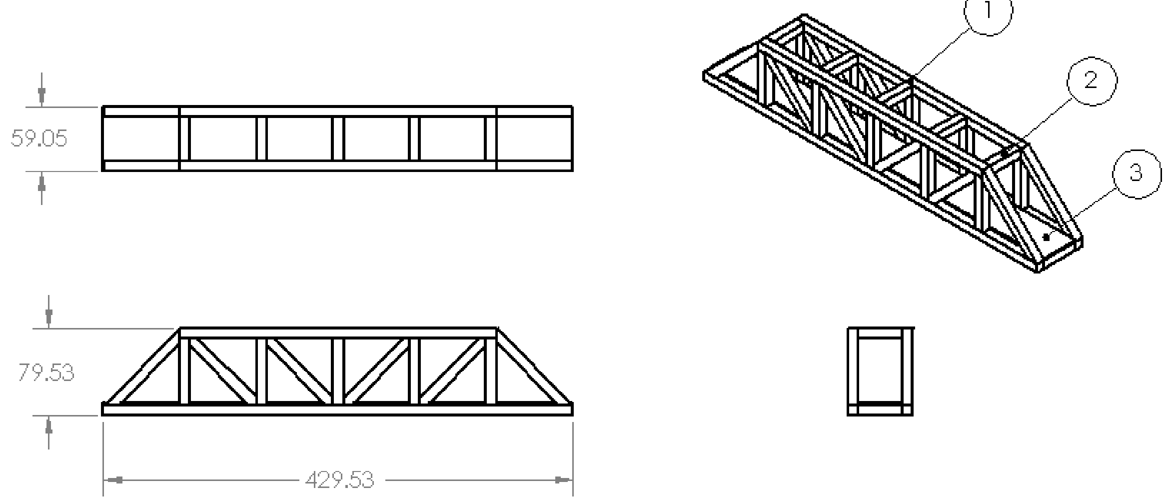
TITLE:
Bridge and Tower Assembly

SIZE A | DWG. NO. NJH-10-001 | REV

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1

Appendix B04 – NJH-10-002 – Bridge Assembly



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	NJH-10-003	Truss Assembly	2
2	NJH-20-006	Road Deck Support	15
3	NJH-20-007	Road Deck	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	NJH	11/28/23
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

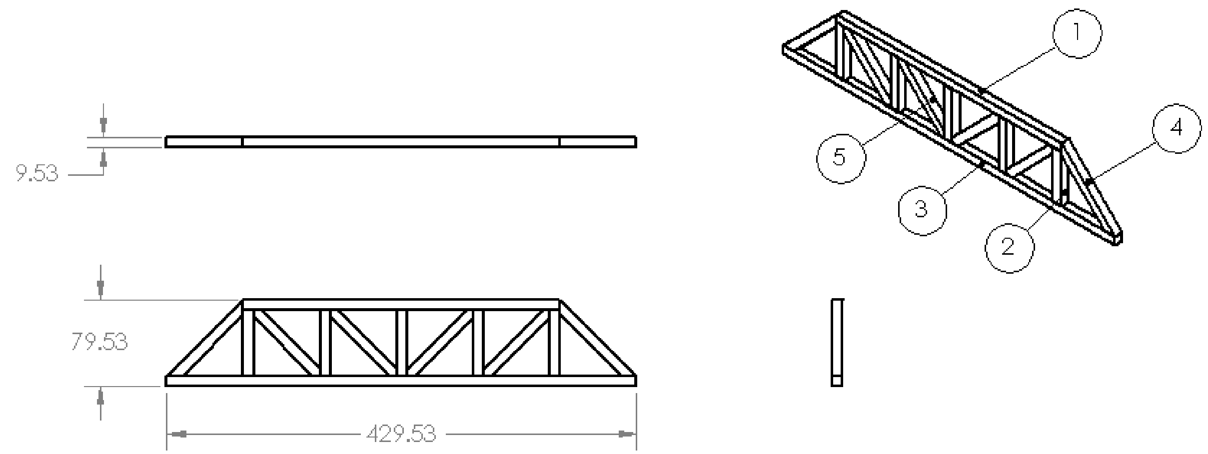
NEXT ASSY | USED ON
APPLICATION

TITLE: Bridge Assembly

SIZE A | DWG. NO. NJH-10-002 | REV

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

Appendix B05 – NJH-10-003 – Truss Assembly



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	NJH-20-002	Top Horizontal Truss	1
2	NJH-20-003	Vertical Truss Member	5
3	NJH-20-001	Bottom Horizontal Truss	1
4	NJH-20-004	Exterior Angled Truss	2
5	NJH-20-005	Interior Angled Truss	4

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NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

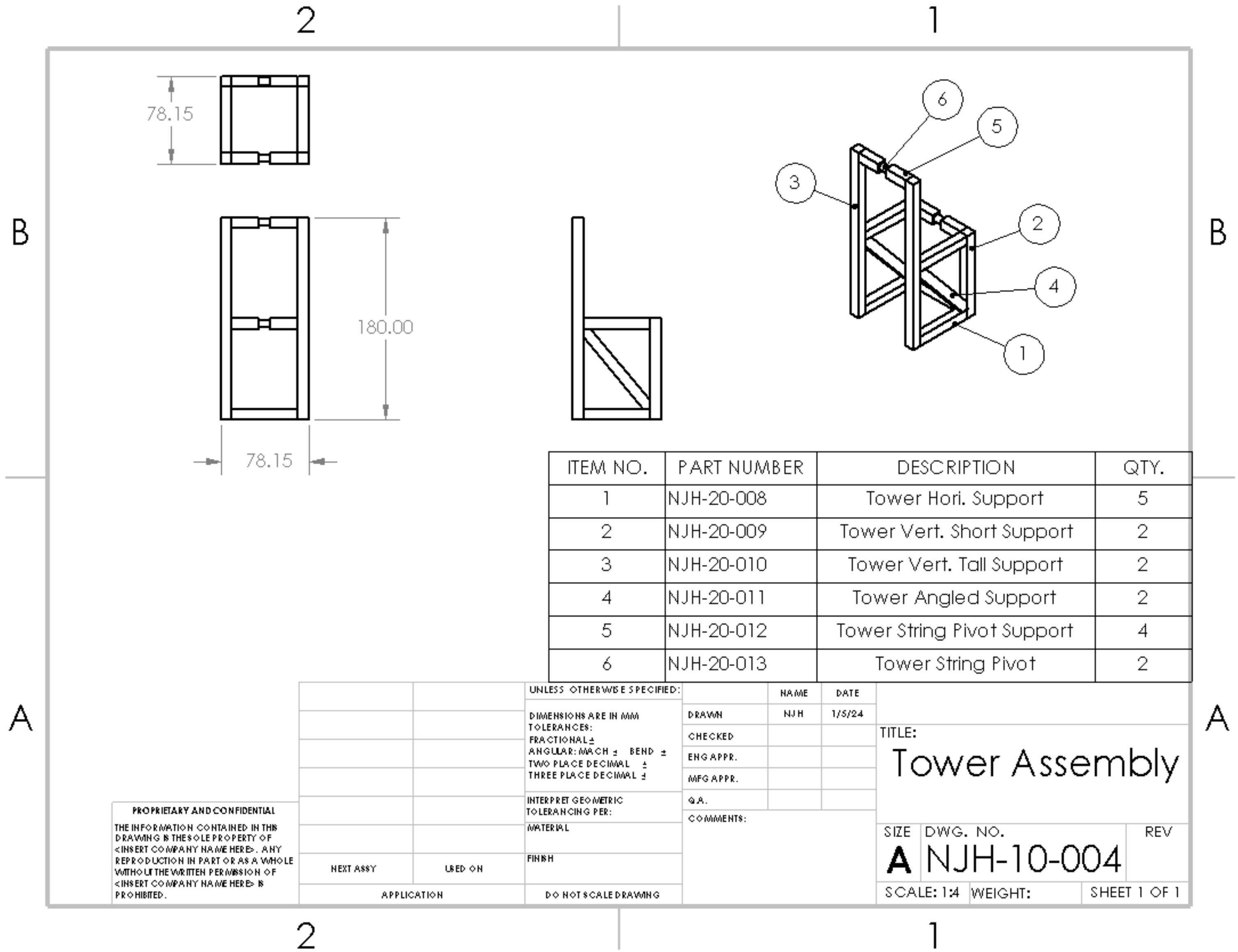
	NAME	DATE
DRAWN	NJH	11/28/23
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Truss Assembly

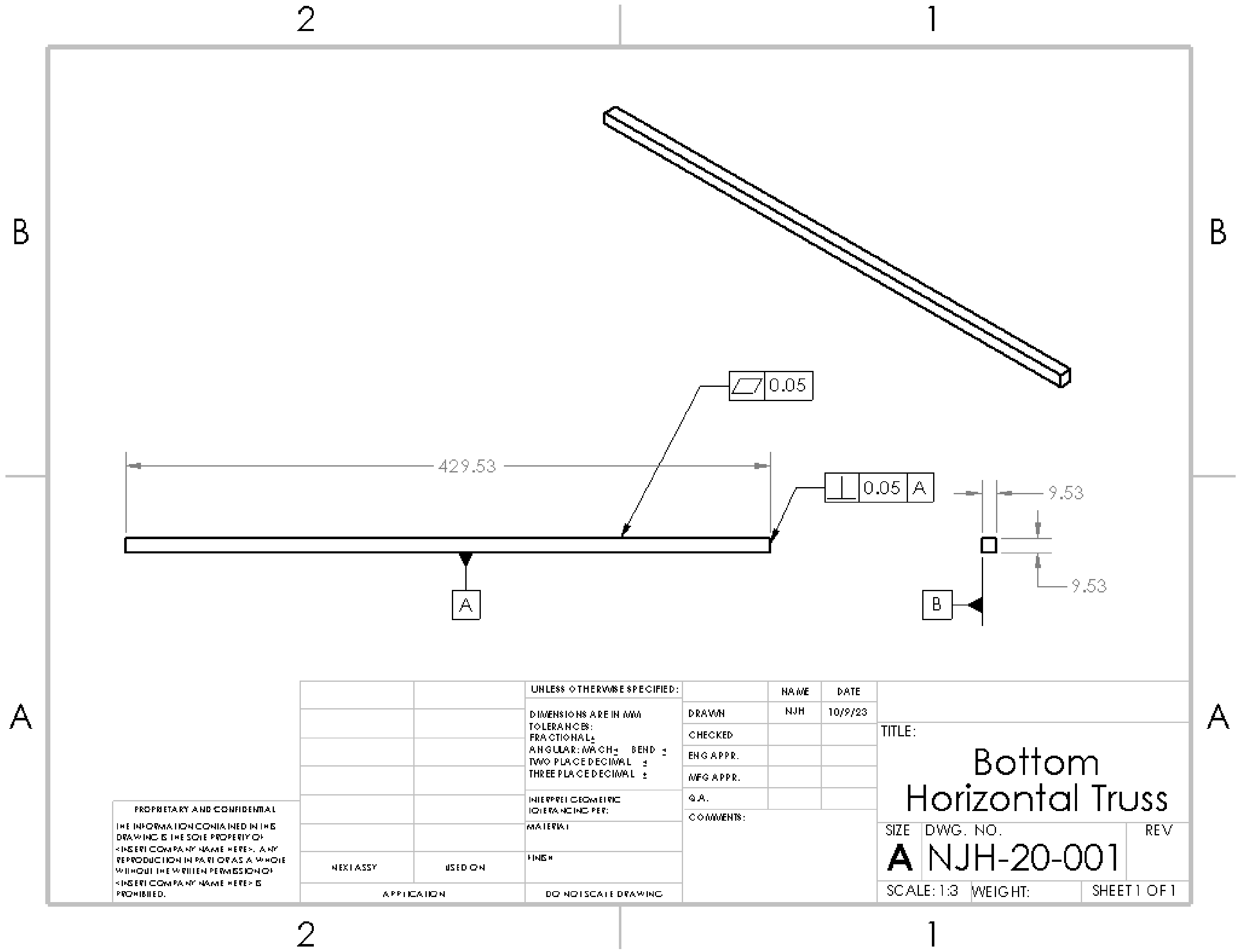
SIZE A | DWG. NO. NJH-10-003 | REV
SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

Appendix B06 – NJH-10-004 – Tower Assembly

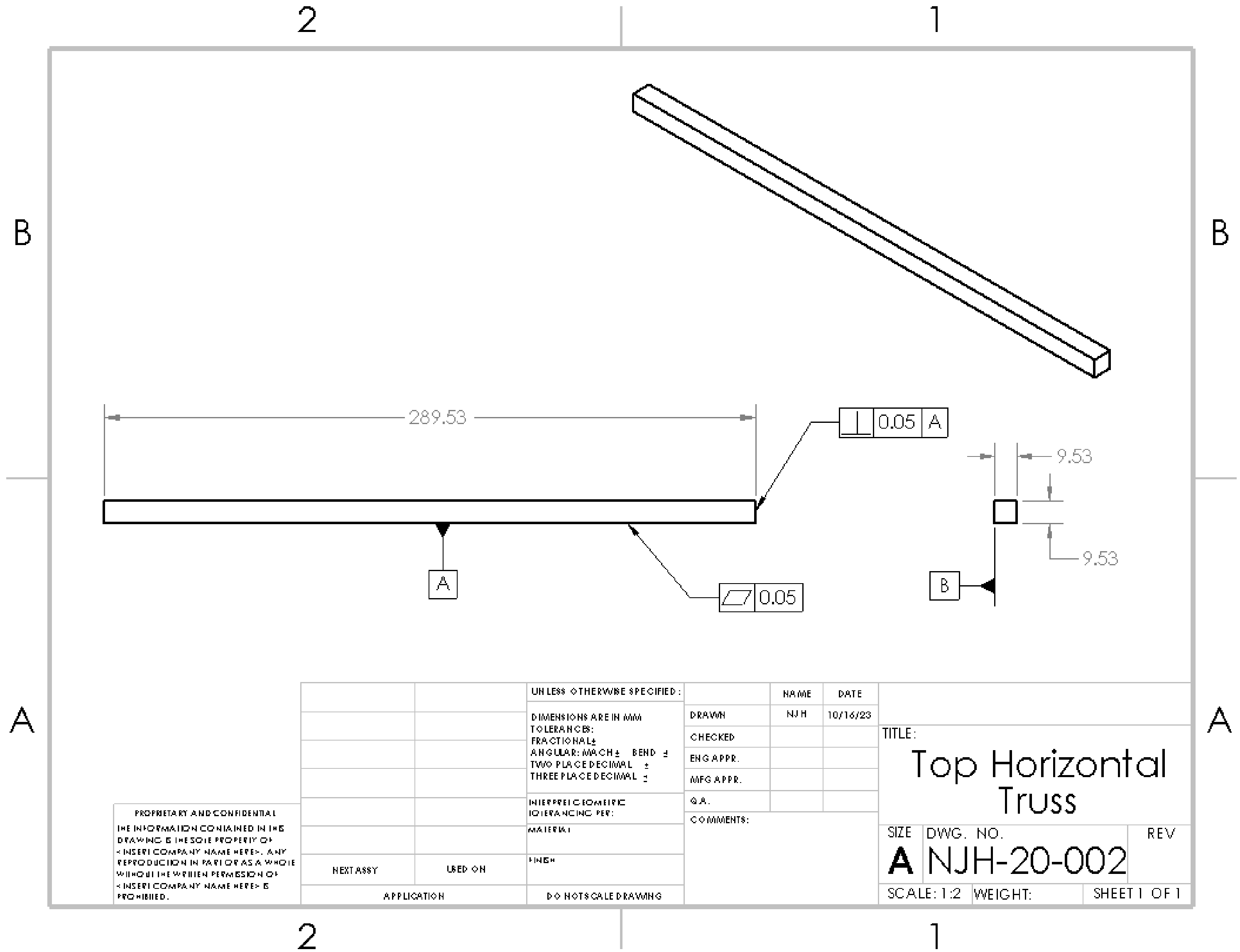


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	NJH-20-008	Tower Hori. Support	5
2	NJH-20-009	Tower Vert. Short Support	2
3	NJH-20-010	Tower Vert. Tall Support	2
4	NJH-20-011	Tower Angled Support	2
5	NJH-20-012	Tower String Pivot Support	4
6	NJH-20-013	Tower String Pivot	2

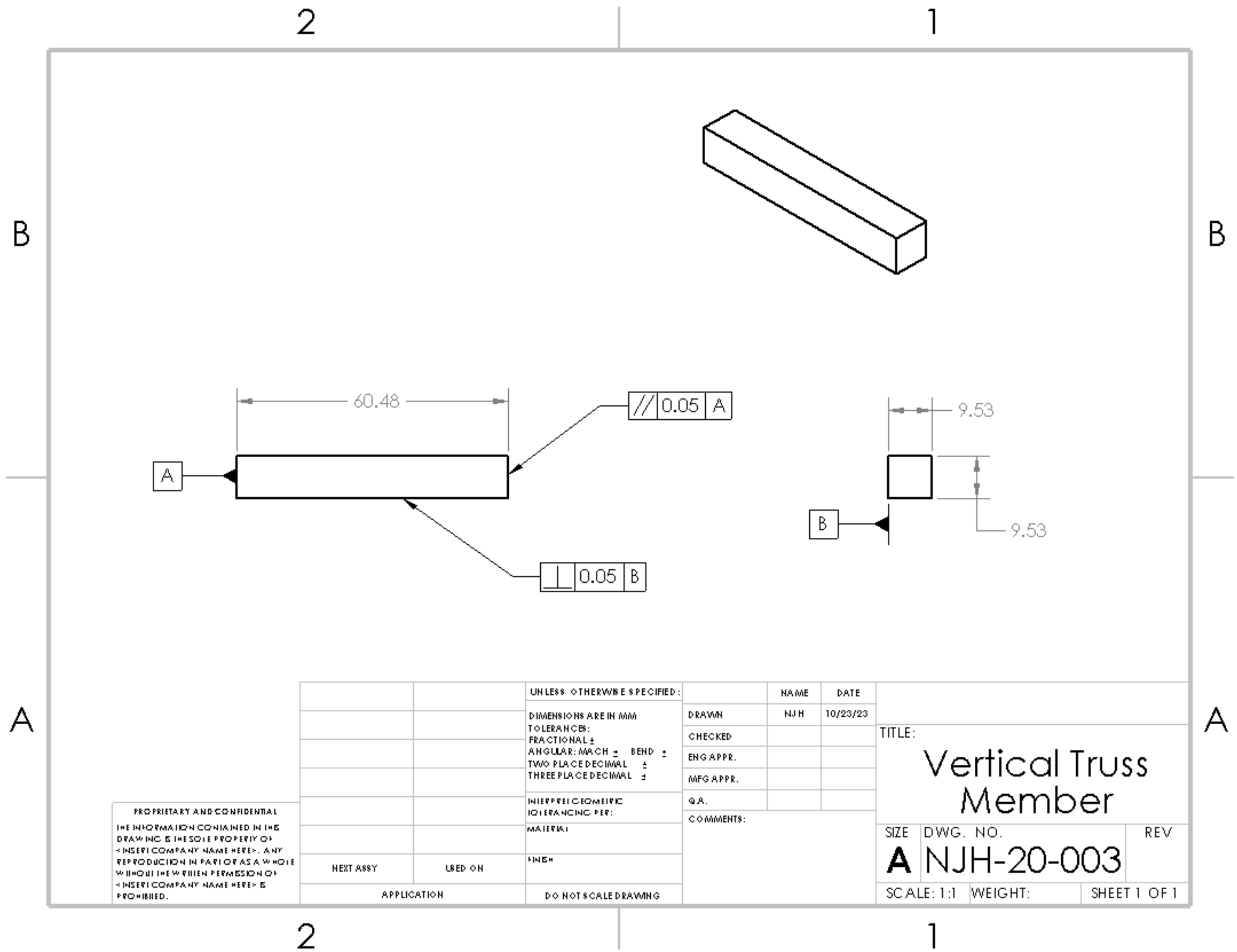
Appendix B07 – NJH-20-001 – Bottom Horizontal Truss



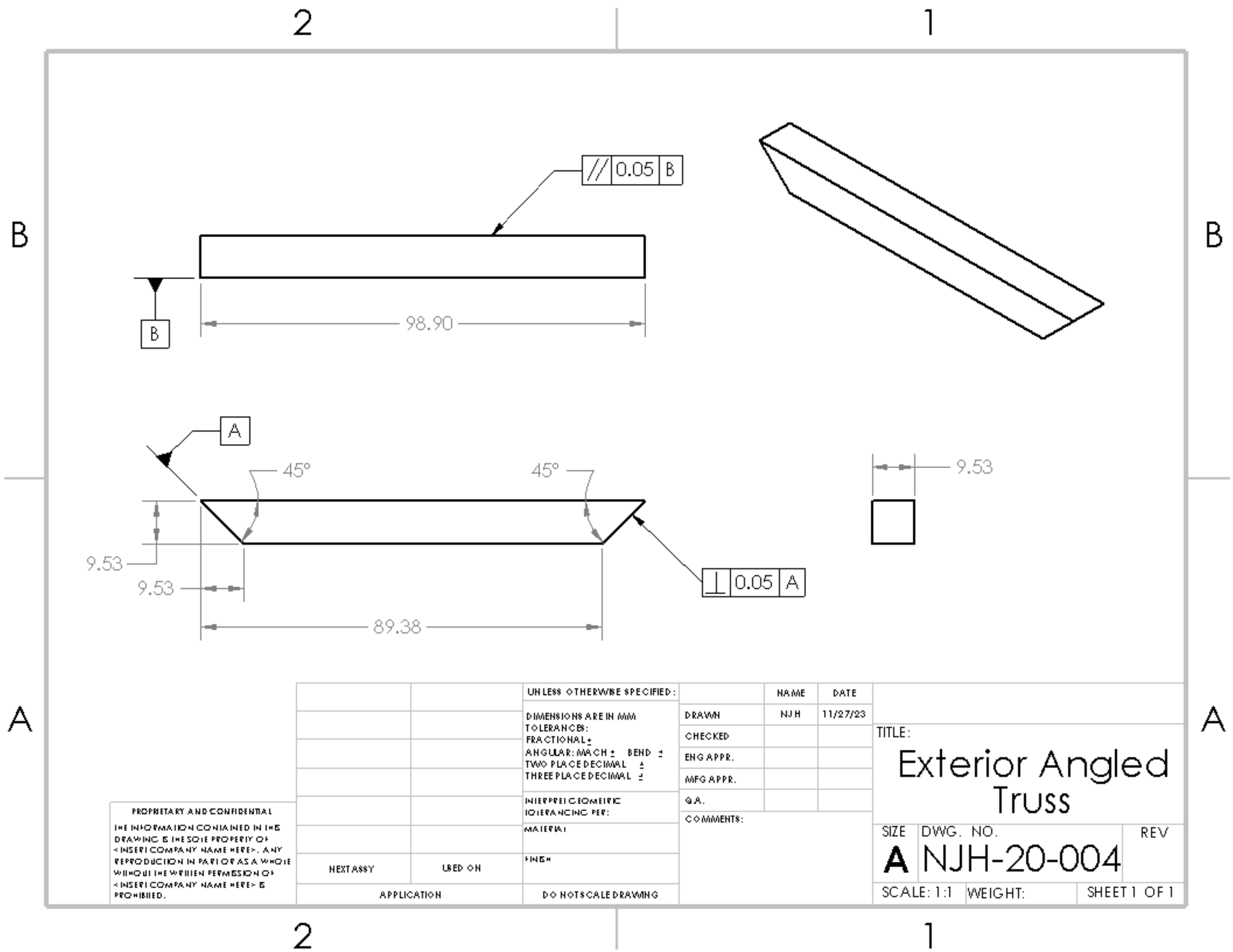
Appendix B08 – NJH-20-002 – Top Horizontal Truss



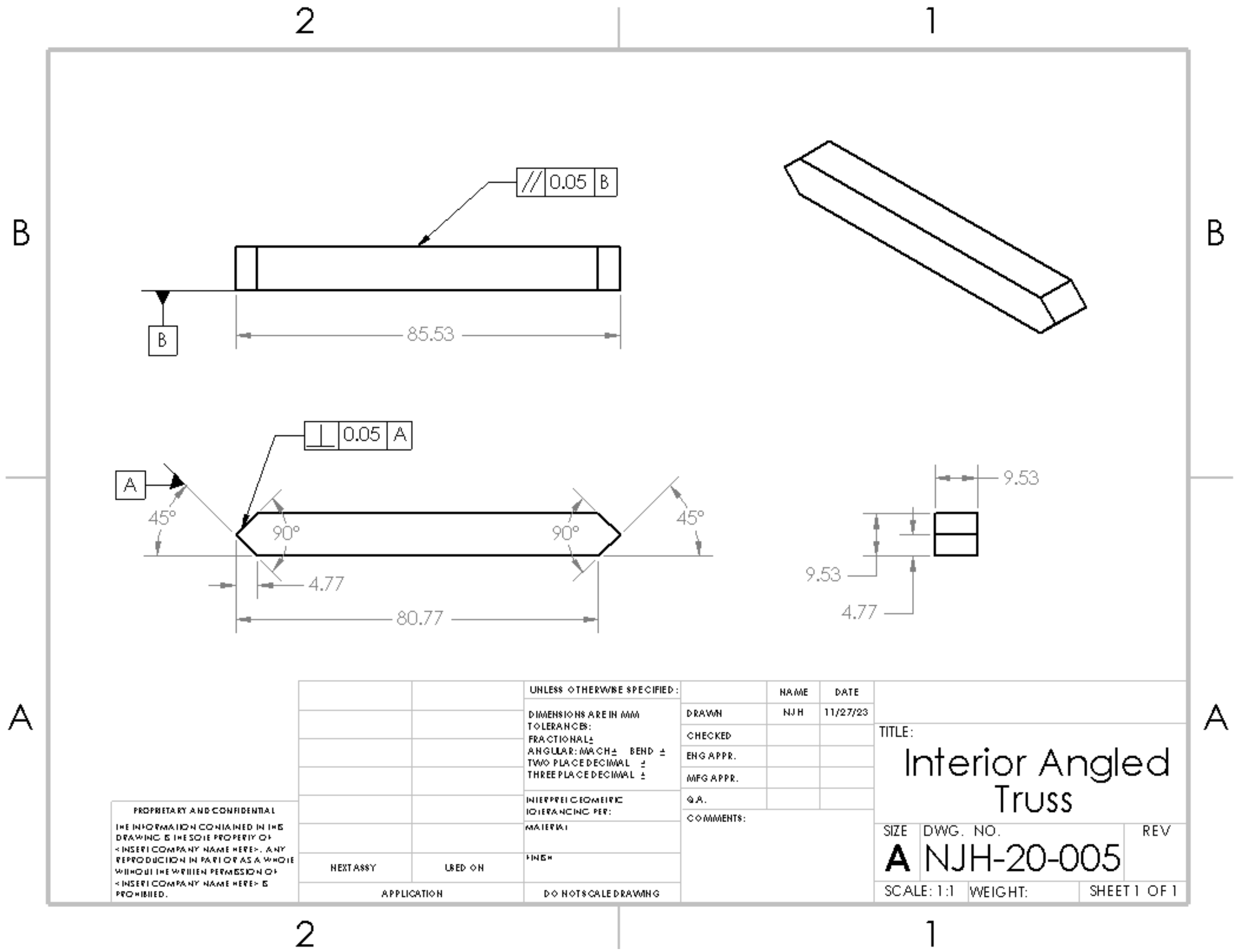
Appendix B09 – NJH-20-003 – Vertical Truss Member



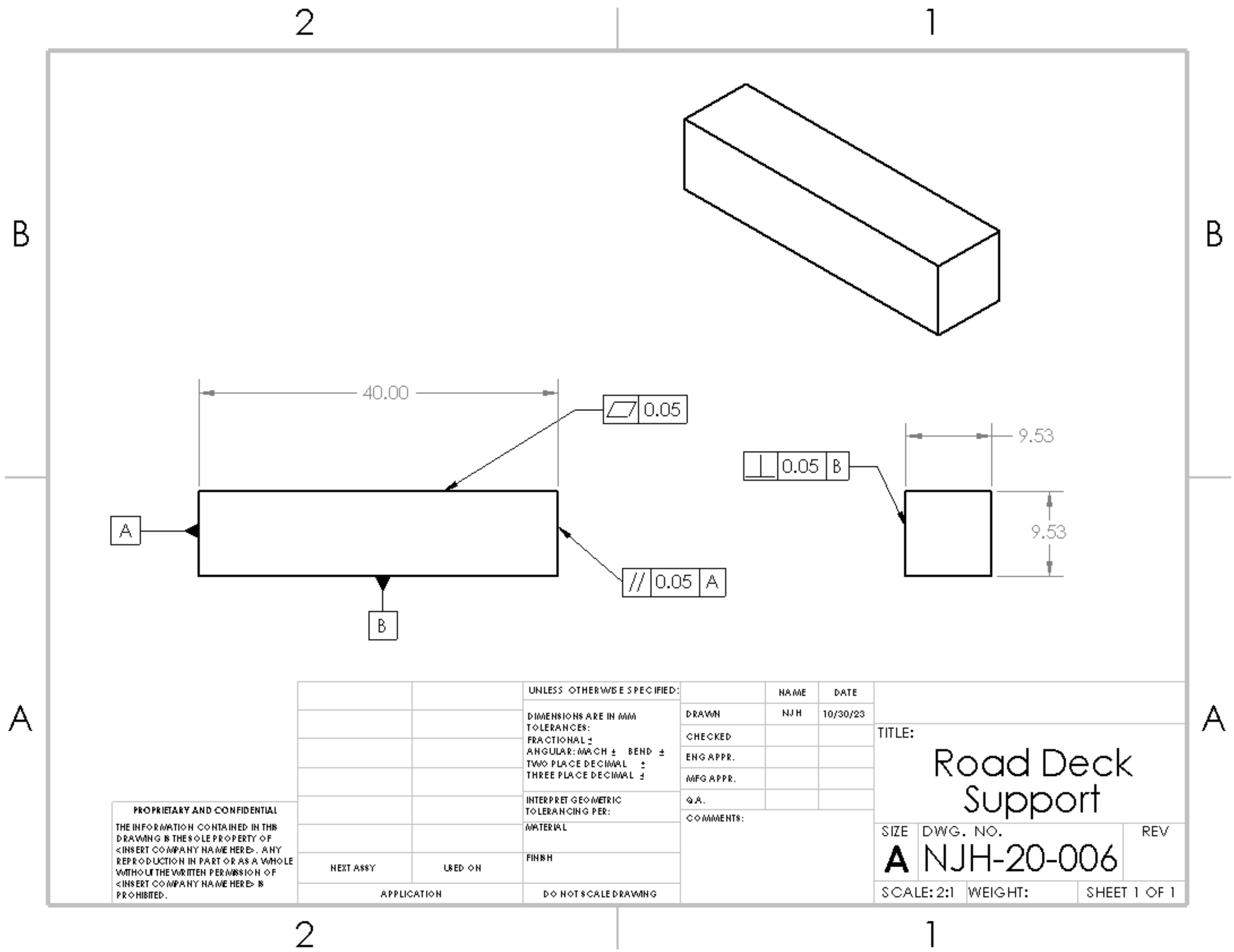
Appendix B10 – NJH-20-004 – Exterior Angled Truss



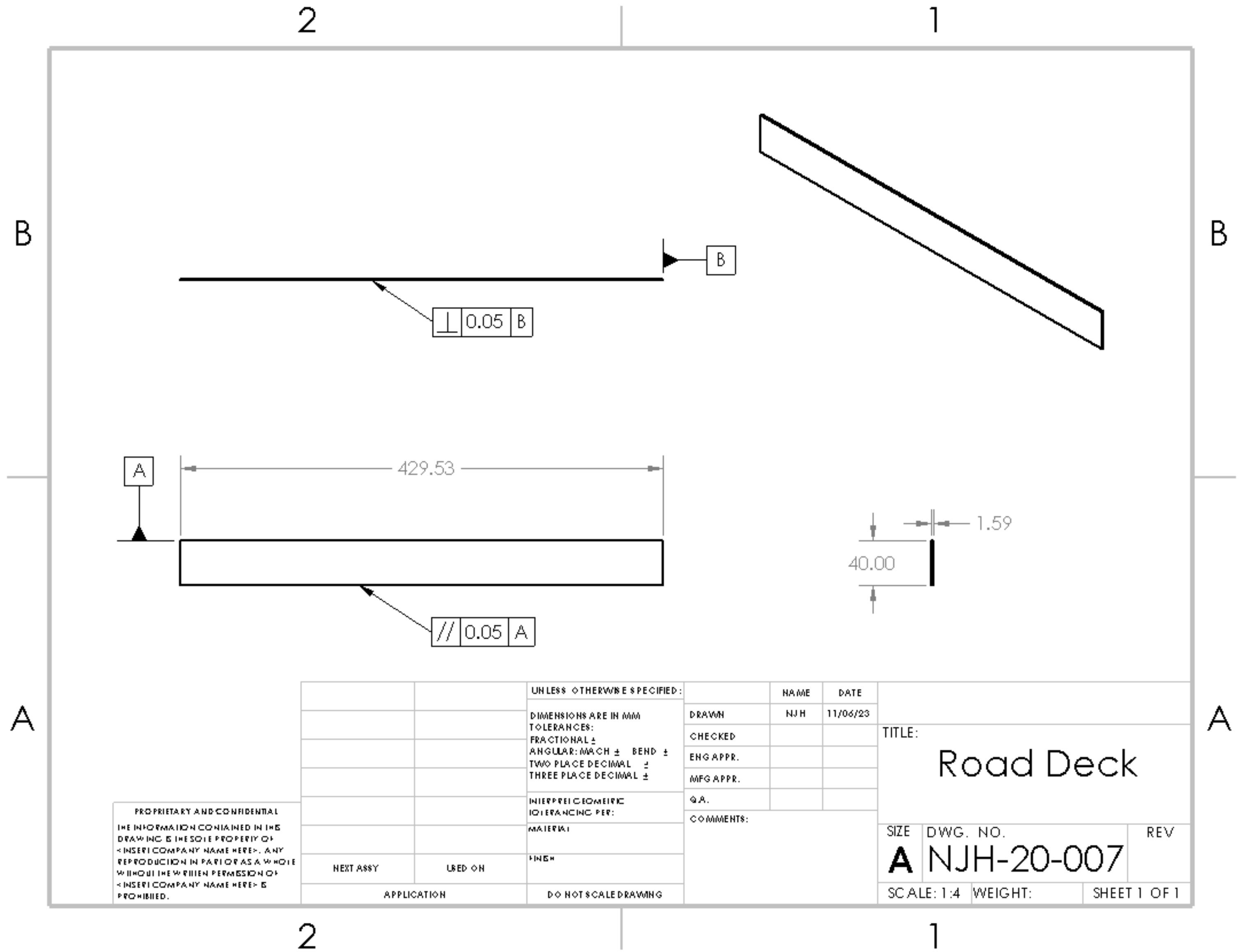
Appendix B11 – NJH-20-005 – Interior Angled Truss



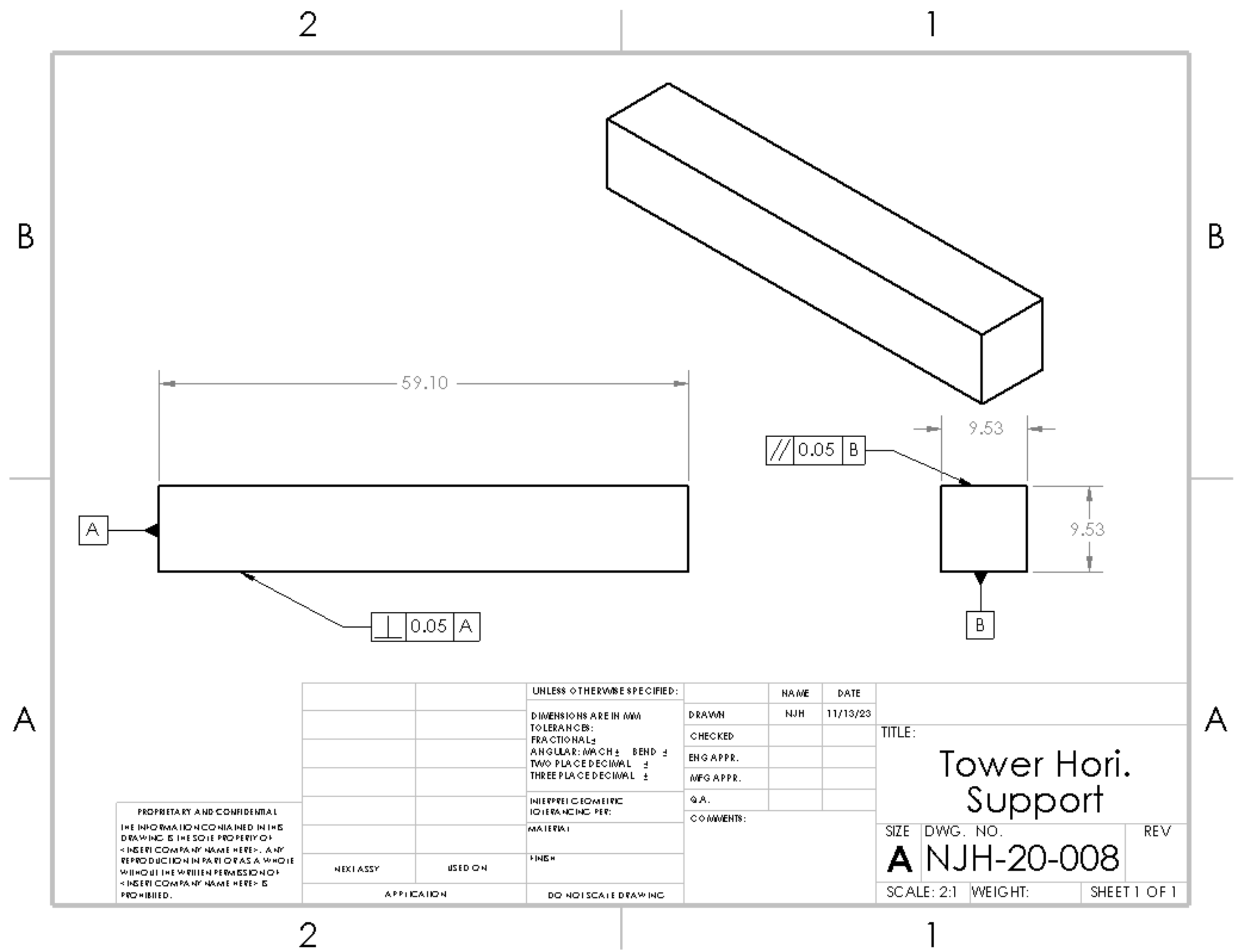
Appendix B12 – NJH-20-006 – Road Deck Support



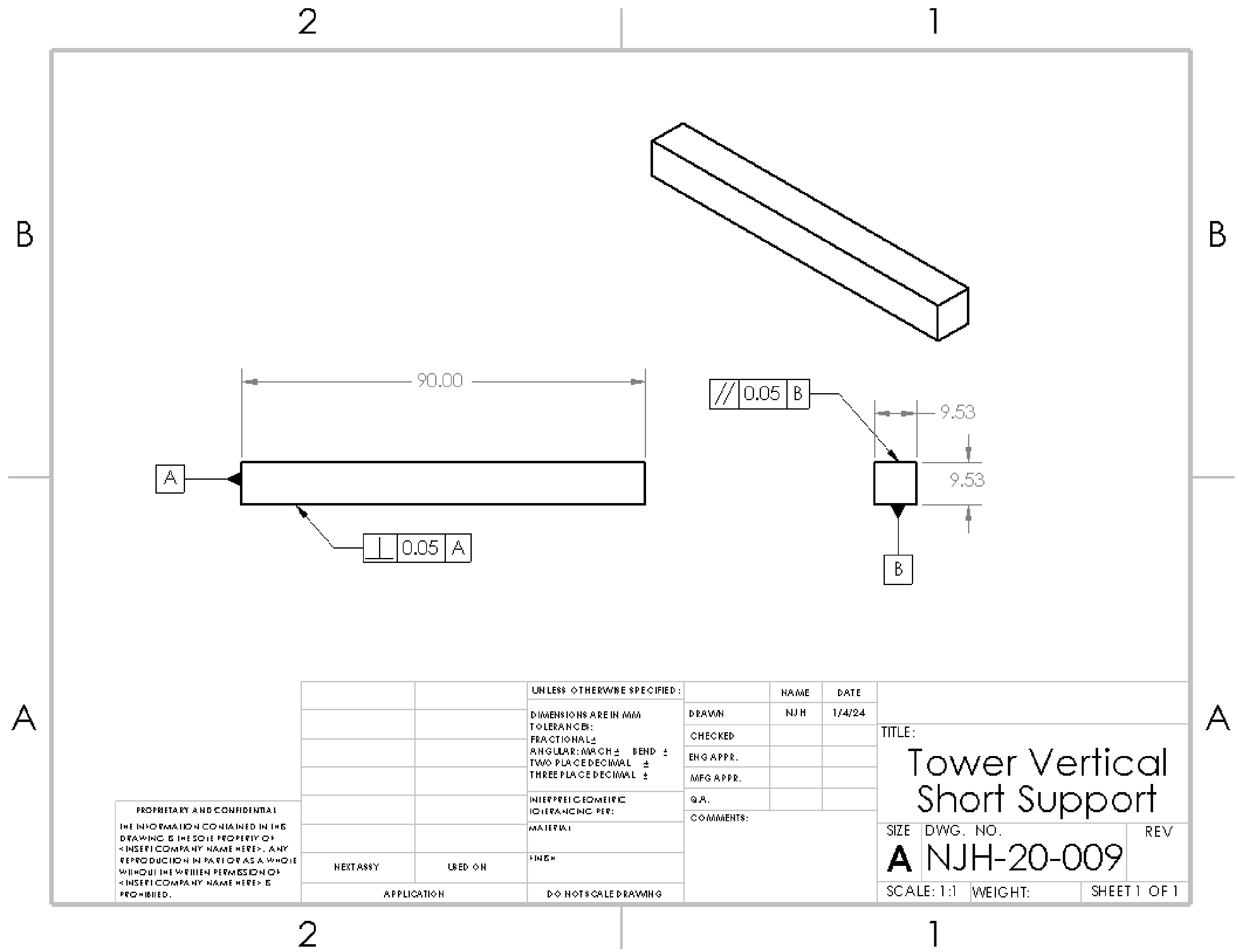
Appendix B13 – NJH-20-007 – Road Deck



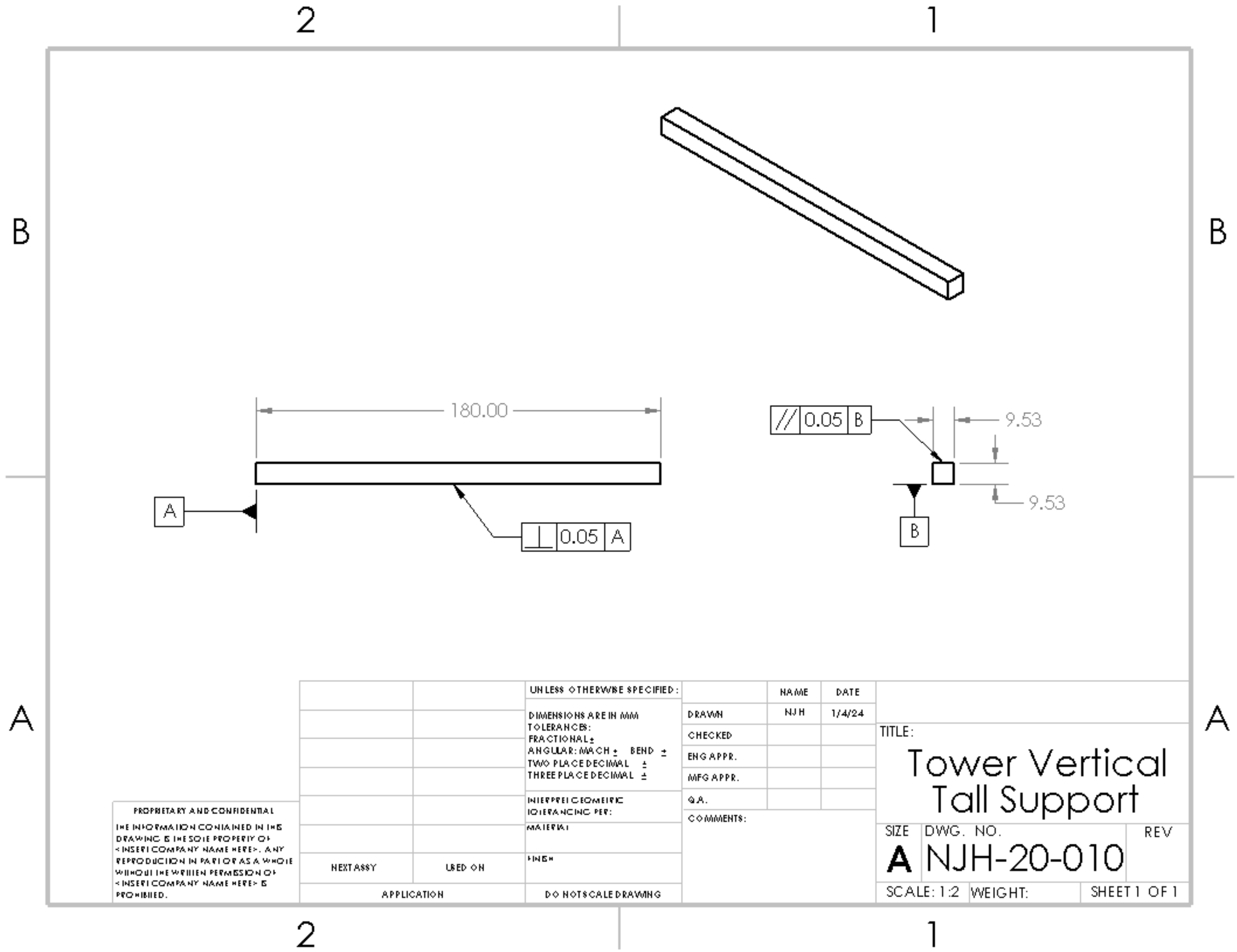
Appendix B14 – NJH-20-008 – Tower Horizontal Support



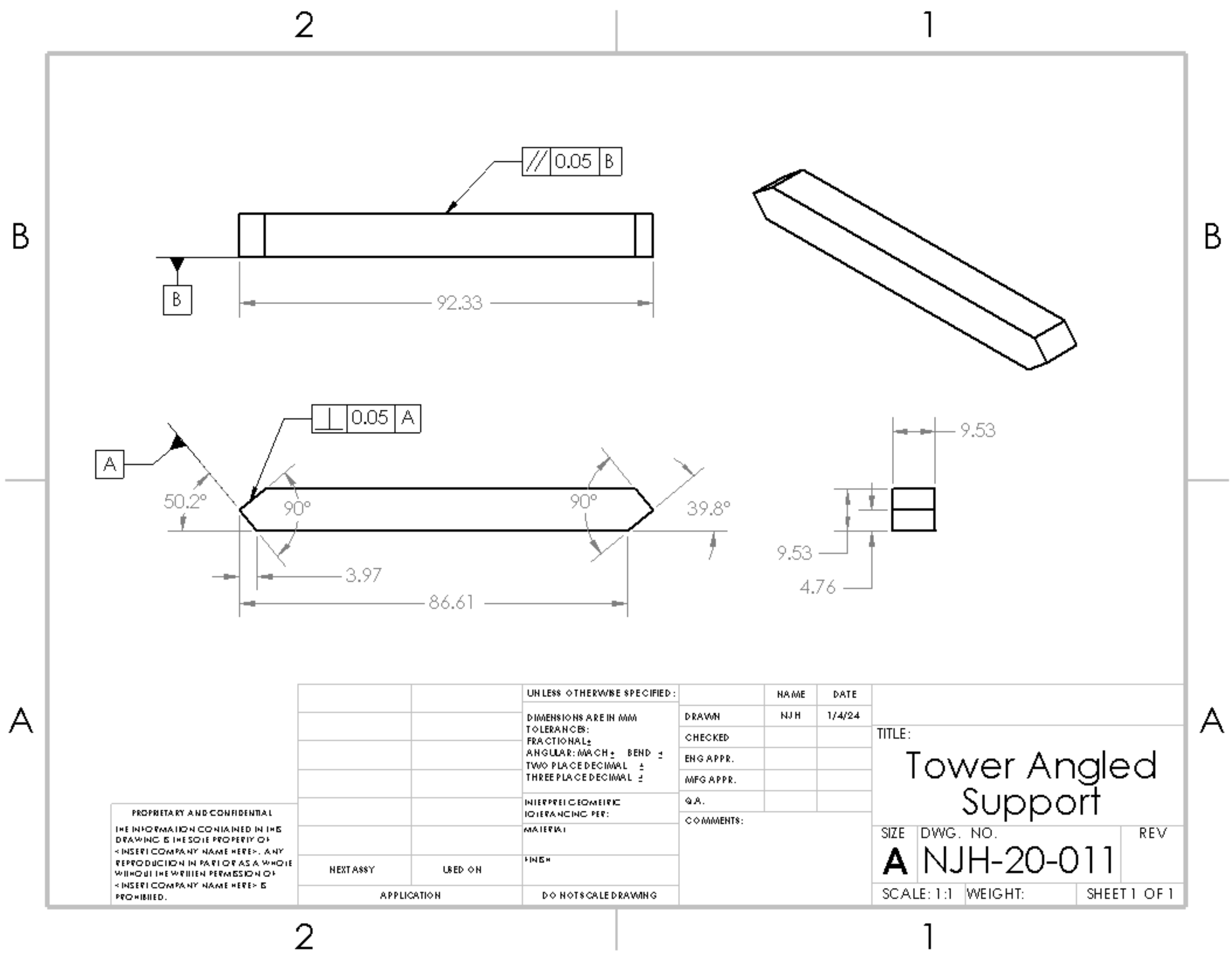
Appendix B15 – NJH-20-009 – Tower Vertical Short Support



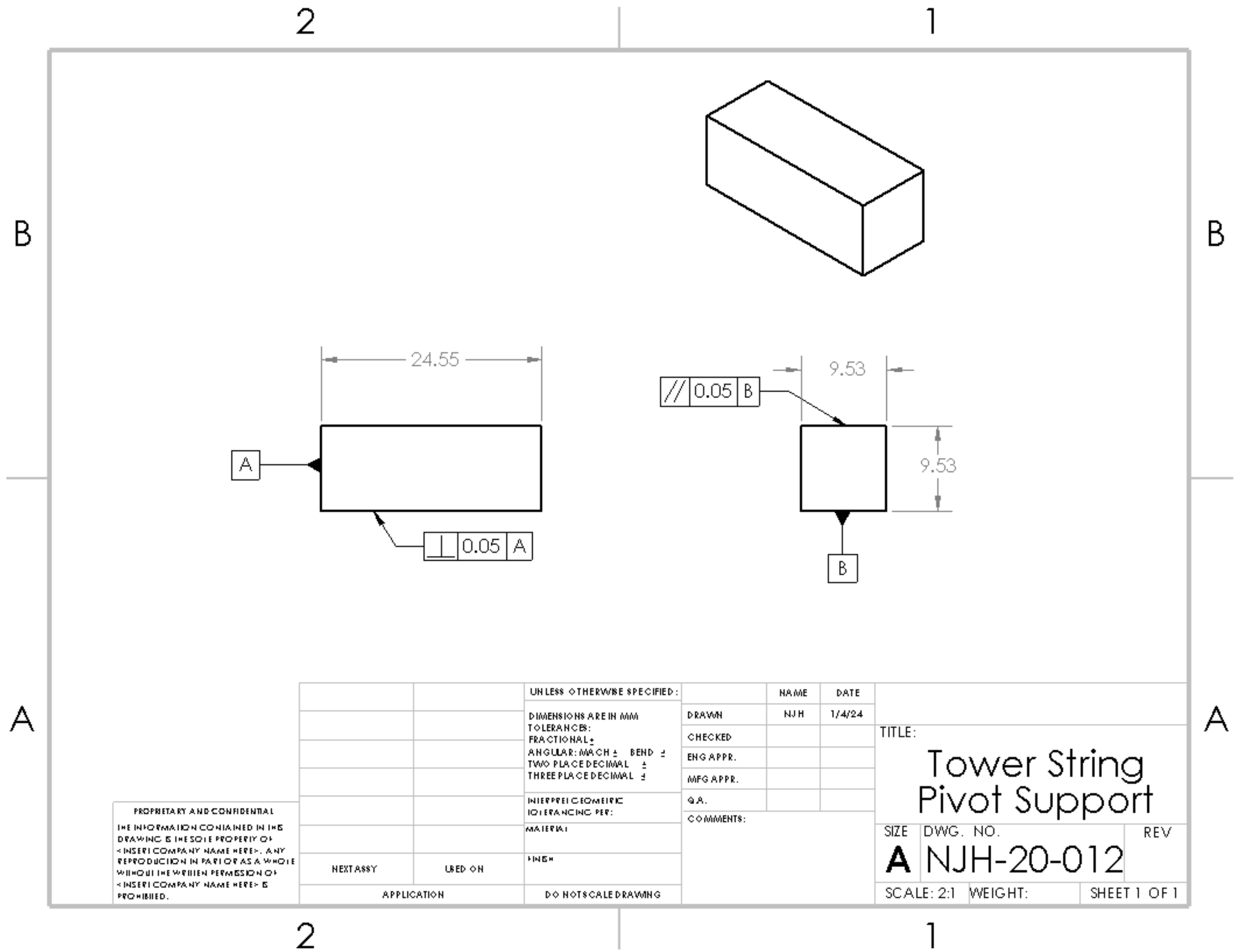
Appendix B16 – NJH-20-010 – Tower Vertical Tall Support



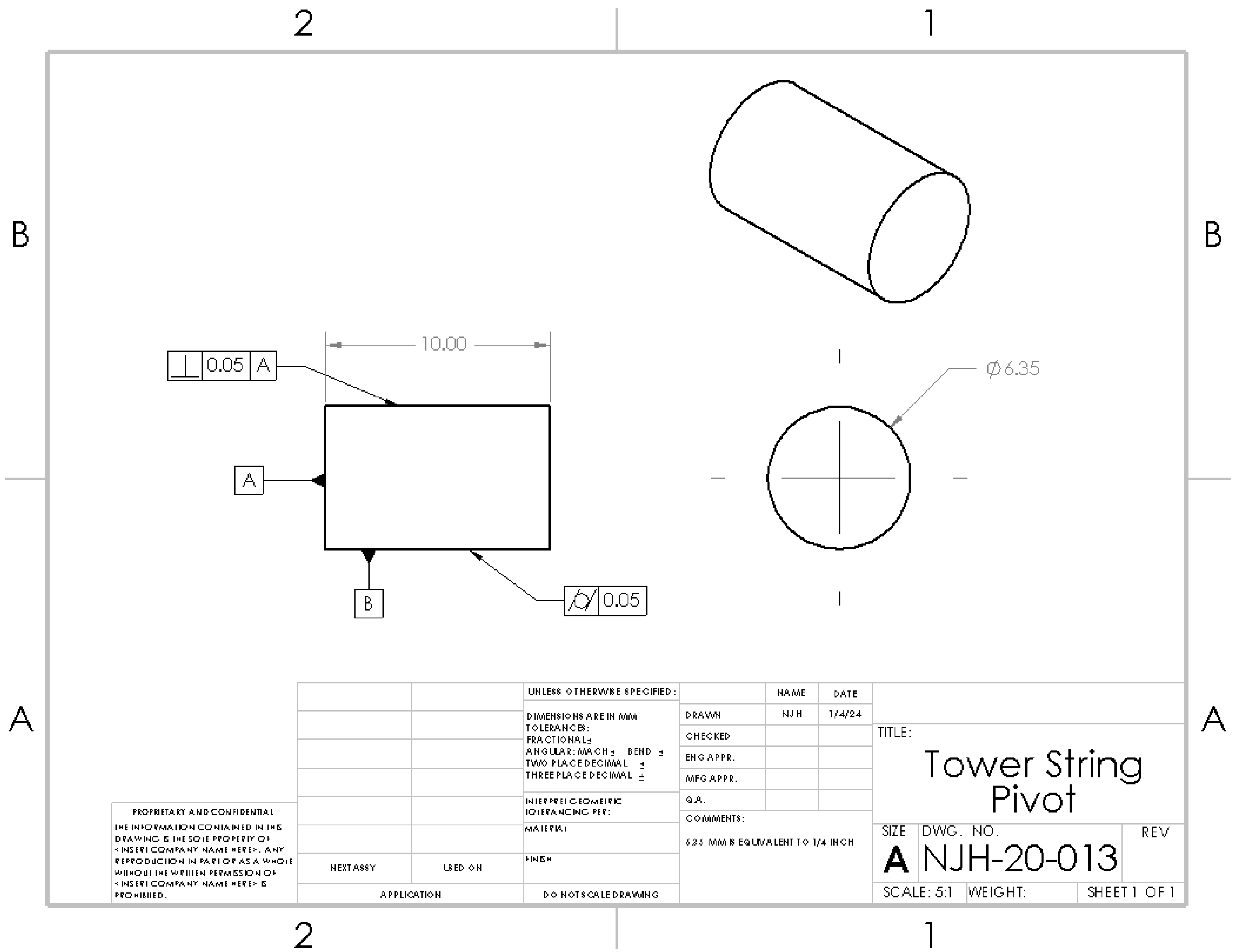
Appendix B17 – NJH-20-011 – Tower Angled Support



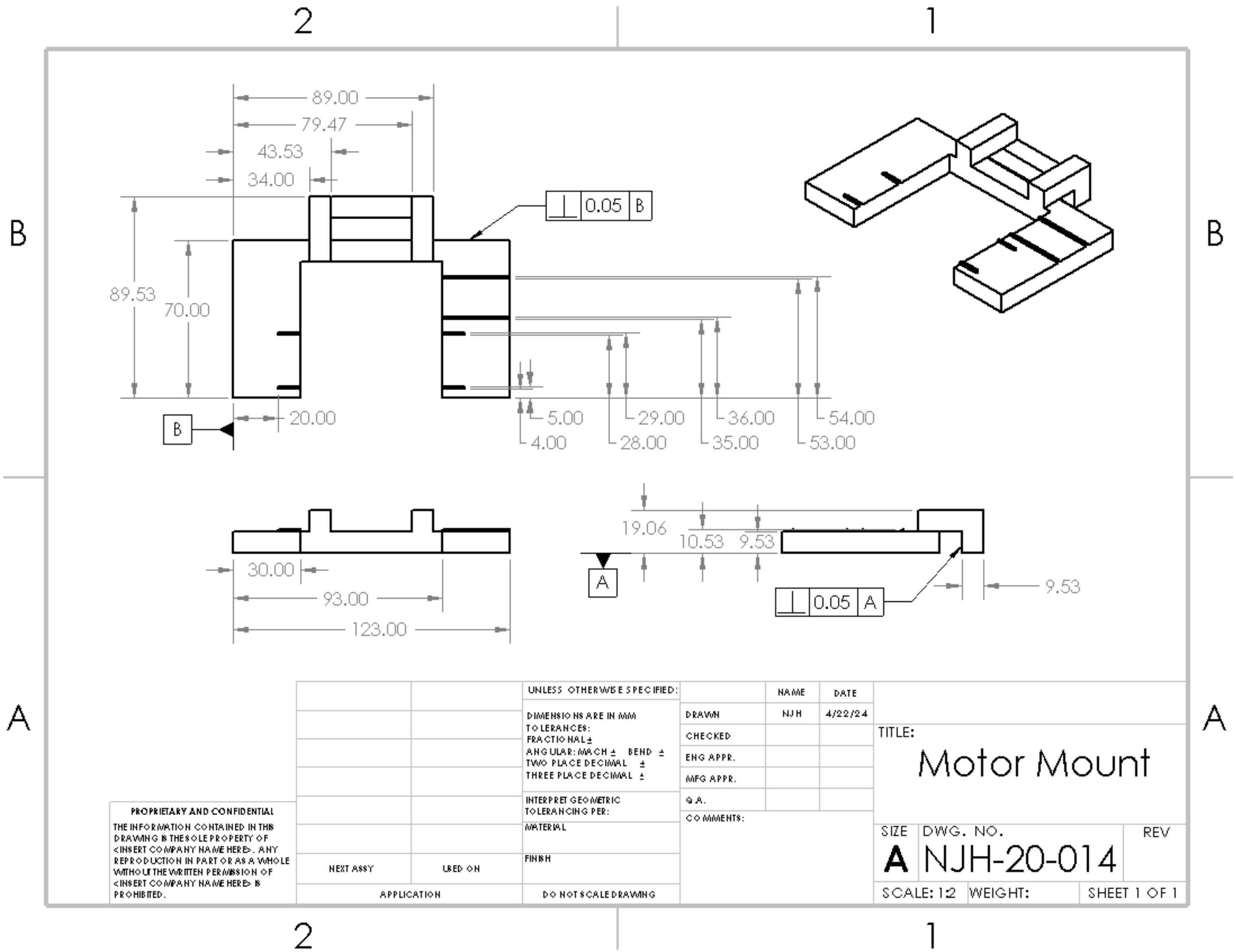
Appendix B18 – NJH-20-012 – Tower String Pivot Support



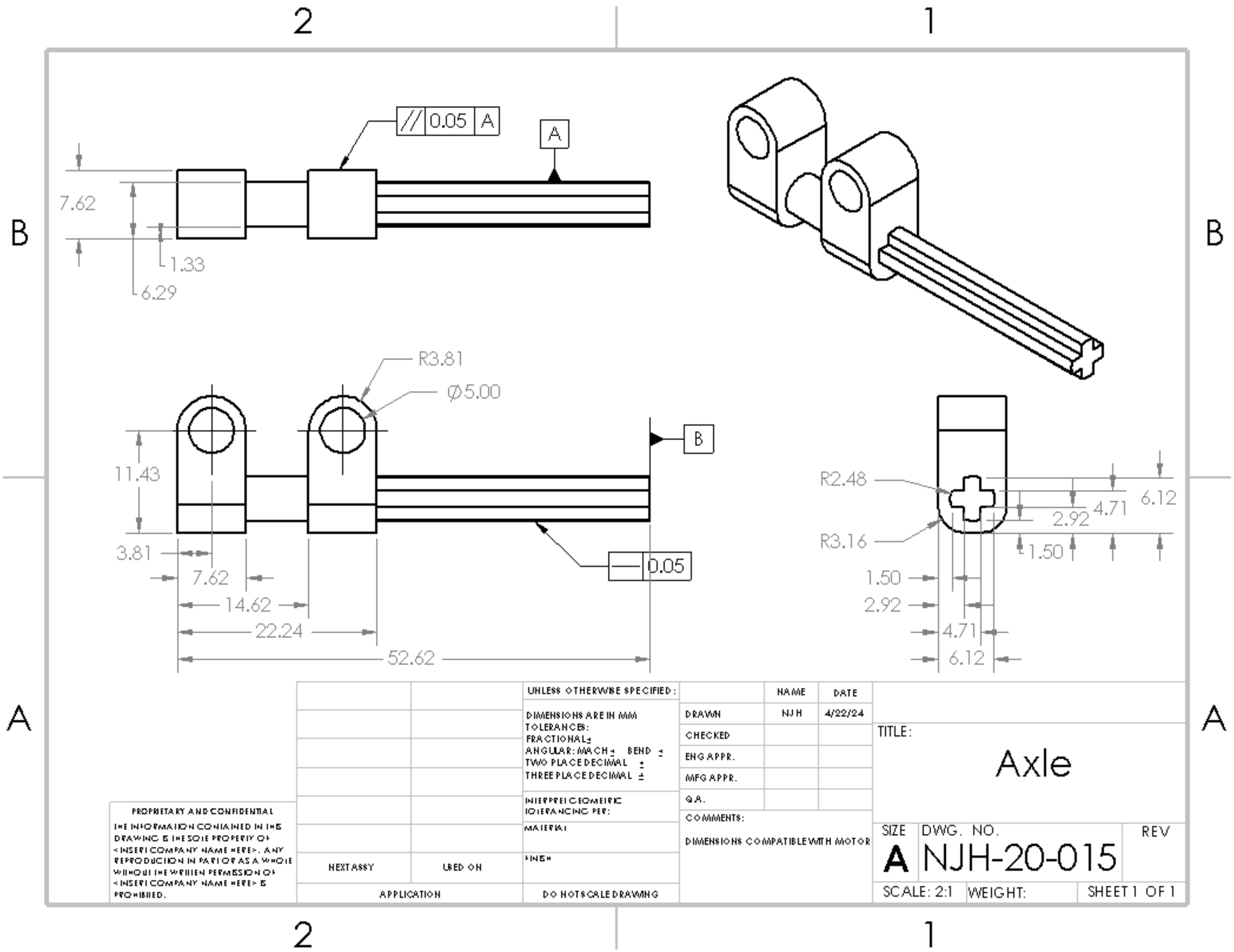
Appendix B19 – NJH-20-013 – Tower String Pivot



Appendix B20 – NJH-20-014 – Motor Mount



Appendix B21 – NJH-20-015 – Axle



APPENDIX C – Parts List and Costs

Part Number	Qty	Part Description	Source	Cost	Disposition
20-001	2	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/11/2023
20-002	2	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/11/2023
20-003	10	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/11/2023
20-004	4	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/11/2023
20-005	8	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/24/2023
20-006	15	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/24/2023
20-007	1	1/16 x 3 x 36 in Balsa Wood	Hobby Lobby Item 402776	$3.89	Purchased 11/11/2023
20-008 20-009	11 2	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/24/2023
20-010 20-011 20-012	2 2 4	3/8 x 3/8 x 36 in Balsa Wood	Hobby Lobby Item 402677	$3.24	Purchased 11/24/2023
20-013	2	Round ¼x1/4x12 Inch Balsa Wood	Amazon Item B09VG6VDK1	$13.01	Received 2/13/2024
55-001	1	Gorilla 4oz Wood Glue	Target Item: 081-22-4242	$3.89	Purchased 11/11/2023
55-002	1	Technic M-Motor and Battery Box	Amazon Item: B0C1MQDJYL	$15.24	Received 11/24/2023
55-003	1	AA Batteries	Fred Meyer Item: 0003980010797	$8.79	Purchased 2/28/2024
55-004	1	Cotton Craft Cord	Hobby Lobby Item: 2316248	$2.14	Purchased 3/2/2024
55-005	2	Nail	Ace Hardware Item: 53228	-	Donated 3/2/2024
Total Parts: 20			Cost Total:	$72.88	

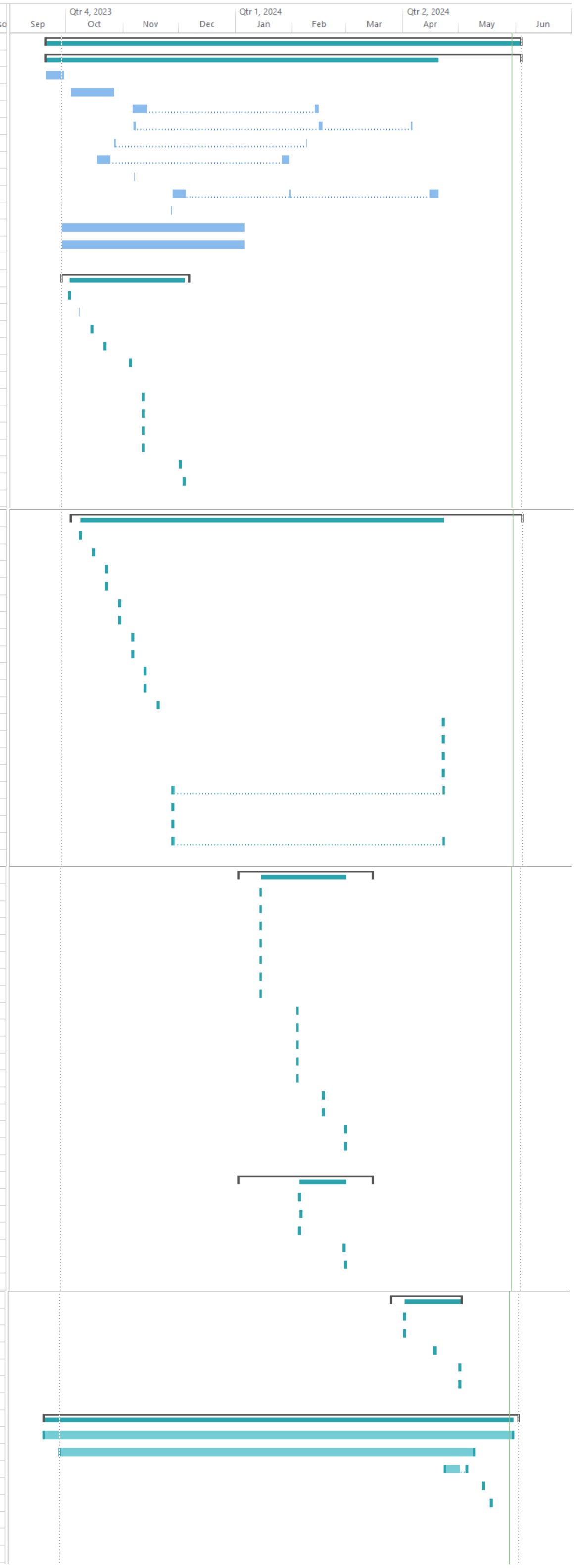
Costs include tax and/or shipping, unless otherwise specified.

APPENDIX D – Budget

Item	Qty	Description	Cost
Materials	1	Materials to build project.	$72.88
Donated Parts	1	Parts donated to project.	$0
Labor	1	Cost to manufacture and construct parts.	$0
Backup Funds	1	Contingency funds.	$2.12
		Budget Total	$75.00

APPENDIX E - Schedule

	ID	Task Name	Start	Finish	Duration	Predecessors
		Senior Project	**Wed 9/20/2**	**Mon 6/3/24**	**186 days?**	
	1	**PROPOSAL/REPORT WRITING**	**Wed 9/20/2**	**Mon 6/3/24**	**186 days**	
	1a	Intro	Wed 9/20/2	Fri 9/29/23	64 hrs	
	1b	Analysis	Wed 10/4/2	Thu 10/26/23	144 hrs	
	1c	Methods	Mon 11/6/2	Wed 2/14/24	64 hrs	
	1d	Testing	Mon 11/6/2	Fri 4/5/24	32 hrs	
	1e	Budget	Fri 10/27/23	Thu 2/8/24	9 hrs	
	1f	Schedule	Wed 10/18/	Mon 1/29/24	56 hrs	
	1g	Project Management	Tue 11/7/23	Tue 11/7/23	3 hrs	
	1h	Discussion	Tue 11/28/2	Fri 4/19/24	88 hrs	
	1i	Conclusion	Mon 11/27/	Mon 11/27/23	2 hrs	
	1j	Drawings	Fri 9/29/23	Fri 1/5/24	584 hrs	
	1k	Appendix	Fri 9/29/23	Fri 1/5/24	584 hrs	
	2	**ANALYSIS**	**Fri 9/29/23**	**Wed 12/6/23**	**51 days?**	
	2a	Angle Of Elevation for Bridge	Tue 10/3/23	Tue 10/3/23	1 hr	
	2b	Forces in Truss Members	Sun 10/8/23	Sun 10/8/23	4 hrs	
	2c	Cross-Sectional Area of Truss Members	Sun 10/15/2	Sun 10/15/23	2 hrs	
	2d	Dimensions of Truss Members	Sun 10/22/2	Sun 10/22/23	3 hrs	
	2e	Thickness of Road Deck Support	Sun 11/5/23	Sun 11/5/23	2 hrs	
	2f	Shear Strength of Adhesive	Sun 11/5/23	Sun 11/5/23	1 hr	
	2g	Power to Articulate Bridge	Sun 11/12/2	Sun 11/12/23	2 hrs	
	2h	Deflection of Road Deck	Sun 11/12/2	Sun 11/12/23	2 hrs	
	2i	Total Mass of Bridge	Sun 11/12/2	Sun 11/12/23	2 hrs	
	2j	Dimensions of Articulation Tower	Sun 11/12/2	Sun 11/12/23	3 hrs	
	2k	Fatigue Analysis	Sat 12/2/23	Sat 12/2/23	2 hrs	
	2l	Stress on Road Deck	Mon 12/4/2	Mon 12/4/23	2 hrs	
	3	**DOCUMENTATION**	**Wed 10/4/2**	**Mon 6/3/24**	**175 days?**	
	3a	NJH-20-001	Mon 10/9/2	Mon 10/9/23	2 hrs	
	3b	NJH-20-002	Mon 10/16/	Mon 10/16/23	2 hrs	
	3c	NJH-20-003	Mon 10/23/	Mon 10/23/23	2 hrs	
	3d	NJH-20-004	Mon 10/23/	Mon 10/23/23	2 hrs	
	3e	NJH-20-005	Mon 10/30/	Mon 10/30/23	2 hrs	
	3f	NJH-20-006	Mon 10/30/	Mon 10/30/23	2 hrs	
	3g	NJH-20-007	Mon 11/6/2	Mon 11/6/23	2 hrs	
	3h	NJH-20-008	Mon 11/6/2	Mon 11/6/23	2 hrs	
	3i	NJH-20-009	Mon 11/13/	Mon 11/13/23	2 hrs	
	3j	NJH-20-010	Mon 11/13/	Mon 11/13/23	2 hrs	
	3k	NJH-20-011	Mon 11/20/	Mon 11/20/23	2 hrs	
	3l	NJH-20-012	Mon 4/22/24	Mon 4/22/24	2 hrs	
	3m	NJH-20-013	Mon 4/22/24	Mon 4/22/24	2 hrs	
	3n	NJH-20-014	Mon 4/22/24	Mon 4/22/24	2 hrs	
	3o	NJH-20-015	Mon 4/22/24	Mon 4/22/24	2 hrs	
	3p	NJH-10-001	Tue 11/28/2	Mon 4/22/24	9 hrs	
	3q	NJH-10-002	Tue 11/28/2	Tue 11/28/23	2 hrs	
	3r	NJH-10-003	Tue 11/28/2	Tue 11/28/23	2 hrs	
	3s	NJH-10-004	Tue 11/28/2	Mon 4/22/24	9 hrs	
	4	**PART MANUFACTURING**	**Wed 1/3/24**	**Fri 3/15/24**	**53 days?**	
	4a	Cut Bottom Horizontal Members to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4b	Cut Top Horizontal Members to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4c	Cut Vertical Members to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4d	Cut Exterior Angled Members to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4e	Cut Interior Angled Members to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4f	Cut Road Deck Support to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4g	Cut Road Deck to Length	Mon 1/15/24	Mon 1/15/24	0.5 hrs	
	4h	Cut Tower Horizontal Members to Length	Sun 2/4/24	Sun 2/4/24	0.5 hrs	
	4i	Cut Tower Vert. Short Members to Length	Sun 2/4/24	Sun 2/4/24	0.5 hrs	
	4j	Cut Tower Vert. Tall Members to Length	Sun 2/4/24	Sun 2/4/24	0.5 hrs	
	4k	Cut Tower Angled Member to Length	Sun 2/4/24	Sun 2/4/24	0.5 hrs	
	4l	Cut Tower String Pivot Support to Length	Sun 2/4/24	Sun 2/4/24	0.5 hrs	
	4m	Cut Tower String Pivot to Length	Sun 2/18/24	Sun 2/18/24	0.5 hrs	
	4n	Cut Bridge Tower Pivot to Length	Sun 2/18/24	Sun 2/18/24	0.5 hrs	
	4o	3D Print Motor Mount	Fri 3/1/24	Fri 3/1/24	6 hrs	
	4p	3D Print Axle	Fri 3/1/24	Fri 3/1/24	3 hrs	
	5	**DEVICE MANUFACTURING**	**Wed 1/3/24**	**Fri 3/15/24**	**53 days?**	
	5a	Construct Truss	Mon 2/5/24	Mon 2/5/24	1 hr	
	5b	Construct Bridge	Tue 2/6/24	Tue 2/6/24	1 hr	
	5c	Construct Articulation Tower	Mon 2/5/24	Mon 2/5/24	1 hr	
	5d	Construct Final Assembly	Thu 2/29/24	Thu 2/29/24	3 hrs	
	5e	Attach Motor	Fri 3/1/24	Fri 3/1/24	2 hrs	
	6	**DEVICE EVALUATION**	**Wed 3/27/2**	**Fri 5/3/24**	**28 days?**	
	6a	Final Bridge Measurements	Wed 4/3/24	Wed 4/3/24	1 hr	
	6b	Articulation Test	Wed 4/3/24	Wed 4/3/24	1 hr	
	6c	Tensile Test	Fri 4/19/24	Fri 4/19/24	1 day	
	6d	Loading Test	Fri 5/3/24	Fri 5/3/24	1 hr	
	6e	Bridge Mass Test	Fri 5/3/24	Fri 5/3/24	0.25 hrs	
	7	**DELIVERABLES**	**Wed 9/20/2**	**Mon 6/3/24**	**186 days?**	
	7a	Project Report	Wed 9/20/2	Fri 5/31/24	185 days	
	7b	Webpage	Fri 9/29/23	Fri 5/10/24	163 days	
	7c	SOURCE Poster	Thu 4/25/24	Mon 5/6/24	7 days	
	7d	SOURCE Presentation	Thu 5/16/24	Thu 5/16/24	2 hrs	
	7e	Final Presentation	Mon 5/20/24	Mon 5/20/24	0.25 hrs	



APPENDIX F – Expertise and Resources

Criterion	Weight 1 to 3	Best Possible 3	Bascule	Score x Wt	Drawbridge Flat	Score x Wt	Drawbridge Curved	Score x Wt	
Weight Distribution	3	9	1	3	3	9	3	9	
Manufacturability	2	6	2	4	3	6	1	2	
Articulation	3	9	1	3	2	6	2	6	
Cost	1	3	2	2	2	2	2	2	
Prismatic vs non prismatic	2	6	2	4	3	6	1	2	
Total	11	33		16		29		21	
NORMALIZE THE DATA (muliply by fraction, N)		3.03		48.5		87.9		63.6	Percent

Decide if Bias is Good or Bad	Good Bias:	Standard Deviation is two or more digits	Good? Then done.	66.7 Average
	Poor Bias:	Standard Deviation is one or less digits	Poor? Change something!	20 Std Dev.
		You can change the criteria, weighting, or the projects themselves…		

Weighting/Scoring Scale

1 Worst (too costly, low confidence, too big, etc.)
2 Median Values, or Unsure of actual value
3 Best (Low Cost, high confidence, etc.)

Criterion

Weight Distribution	How well is the bridge going to hold 20kg?
Manufacturability	Is it simple to produce? Are there multiple process for a single component?
Articulation	Will the bridge design allow easy articulation?
Cost	More mass is more cost
Prismatic vs non prismatic	Is the shape prismatic (retangle, square, etc) or is it irregullarly shaped to meet the engineering needs

Comments:

The bascule bridge was rated as it was due to the fact that it would require more materials to produce the design, and the fact that having a bridge of that shape meant that it likely would have two points of deflection.
The flat drawbridge was rated as it was because the design was rectangular, will likely allow for easy articulation, and will have a better weight distribution than the bascule bridge.
The curved drawbridge was rated as it was because it's design is irregularaly shaped, meaning it would be harder to manufacture.

Table F01: Design Matrix for Balsa Wood Bridge.

Criterion	Weight 1 to 3	Best Possible 3	Carving Knife	Score x Wt	Wood Saw	Score x Wt		
Time	2	6	1	2	3	6		
Precision	3	9	3	9	1	3		
Availability	3	9	3	9	2	6		
Manufacturability	2	6	2	4	3	6		
Cost	1	3	2	2	2	2		
Total	11	33		26		23	0	
NORMALIZE THE DATA (muliply by fraction, N)		3.03		78.8		69.7	0.0	Percent

Decide if Bias is Good or Bad	Good Bias:	Standard Deviation is two or more digits	Good? Then done.	74.2 Average
	Poor Bias:	Standard Deviation is one or less digits	Poor? Change something!!!	6 Std Dev.
		You can change the criteria, weighting, or the projects themselves…		

Weighting/Scoring Scale

1 Worst (too costly, low confidence, too big, etc.)
2 Median Values, or Unsure of actual value
3 Best (Low Cost, high confidence, etc.)

Criterion

Time	How long does it take to manufacture one component?
Precision	Does this method result in precise dimensions for the part?
Availability	Are the tool necessary to manufacture easily available?
Manufacturability	Is it simple to produce? Are there multiple process for a single component?
Cost	Does manufacturing with this method cost extra money?

Table F02: Design Matrix for Manufacturing Processes.

Criterion	Weight 1 to 3	Best Possible 3	Gorilla Wood Glue	Score x Wt	Titebond II Premuim	Score x Wt	Elmer's Wood Glue	Score x Wt
Cost	2	6	2	4	3	6	1	2
Availability	1	3	3	3	3	3	3	3
Spec Sheet	3	9	2	6	3	9	1	3
Strength	2	6	3	6	2	4	2	4
Cure Time	2	6	2	4	2	4	2	4
			3900 psi 24 hours		3750 psi 25 mpa 24 hr cure time		3600 psi 24 hr cure time	
Total	10	30		23		26		16
NORMALIZE THE DATA (muliply by fraction, N)		3.33		76.7		86.7		53.3 Percent

Decide if Bias is Good or Bad

Good Bias: Standard Deviation is two or more digits
Poor Bias: Standard Deviation is one or less digits
You can change the criteria, weighting, or the projects themselves…

Good? Then done.
Poor? Change something!!!

72.2 Average
17 Std Dev.

Weighting/Scoring Scale

1 Worst (too costly, low confidence, too big, etc.)
2 Median Values, or Unsure of actual value
3 Best (Low Cost, high confidence, etc.)

Criterion

Cost The adhesive is a reasonable price
Availability The glue is widely available at local or online retailers
Spec Sheet Is the spec sheet available? Do you know if it's accurate
Strength Is the shear strength strong relative to other adhesives?
Cure Time How long does it take to fully cure?

Table F03: Design Matrix for Adhesive Brand.

Criterion	Weight 1 to 3	Best Possible 3	Balsa Wood	Score x Wt	3D Print	Score x Wt	Pully	Score x Wt
Time	2	6	3	6	1	2	2	4
Cost	3	9	3	9	2	6	3	9
Friction	3	9	1	3	2	6	3	9
Manufacturability	2	6	3	6	2	4	2	4
Total	10	30		24		18		26
NORMALIZE THE DATA (muliply by fraction, N)		3.33		80.0		60.0		86.7 Percent

Decide if Bias is Good or Bad

Good Bias: Standard Deviation is two or more digits
Poor Bias: Standard Deviation is one or less digits
You can change the criteria, weighting, or the projects themselves…

Good? Then done.
Poor? Change something!!!

75.6 Average
14 Std Dev.

Weighting/Scoring Scale

1 Worst (too costly, low confidence, too big, etc.)
2 Median Values, or Unsure of actual value
3 Best (Low Cost, high confidence, etc.)

Criterion

Time Is this method time efficient
Cost Does this cost the project extra money?
Friction Will this cause friction? Will it damage the articulation support?
Manufacturability Is it simple to produce? Are there multiple process for a single component?

Table F04: Design Matrix for Articulation Support of String

APPENDIX G – Testing Report

Appendix G1 - Articulation Test

Introduction:

The articulation test measured the height that the midpoint of the road deck reached when the bridge was articulated open and the time it took for the bridge to articulate open. The requirements of the project were 140 mm minimum and under 60 seconds respectively (refer to Section 1d-2 and 1d-11). A parameter of interest was the mass of the bridge since that can impact the speed of the articulation. The bridge midpoint was predicted to reach a height of 148.5 mm and articulate fully open in 1.26 seconds (refer to Appendix A01 and A07 respectively).

Data was collected using a tape measure and a smartphone camera application. The height of the midpoint was measured using a tape measure and written down on a sheet of notepaper. Each test trial was recorded on a smartphone camera. Using the video editing feature on the camera roll application, the exact start and end of the articulation open cycle was written down on the note sheet, and the difference between the values was the articulation time. This test was scheduled to take only one hour to set up, test, and clean up (refer to Section 6 of the Gantt chart in Appendix E).

Method/Approach:

Hard resources needed for the articulation test were the bridge, a flat surface such as a table, notepaper and a writing utensil, a tape measure or ruler with cm or mm increments, and a recording device such as a smartphone. The soft resource was Microsoft Excel. Data capturing was done using the smartphone and measuring device. This test was completed by one person and did not have any costs. Data documentation was done on a note sheet, which was later input into Microsoft Excel. The test procedure consisted of the smartphone recording the bridge articulating open, and the measuring device determining the height of the midpoint of the bridge. The video editing application was used to determine the exact start and end times of the articulation cycle.

Operational limits consisted of the bridge's articulation component, as it was required to be functional to test. The tape measure used in the test was precise to one millimeter and the video editing application was precise to one hundredth of a second. The data was recorded on a sheet of notepaper, which was then input into Microsoft Excel for ease of analysis. Data was presented in both tables and graphs.

Test Procedure:

This procedure documents the process of recording, measuring the time for the balsa wood bridge to articulate from closed to fully open and the maximum height of the midpoint when fully articulated, and processing the results.

Time: This test was conducted on 4/3/2024 from 8:30 AM to 9:00 AM in Hogue 127. After the test, 10 minutes was used to return equipment and clean the testing area.
Place: Room 127, Hogue Hall, Central Washington University campus in Ellensburg, WA.
Required Resources:

- iPhone 13
- Articulating balsa wood bridge
- Table
- Note sheet
- Writing utensil
- Tape measure with cm or mm units

Risk and Safety:
Safety glasses must be worn at all times while testing.

Test procedure:

1. Collect equipment:
    a. Articulating balsa wood bridge, table, note sheet, writing utensil, and tape measure from Hogue 127.
2. Go to Hogue 127.
3. Place all equipment on table closest to whiteboard (Southmost side of room).
4. Measure the length road deck. Using the writing utensil, mark the midpoint of the road deck along the thin side of the road deck such that the mark can be seen when viewing the bridge from the side.
    a. If a vertical truss member is located where the mark should be, mark that location on the exterior of the truss where the road deck is located. Refer to Figures G1.1 and G1.2

Figure G1.1 Measuring midpoint of the road deck.

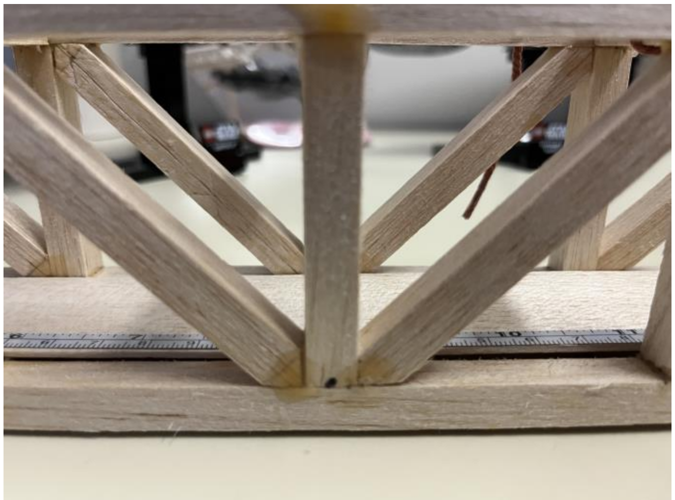


Figure G1.2 Marking midpoint of road deck.

5. On the note sheet, create a table that's 3 rows tall and 4 columns long.
    a. From top to bottom, label the top rows "start time," "end time," "articulation time," and "road deck height."
    b. Label the three columns "Trial 1," "Trial 2," and "Trial 3."
6. Open camera application on the iPhone. Prop smartphone in horizontal orientation and ensure that the entire bridge and articulation tower is in frame. Begin recording.
7. Place one hand on the lever that articulated the bridge. When ready, articulate the bridge open.
    a. To articulate the bridge fully open, move the lever to the right. To stop the motor, put the lever in the middle. To articulate the bridge closed, move the to the left.
        i. The lever on the motor is labeled "u" for up and "d" for down. See figure G1.3.

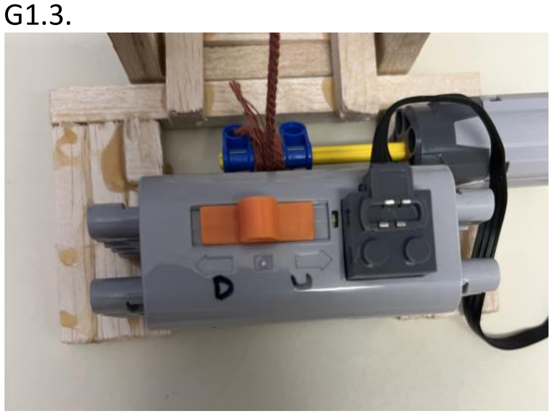


Figure G1.3 Motor labels.

8. When the bridge has reached its maximum height put the articulation lever in the middle configuration to stop the motor.
    a. Leave the bridge articulated open.
9. Place the measuring device such that the cm/mm units are directly measuring at the previously marked location of the midpoint of the bridge. Ensure the measuring device is perpendicular to the surface of the table.

10. Record the height of the midpoint of the bridge on the note sheet under Trial 1.
11. Stop recording on the iPhone.
12. Open the photo app on the iPhone and select the video that was recorded. Select the "Edit" option in the top left. Use the white line on the video timeline to find the time the bridge began articulating open and the time the bridge reached its maximum height to the nearest hundredth of a millisecond. Record both times under "start time" and "end time" respectively. Refer to Figures G1.4 and G1.5

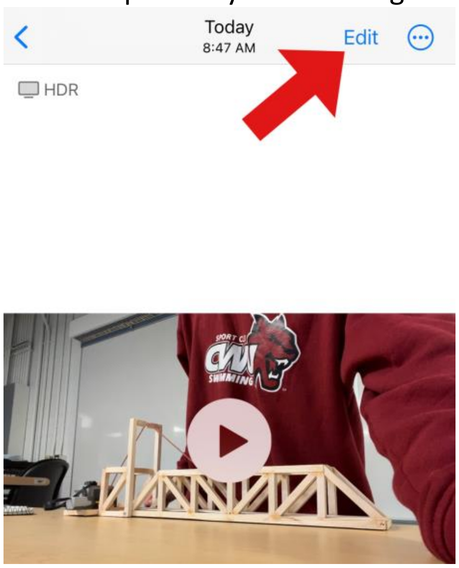


Figure G1.4 Edit recording of articulation.

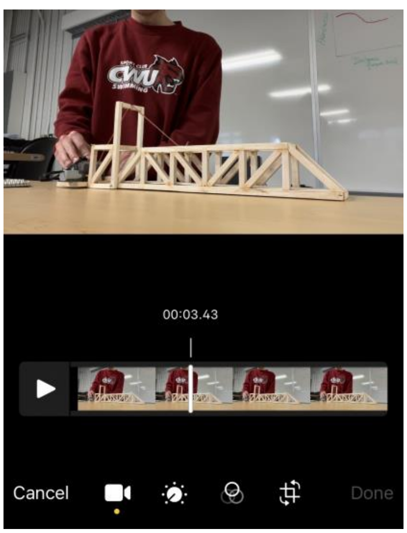


Figure G1.5 Determining time of articulation.

13. Find the difference between the start and end time and record it under "articulation time."
14. Articulate the bridge closed.
15. Repeat steps 5-14 for trials 2 and 3.
16. Return all lab equipment to its original location.

The testing process was successful. All three trials ran without issue and no unexpected challenges were encountered. There were a few small updates and clarifications that needed to be made to the testing process, such as including images for the video editing and including enough information in the procedure such that the process could be replicated. Outside of those small revisions, the test was successful.

Deliverables:

Over the three trials, the midpoint of the road deck reached a height of 156mm, 154mm, and 156mm. This was calculated to be an average of 155.3 mm. The time it took for the bridge to articulate was calculated to be 0.77 seconds, 1.07 seconds, and 1.11 seconds, for an average of 0.97 seconds. The two deliverables measured during the test passed the requirements defined in Section 1d-2 and 1d-11. The project successfully passed both requirements that the test measured.

Appendix G1.1 – Procedure Checklist

- iPhone 13
- Articulating balsa wood bridge
- Table
- Note sheet
- Writing utensil
- Tape measure
- Computer with access to Microsoft Excel

Appendix G1.2 – Data Forms

	Start Time (sec)	End Time (sec)	Articulation Time (sec)	Road Deck Height (mm)
Trial 1				
Trial 2				
Trial 3				

Appendix G1.3 – Raw Data

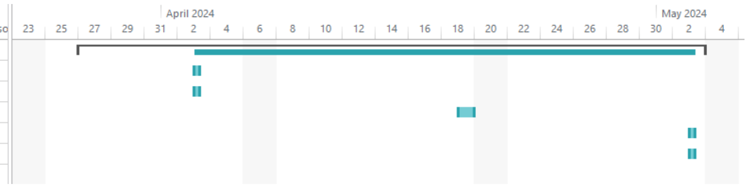
	Start Time (sec)	End Time (sec)	Articulation Time (sec)	Road Deck Height (mm)
Trial 1	6.14	6.91	0.77	156
Trial 2	2.58	3.61	1.03	154
Trial 3	1.5	2.61	1.11	156

Appendix G1.4 – Evaluation Sheet

Avg Articulation Time (sec)	0.97
Avg Road Deck Height (mm)	155.3

Appendix G1.5 – Schedule (Testing)

	Task Name	Start	Finish	Duration	Predecesso
6	**DEVICE EVALUATION**	**Wed 3/27/2**	**Fri 5/3/24**	**28 days?**	
6a	Final Bridge Measurement	Wed 4/3/24	Wed 4/3/24	1 hr	
6b	Articulation Test	Wed 4/3/24	Wed 4/3/24	1 hr	
6c	Tensile Test	Fri 4/19/24	Fri 4/19/24	1 day	
6d	Loading Test	Fri 5/3/24	Fri 5/3/24	1 hr?	
6e	Bridge Mass Test	Fri 5/3/24	Fri 5/3/24	0.25 hrs	



Appendix G2 – Tensile Test

Introduction:

The tensile test measured weight distribution of the bridge and the tensile strength of the articulation cord. The bridge had to lift enough so a sheet of standard printer paper could be slid under the bridge when a 10-gram load was applied to the articulation component (refer to Section 1d-6). A parameter of interest was the mass of the bridge, since that affected the weight that would cause lift. The bridge was predicted to lift when a 28-gram load was applied to the articulation cord (refer to Appendix A12). Data was be collected by using a scale to measure the weight that was applied to the articulation cord, and the number of sheets of paper that were able to fit in the gap under that specific weight were written down. The tensile test was scheduled to take only one hour to set up, test, and clean up (refer to Section 6 of the Gantt chart in Appendix E).

Method/Approach:

Resources required for this test were the project, a recording device, a flat surface to test on, a weight and scale, and a note sheet and writing utensil. A soft resource was Microsoft Excel. The test was completed by one person and did not have any additional costs. Data was captured by recording the test on a smartphone camera. Data was documented on a note sheet and later input into Microsoft Excel.

An overview of the testing procedure: a weight was hung from the articulation cord. A sheet of printer paper was attempted to be slid under the bridge. If the paper slid under, more sheets were added until no more sheets could be slid under the bridge, and the mass and total sheets were recorded. A smartphone recorded the testing process for all three trials. Operational limits of the test consisted of the bridge's articulation range, which was roughly 45 degrees. Another operational limit depended on the weight, as it was required to measure in gram increments.

The mass of the weight was precise to 1 gram. The height of the gap under the bridge was accurate to 0.05 mm, since a standard sheet of printer paper thickness ranges from 0.05 to 0.1 mm. During testing, the data was recorded on a note sheet. Data was then input into Microsoft Excel. Data will be presented as tables and graphs.

Due to no hanging weights being available in Hogue during the time of testing, a makeshift weight had to be created using a Ziplock bag, paper clip, and popsicle sticks. The popsicle sticks were added to the Ziplock bag and hung from the articulation cord using the paper clip. The mass of the makeshift weight was measured using a scale, and the mass could be increased by adding popsicle sticks.

Test Procedure:

This procedure documents the process of recording, measuring the deflection of the bridge when a 10-gram mass hung on the string, and processing the results.

Time: This test was conducted on 4/19/2024 from 8:30 to 9:30 AM in Hogue 127. After the test, 15 minutes was used to return equipment and clean the testing area.
Place: Room 127, Hogue Hall, Central Washington University campus in Ellensburg, WA.
Required Resources:

- iPhone 13
- Articulating balsa wood bridge
- Table
- Note sheet
- Writing utensil
- Scale
- 1 Ziplock bag
- 1 paper clip
- Minimum 11 popsicle sticks
- Minimum 6 sheets of printer paper

Risk and Safety:
Safety glasses must be worn at all times while testing.

Testing Procedure:

1. Collect Equipment:
   a. Table, note sheet, writing utensil, Ziplock bag, paper clip, and printer paper from Hogue 127.
   b. Scale and popsicle sticks from Hogue 127B Polishing Room.
2. Go to Hogue 127.
3. Place all equipment on the table closest to the whiteboard (Southmost part of the room).
4. Place the articulating balsa wood bridge on the table. Ensure the bridge is in the closed configuration (road deck is not articulated up). Ensure the articulation string is as tense as possible while still maintaining the bridge in the closed position. This may require manually turning the axle.
5. On the note sheet, create 2 columns. Label one column "mass" and the other "lift."
6. Open the Ziplock bag and place 5 popsicle sticks into the Ziplock bag. Close the Ziplock bag and puncture the bag with the paper clip such that the bag hangs from the paper clip.
7. Place the bag with paper clip on the scale to measure 10 grams. Note the mass on the note sheet.
   a. Additional popsicle sticks may be added or removed to reach 10 grams.

Figure G2.1 Determine mass of weight.

8. Hang the paper clip on the articulation string between the bridge and articulation tower.
9. Take 1 sheet of printer paper and attempt to slide the paper under the side of the bridge opposite the articulation tower.
10. If the printer paper does not slide under the bridge, take the weight off the string. Increase the mass of the weight up by 1 gram and repeat steps 6 – 9.
    a. Increase the mass by adding additional popsicle sticks to the Ziplock bag.
    b. Note the mass of the weight and "no lift" on the note sheet.
11. If the printed paper does slide under the bridge, continue adding one sheet of printer paper to the stack and sliding under the bridge under the stack no longer slides under the bridge.
    a. Note the mass of the weight and the number of sheets of paper able to slide under the bridge on the note sheet.
12. Return all lab equipment to its original location.

Initial challenges with the testing process came from the fact that there were no hanging weights available at the time of testing. However, as discussed in better detail in the Methods/Approach section, a makeshift weight was created and used for testing. The test procedure was updated to include steps for creating the makeshift weight.

Deliverables

One trial was conducted, and one sheet of printer paper was able to slide under the bridge when the articulation cord was under a 15-gram load. No calculations were done during this test. For the bridge to successfully meet the requirement, the bridge needed to allow printer paper to slide under at a 10-gram load or less. The test was successfully conducted, but the project did not meet the requirement of a 10-gram load to lift the bridge.

Appendix G2.1 – Procedure Checklist

Resources

- iPhone 13
- Articulating balsa wood bridge
- Table
- Note sheet
- Writing utensil
- Scale
- 1 Ziplock bag
- 1 paper clip
- Minimum 11 popsicle sticks
- Minimum 6 sheets of printer paper

Complete Before Test

- Create makeshift weight
- Tare the scale

Appendix G2.2 – Data Forms

Mass of Weight (g)	Total Sheets of Paper Under	Height Lifted (mm)

Appendix G2.3 – Raw Data

Mass of Weight (g)	Total Sheets of Paper Under	Height Lifted (mm)
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	1	0.1
16	5	0.5

Appendix G2.4 – Evaluation Sheet

Not applicable to test.

Appendix G2.5 – Schedule (Testing)

ID	Task Name	Start	Finish	Duration	Predecesso
6	**DEVICE EVALUATION**	**Wed 3/27/24**	**Fri 5/3/24**	**28 days?**	
6a	Final Bridge Measurement	Wed 4/3/24	Wed 4/3/24	1 hr	
6b	Articulation Test	Wed 4/3/24	Wed 4/3/24	1 hr	
6c	Tensile Test	Fri 4/19/24	Fri 4/19/24	1 day	
6d	Loading Test	Fri 5/3/24	Fri 5/3/24	1 hr?	
6e	Bridge Mass Test	Fri 5/3/24	Fri 5/3/24	0.25 hrs	

Appendix G3 – Load Test

Introduction

The load test measured the weight that the bridge was able to support, as well as the bridge's deflection under that load. The bridge was required to support a load between 18.9 and 20 kg and deflect less than 25 mm under that load (refer to Section 1d-7 and 1d-9). Parameters of interest were the length of the bridge and the weight of the bridge. The bridge was predicted to support a 25 kg load, as the calculations in Appendix A02 and A03 were based on a load of 25 kg. Data will be recorded using the Instron, which automatically collects the load and deflection onto a spreadsheet. This test was scheduled to take 1 hour on the Gantt Chart in Appendix E.

Method/Approach

Resources needed for the test were the Instron and the abutment. The abutment was constructed by the project mentors and allowed for the bridge to be placed into the Instron. Soft resources were Microsoft Excel. Someone who could log into and operate the Instron was needed for the test. The test did not impact costs or the budget. Data was automatically documented by the Instron during the test, and the entire test was recorded using a smartphone.

The test procedure went as followed: the bridge was placed into the abutment, and the Instron was powered on and simulated a hanging load from the bridge by pulling on the bottom of the bridge. Operational limits of the test were that the bridge could only support a certain load until permanent deformation or failure. The Instron recorded the Force in kN and deflection in mm to ten-thousandths of a decimal. Data was recorded by the Instron and stored on a Microsoft Excel spreadsheet. That same spreadsheet was used to analyze the data. Data was presented as a force vs deflection graph.

Test Procedure

This procedure documents the process of recording, measuring the force the bridge was withstand and the bridge's deflection under that force using the Instron.

Time: This test was conducted on 5/3/2024 from 8:00 to 9:00 AM in Hogue 127. After the test, 15 minutes was used to return equipment and clean the testing area.
Place: Room 127, Hogue Hall, Central Washington University campus in Ellensburg, WA.
Required Resources:

- iPhone 13
- Articulating balsa wood bridge
- Instron
- Instron Operator

Risk and Safety:
Safety glasses must be worn at all times while testing.

Testing Procedure:
Note: test procedure for Instron is awaiting instructor's SOP. Once provided, the testing procedure will be updated to be more thorough.

1. Collect Equipment:
    a. Instron, Instron operator in Hogue 127.
2. Go to Hogue 127.
3. Remove bridge from articulation tower and remove other articulation components attached to bridge.
4. Slide the metal rod through the 8mm diameter hole in the center of the road deck. Fasten the metal rod to the bridge using the washer and nut.
5. Place bridge with metal rod into the abutment in the Instron. Place bridge upside down in abutment. The road deck side of the bridge should be facing toward the ceiling.
6. Secure the metal rod into the top of the Instron.
7. Raise the Instron such that the bridge is securely and evenly fixed in the abutment.
8. Start the Instron. The Instron will automatically lower the force once the force reaches roughly 190 N.
9. Stop the Instron.
10. Remove the bridge from the abutment and remove the metal rod from the bridge.
11. Have the Instron operator email the Microsoft Excel file containing the testing data to a convenient email.

One issue with testing was that the initial load test that was completed did not record the data onto a spreadsheet. Although an image of the maximum force and deflection was taken, a graph could not be created from the test data. Since the bridge did not experience any permanent deformation, a second test was conducted to resolve this issue. A spreadsheet for the second test was successfully created. The testing procedure also required updates after the instructor provided the load test SOP.

Deliverables

The bridge was able to withstand a 190.02 N load and deflected 1.6577 mm under that load. The maximum load was calculated to be 19.4 kg. The bridge met both the load and deflection requirements for the project, and the bridge also did not experience any permanent deformation after the test. Despite the initial issues with the test, the load test was successful.

Appendix G3.1 – Procedure Checklist

- Abutment constructed.
- Operator logged into the Instron.
- Metal rod securely attached to the bridge through 8 mm diameter hole.
- Bridge secure in the abutment in the Instron.

Appendix G3.2 – Data Forms

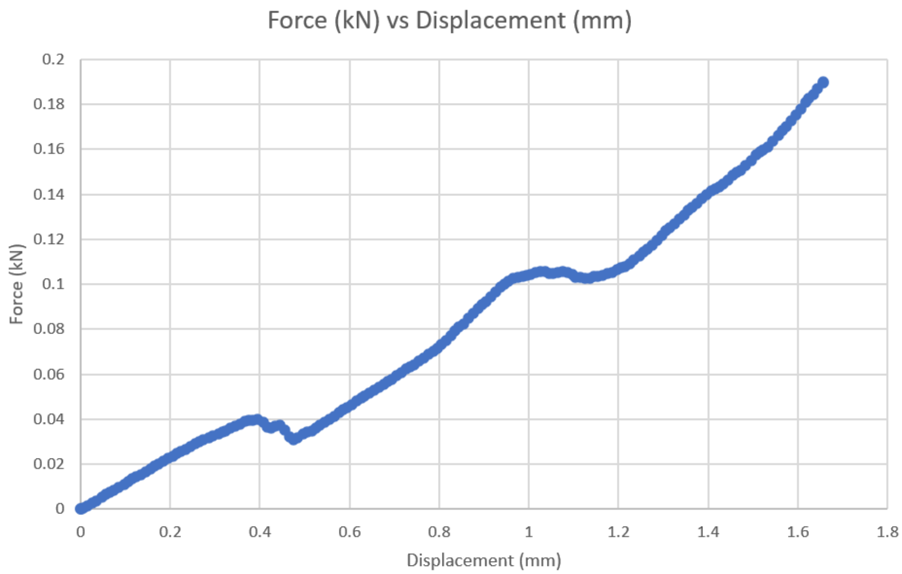
Not applicable to test. Instron automatically records data to a spreadsheet. Refer to Appendix G3.3.

Appendix G3.3 – Raw Data

Time	Displacement	Force
(s)	(mm)	(kN)
0	0	0
0.05	0.0007	0
0.1	0.0024	0.0001
0.15	0.0062	0.0004
0.2	0.0155	0.0013
0.25	0.0255	0.0026
0.3	0.0348	0.0037
0.35	0.0467	0.0051
0.4	0.0554	0.0064
0.45	0.0642	0.0074
0.5	0.0746	0.0085
0.55	0.0854	0.0098
0.6	0.0966	0.0111
0.65	0.1058	0.0123
0.7	0.1142	0.0133
0.75	0.1239	0.0142
0.8	0.1343	0.0153
0.85	0.1452	0.0166
0.9	0.1567	0.018
-break-		
8.409	1.6577	0.19

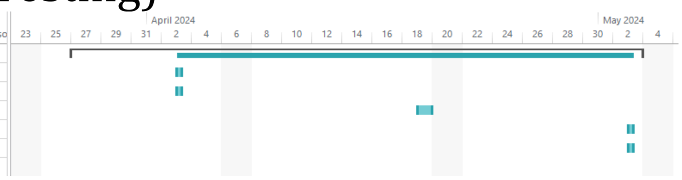
Note: The above data showed only a portion of the data table. There table was too large to practically show the entire table in this document. The first and last data points were shown.

Appendix G3.4 – Evaluation Sheet



Appendix G3.5 – Schedule (Testing)

	Task Name	Start	Finish	Duration	Predecesso
6	**DEVICE EVALUATION**	**Wed 3/27/2**	**Fri 5/3/24**	**28 days?**	
6a	Final Bridge Measurement	Wed 4/3/24	Wed 4/3/24	1 hr	
6b	Articulation Test	Wed 4/3/24	Wed 4/3/24	1 hr	
6c	Tensile Test	Fri 4/19/24	Fri 4/19/24	1 day	
6d	Loading Test	Fri 5/3/24	Fri 5/3/24	1 hr?	
6e	Bridge Mass Test	Fri 5/3/24	Fri 5/3/24	0.25 hrs	



APPENDIX H – Resume

NATE HARRIS

(xxx) xxx xxxx
xxxxxxxxx@gmail.com

street address
city, state, zip

CAREER OBJECTIVE: Use skills and experience from class and work to contribute to an engineering project.

EDUCATION

BS, Mechanical Engineering Technology
Central Washington University, Ellensburg WA **June 2024**

Academic Minor, Physics
Central Washington University, Ellensburg WA **March 2023**

PROFESSIONAL EXPERIENCE

Maintenance Assistant, Central Washington University, Ellensburg, WA **June 2023-Current**
- Utilized various repair skills to maintain university buildings and property.
- Performed simple repairs including setting toilets, repairing sinks, and other basic repairs to upkeep university property.

Assistant Coach, Maple Hills Swim Team, Renton, WA **June 2021 - July 2022**
- Oversaw all practices and competitions, communicated between participants and coworkers.
- Explained basic and advanced skills to children ages 6-18 leading to an undefeated season.
- Coordinated between other coaches, swimmers, board of directors, and parents to allow efficient communication.

Head Lifeguard, Phantom Lake Bath and Tennis, Bellevue, WA **May 2019 - Sept. 2022**
- Led team of 15 lifeguards, communicated with management, and maintained pool property.
- Prevented injury by foreseeing potential harm and creating a safe environment.
- Trained new employees using hands-on and verbal direction for new employee integration.

SKILLS

Applications: SolidWorks, AutoCAD, Excel, Word, PowerPoint.
Metal Fabrication: Lathe, Milling Machine, CNC.

LEADERSHIP

President of Central Washington University Swim Club **Sept. 2022 - Current**
- Led club of 20 members. Coordinated and communicated practices and competitions.
- Navigated through various complications such as pool closures to ensure club continuation.