WALKING MOUNTIAN BRIDGES REPORT

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Contents

Introduction:

At the Walking Mountains Science Schools campus there are a collection of walking trails. The walking trails traverse creeks so they implement bridges for hikers. Some of the bridges were beginning to deteriorate after years of weathering, use, and mediocre initial designs. Markian Feduschak, president of Walking Mountains Science School, offered me an opportunity to replace these three bridges. Replacing the three bridges involved coming up with new designs, doing the engineering, acquiring the materials, and building the bridges. The designs were executed using hand calculations and SolidWorks. I did familiarize myself with REVIT however it was not the correct software for this project. Bridge One and Three are very similar and implement the same design. Bridge Two required a new design because of the different location. Working through the entire process from design to reality requires an understanding of how engineering theory interfaces with the reality.

Bridge One and Three:

Design

Bridges One and Three were both located so that the effective span to consider in my designs was 12 feet. Thus allowing me to use the same design for these two bridges. A critical design factor for me was the remote nature of the bridges, and the frequent use of the bridges during the summer. Meaning I had to work to minimize the amount of time in which there was no bridge there, and all the materials had to be carried to the location of the bridge on foot. As a result, as much of the building that could be done offsite was, this way the assemblies were able to be executed in just one day.

A design flaw of the original bridges was that the railings were planted into the logs so that the moment incurred by someone holding onto the handrail was only countered by a small piece of wood jointery. Over time the rot and use led to a large amount of play and nearly no strength in these joints, hence the railings. Additionally, the logs used for the base are half cylinders, and they hand holes facing up where the railing posts were, making them prone to collecting water, leading to faster rotting.

The initial design for both bridges, seen in Figure 1, used two 4-foot sections of pressure treated 8x8 on each side as the abutments. Three large timbers made up the walkway and provided structure. Four pieces of 2x4 lumber and two pieces of 2x6 lumber made up the horizontal railing sections. Finally, there was a center brace to provide lateral support to railings.

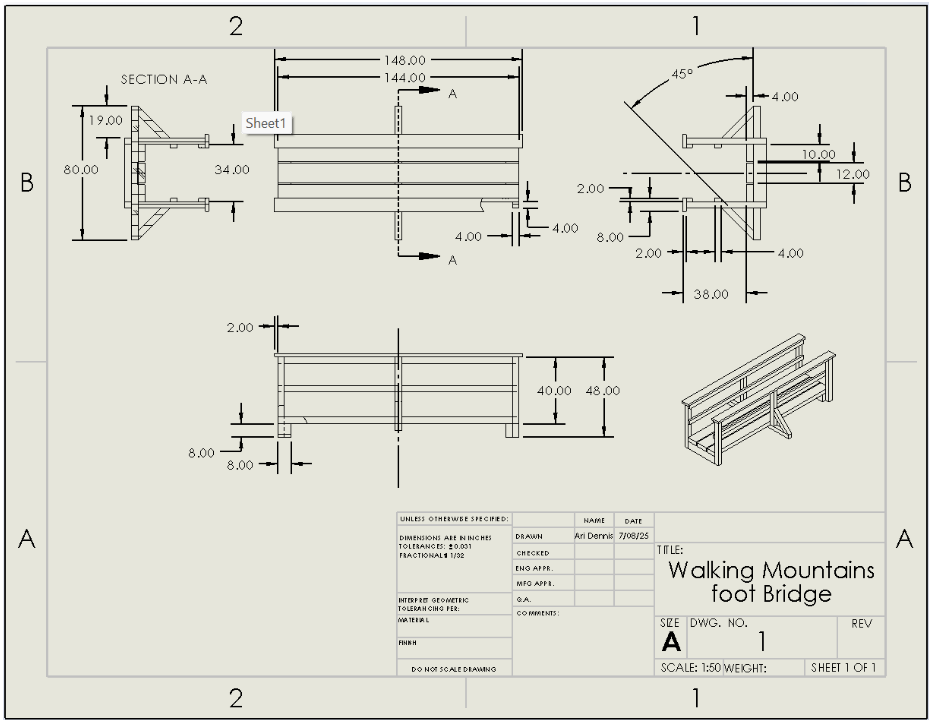


Figure 1. The design for bridge One (also use for bridge three)

Bridge one used a 4x10 timber in the center which was bought from a scrap yard at a significantly reduced price due to a tag, a cosmetic defect that doesn't affect the structural integrity of the timbers. The timbers on either side of this one were 4x12 timbers. Bridge Three used three 4x12 timbers. Both the bridges used a center brace, seen in Figure 2, to resist the moment caused by people leaning on the railings. The timbers sit flush to the abutments with roughly a ¼ inch gap between them. The top of the railings are at 40 inches above the walkway, which is a comfortable railing height for most people. The width of the walkway is 34 inches, wide enough for people to pass or one person to comfortably walk across.

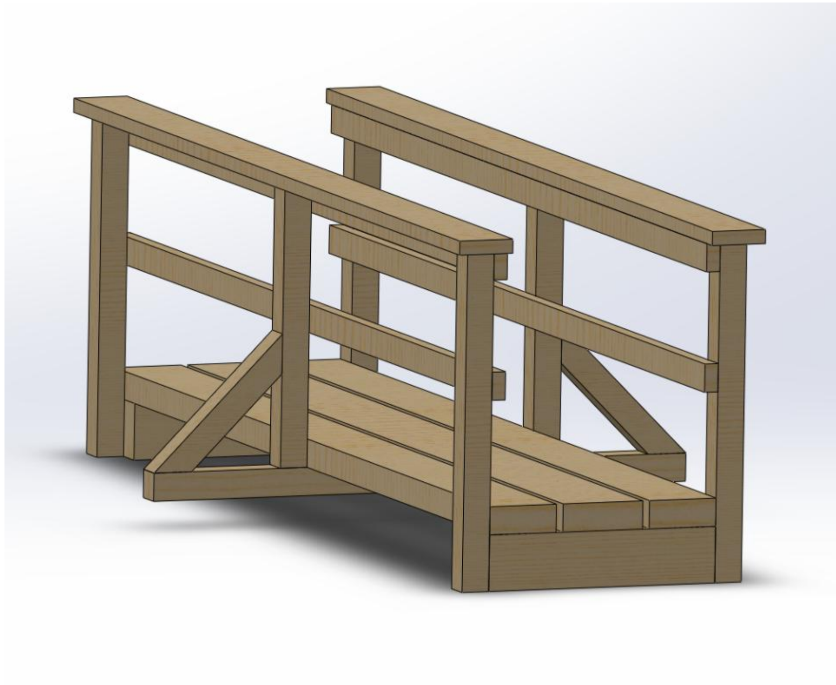


Figure 2. Model of Bridge One and Three

The center section as seen in the center of the model was built using 4x4 lumber. A beam went across the bottom and sat flush to the underside of the timbers, two posts sat flush to the outside of the timbers, and then struts were placed in between the post and beam at a 45° angle. Four 4x4 posts sit at all the outside edges flush to the abutments and timbers, creating the outer posts of the railings. Additionally, 2x4 – 16 ft pieces of lumber were used horizontally as railings to add more strength and cut the air gap in half so kids can't fall through. Finally, 2x8-16 ft pieces of lumber were used as railing caps. These provided significant strength to the railings, and help to keep water from getting into the ends of the posts. The orientation of the caps is so that the larger area moment of inertia is resisting the moment a person pushing on the hand rail would create.

Implementation

During the building process the first step was to set the abutments. This was a critical step since they serve as the bridge's foundation, and thus need to be level, square, and co-linear. This was accomplished using a shovel to add or remove dirt, a level to check that each abutment was level, a laser, and a tape measure to finally ensure that the abutments were square and co-linear. The abutments for bridge one can be seen in Figure 3.

Figure 3. Abutment placing for bridge One (Left) Proper abutment layout (Right)

For Bridge Three two pieces of 2x8 pressure treated wood were added to a low abutment to raise it by three inches. This was done as opposed to adding dirt because it would be difficult to adequately compact the dirt enough so that it would act as a strong foundation. Also because the abutment was placed near the edge of a creek it is possible that added dirt would have been eroded away.

I then needed to build the center section. For the bottom piece I used a 8-foot 4x4 piece of lumber, which is stock and thus reduced the amount of cutting that I had to do. Then the two posts and and the two struts were cut from one 12-foot 4x4 piece of lumber which was cost saving. The cuts were all made using a chop saw. The cut pieces of lumber were then laid on a piece of plywood on which I laid out the template. All the pieces were laid in there respective spots and then clamped, this way I could be sure all cuts were done accurately and all the pieces fit. I did occasionally have to use a marriage cut because of the imperfection when working with wood. The two posts were fastened first with two 6 inch timberlocs. A piece wood was placed in between them in anticipation of the Timberlocs sucking the posts in a small amount because of the fastening nature of Timberlocs, and the decided screw layout (Appendix C). The board placed in the center helped to mitigate this. Then the two struts were fastened to the posts and beam using two 6-inch timberlocs, again according to the screw layout (Appendix C). With the center section assembled, the four 48" posts were cut. After all cuts were completed, and the center section was assembled, I stained all the wood and waited a couple of days for it to dry, Figure 4.

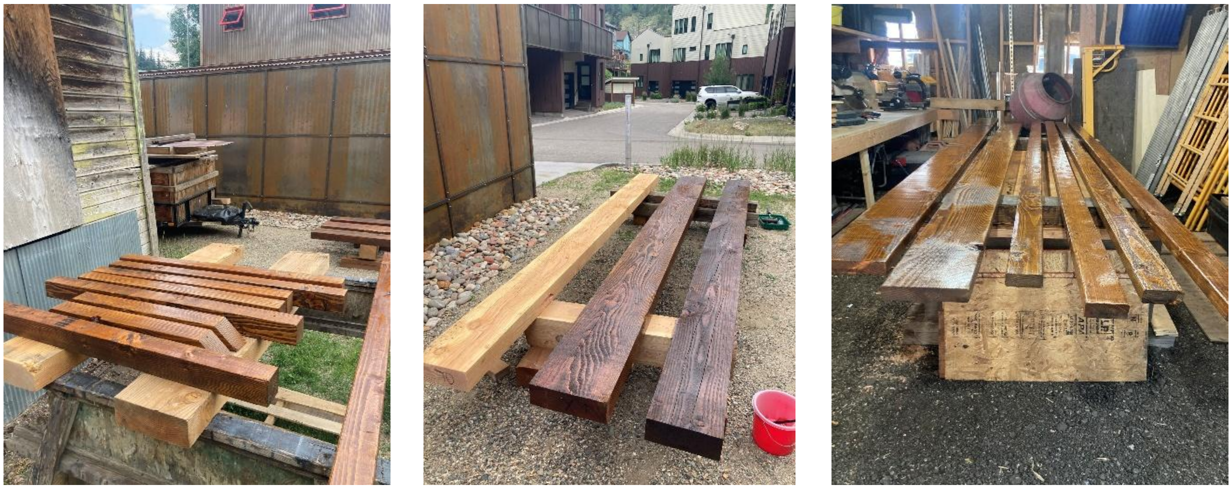


Figure 4. Stained and cut materials in the process of drying

Once all the materials were ready they were transported to Walking Mountains campus and then further carried to the location of the bridges. Pieces of wood were laid in the creek so we had somewhere to walk throughout the assembly process. The large timbers were laid on top of the abutments, Figure 5.

Figure 5. Timbers being placed on the abutments

The Timbers were placed on steel C- channel to allow for air to flow underneath, allowing for drying and prolonging the lifespan of the bridge. The timbers were placed so they were symmetrical and square to the abutments. Then they could be fastened to the abutments using 6-inch timberlocs. Then the center bracing subassembly was clamped onto the bridge in it's correct orientation and Timberlocs were screwed horizontally through the post into the large timbers on each side, as well as vertically through the timbers into the 4x4 beam that was across the bottom. The four posts were installed one at a time, with one screw into the abutment and one into the timber, Figure 6.

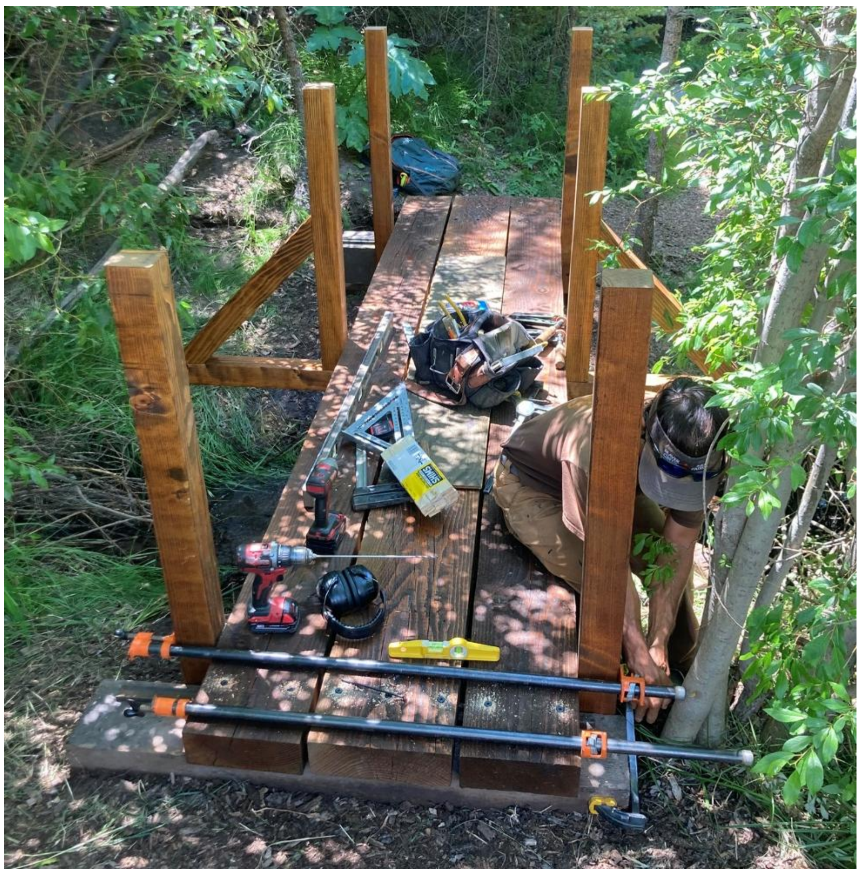


Figure 6. Greg working on a post of bridge One (same process as Bridge Three)

The screw in the timber was first, because we were then able to plum the post, adding shims if necessary. With the center brace and posts done, the next step was the railings. The four 2x4-16 feet lumber pieces were installed first, such that they were level and had an equal amount of overhang on each side. This was also the point where we were able to correct any lean in the center section, making it plum. These railing pieces were installed using standard 3.5-inch GRK fasteners. Finally, the top cap was fastened by using the same 3.5-inch GRK screws and screwing into the 2x4 already placed, seen in figure 7.

Figure 7. Ari Installing a railing cap on bridge Three

Some of the boards throughout the railing install had bow in them. It was important to be aware of this, and when necessary pull this out using clamps, before it was fastened.

Bridge Two:

Design

For Bridge two the design had to be changed from what was done for the first and the thrid bridge because of the increase in span length. Now the effective span was 16 feet. The bridge was designed so that from outside of post to outside of post was exactly 16 feet as seen in Figure 8.

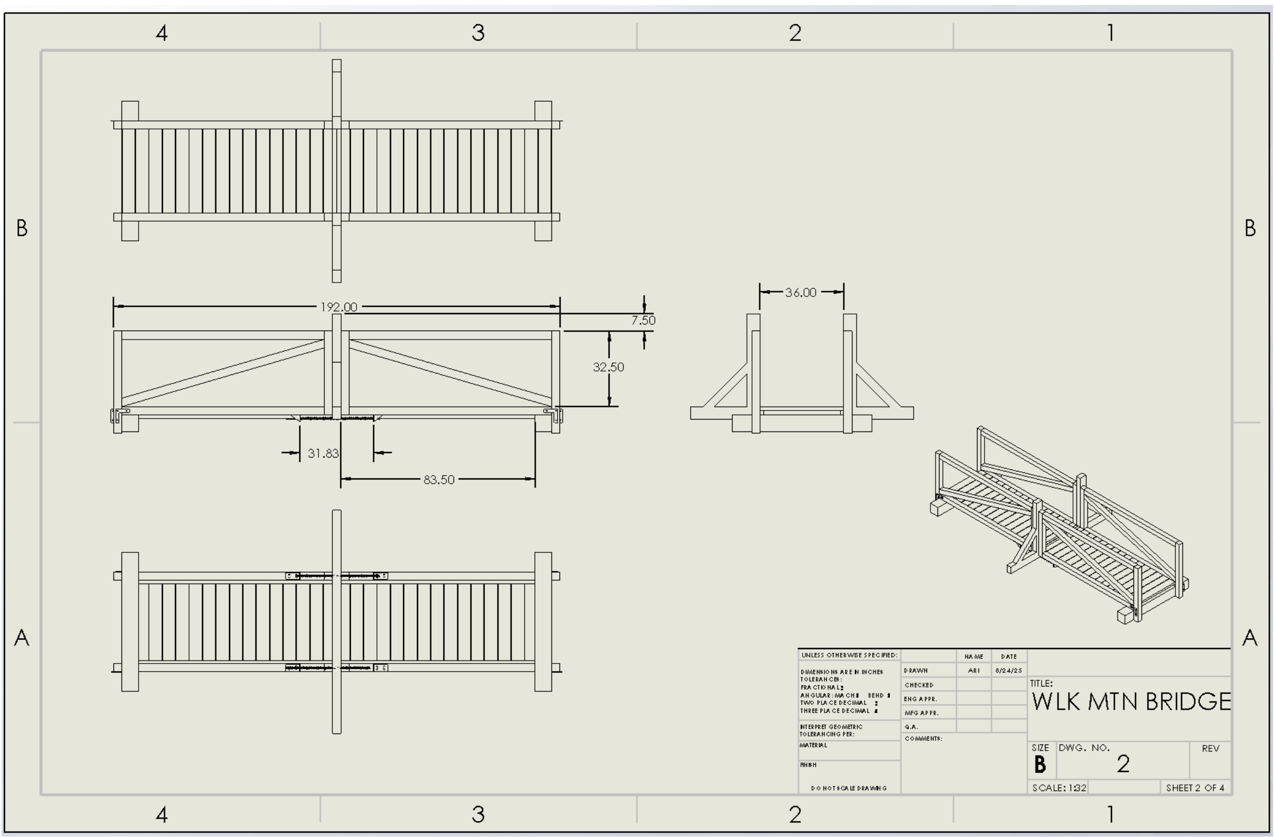


Figure 8. Drawing of Bridge Two

The tops of the railings are at 32.5 inches above where people will be standing, which is a standard height for railings. Using large 4x12 timbers as the primary structure would not work well since buying them at 16 feet would be considerably more expensive, they woud become difficult to carry to the site, and there would be a slight bounce in the center of the bridge. So a new design was developed, Figure 9.

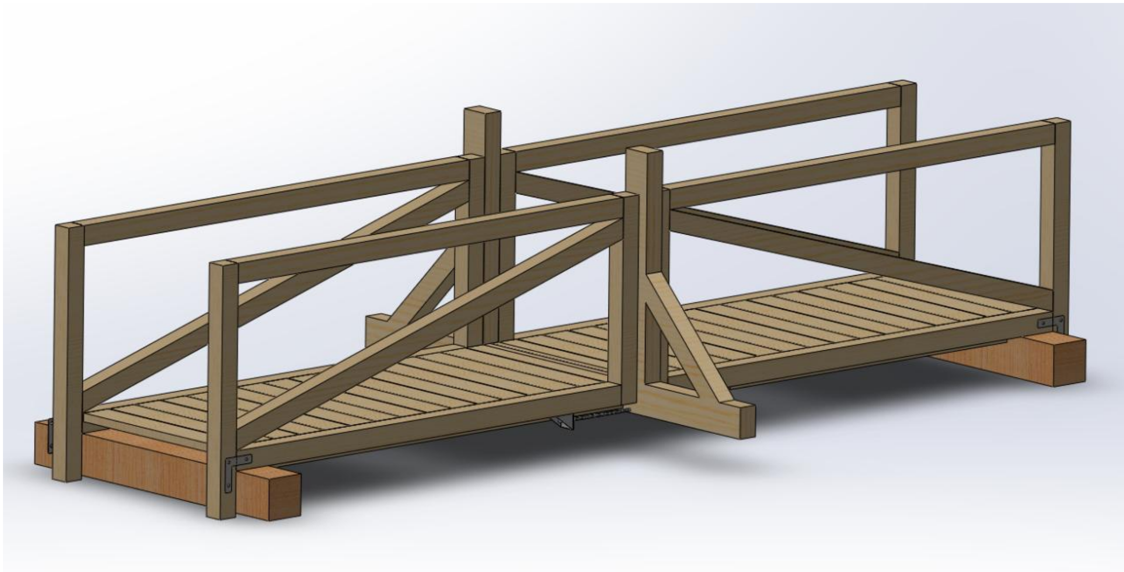


Figure 9. Model of bridge Two

The new design consists of two abutments on each end, a boardwalk that sits on ledgers, four railing sections which act as trusses (see discussion on trusses below), and a center bracing section to provide support for the railings, seen in Figure 9. The center bracing section is made with 4x6 lumber, struts are used at a 45° angle to provide reaction a moment to any forces applied into the railings. The nominal 5.5-inch side of the 4x6 is oriented vertically, increasing it's 2nd area moment of inertia about the horizontal axis, so that it can better resist any moment put on the railings or heavy amounts of weight on the bridge. At the four corners of the bridge a steel L-bracket is used. This provides a massive amount of strength to the connection between two 4x4 lumber pieces. This is a very important connection because the entire load on the bridge is transferred into the abutments and then into the ground through this point. Also, without this L-bracket the connection here would be completely dependent on the strength of the timberloc. The four truss sections, made from 4x4 lumber, meet in the middle where they push up flush to the center section. The two opposite trusses are connected using a Simpson HD3B and a tie rod, seen in Figure 10.

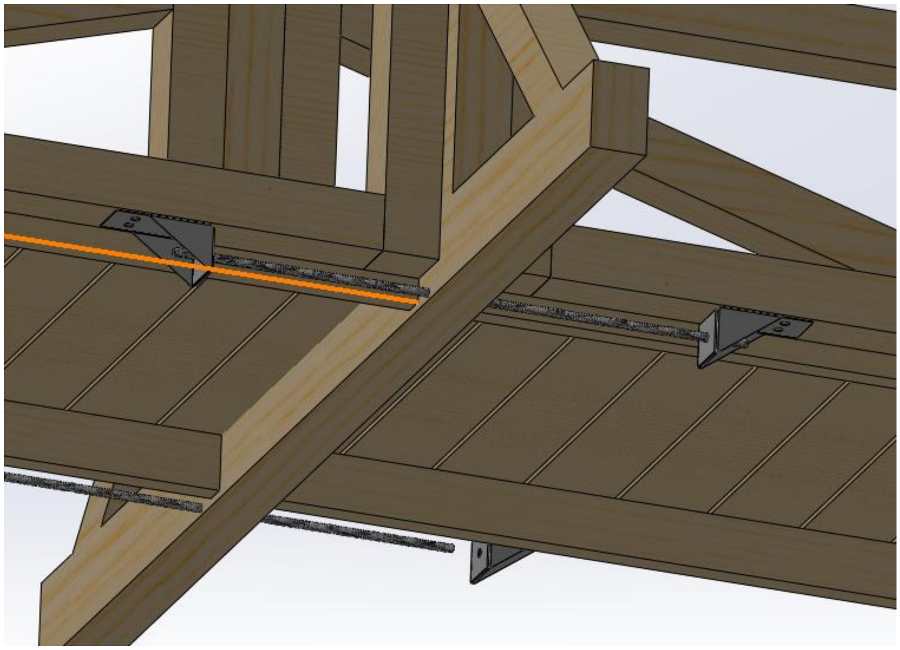


Figure 10. Two HD3B's and a tie rod holding truss sections together

The HD3B's are fastened to the bottom of the trusses using two 5/8-inch lag screws each. Then a 5/8-inch tie rod then goes through the HD3Bs and it fitted with a nut on each side, which is then tightened. This is responsible for carrying the majority of the load. The main vertical load of the bridge acts to pull apart the the center section. The tie rod along with HD3Bs prevents this and takes up that load in horizontal tension. Each rod can carry about 13500 lbf based on an average tensile value of steel from Shigleys Mechanical Engineering Design, therefore this is an effective way to handle the load on the bridge.

Truss Design and Behavior

By creating a railing that is also a truss it allows for the strength of the bridge to be elegantly incorporated into the railing. Trusses are static structural systems composed of 2 force members and joints, seen in Figure 11.

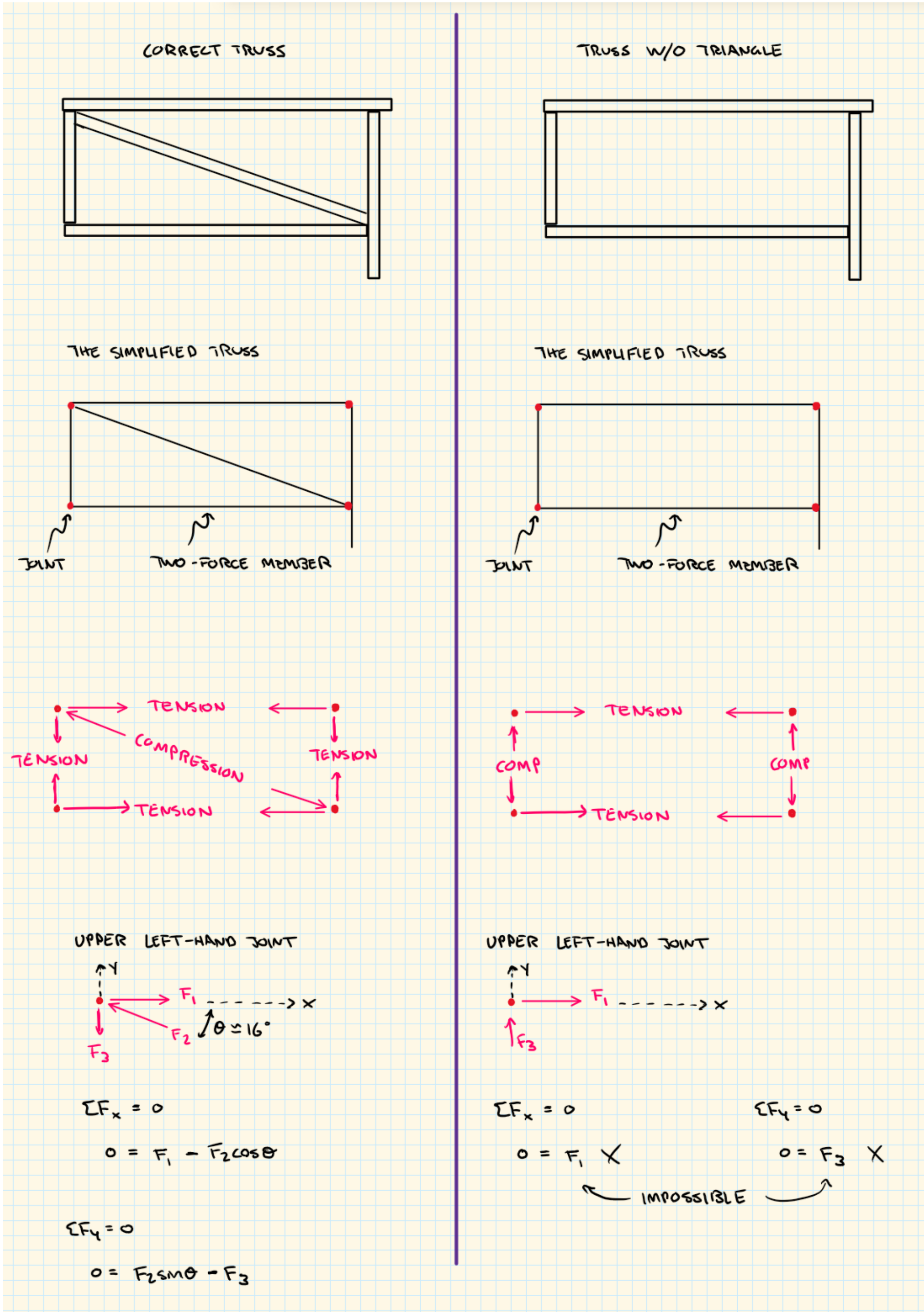


Figure 11. On left, the proper Truss. Right, the incorrect truss without triangles

A two-force member is a theoretical simplification that is used because it yields accurate results. A two-force member is a straight member connected at it's end by pinned joints and there are only forces at the two pins. Also, the weight of the members is very small compared to the loads they're carrying and thus they're own weight can be neglected. The members of a truss can theoretically only carry axial forces (tension or compression). The series of members and joints forms a series of interconnected triangles. Because triangles are geometrically stable, trusses efficiently transfer applied loads. This allows the structure to resist bending and shear more effectively. The Railing section built can be seen on the top left of Figure 11, and directly below that is the simplified truss model. To understand why the triangle really helps the structure it is of interest to investigate the forces. To effectively view the forces vectors are used to denote the direction of the force between the joints, this can be seen as the 3rd drawing down (pink) in Figure 11. The bottom member is in tension because of the way the HD3B's are taking up the load, previously discussed. From this, statics allows us to determine whether the other members are in tension or compression. The significance of a static structure, like trusses, is that they are not moving. From a physics standpoint this means that all the forces are balanced, and there is not a net force in any direction. This further means that all the vectors must be balanced at every joint. For example, at the bottom right joint of the correct truss the force from tension is a horizontal vector to the left. To balance this there must be a force to the right, the only way this can be done is from the diagonal so it's vector must be pointing to the right along the axis of the member. This further means that this diagonal member is in compression. Now this diagonal member introduces a force in the vertical direction, but the bottom beam, being a two-force member can only handle horizontal loads, thus the vertical component must be taken up by the post. And to maintain static equilibrium the vector must be pointing up, meaning that member is in tension. The fourth drawing down in Figure 11 is a representation of the forces at the top left hand joint, although it could be any joint, the results would be the same. On left, F1 is the force from the top beam, F2 from the diagonal member, and F3 from the post. Statics tells us that the sum of our forces in the vertical direction (y-axis) or horizontal direction (x-axis) are equal to zero. We get that

$$F_1 = F_2 * \cos(\theta) \tag{1}$$

$$F_3 = F_2 * \sin(\theta) \tag{2}$$

Which is totally possible.

In the scenario that our truss does not have the long section creating triangles that it is theoretically an impossible structure. The sum of our forces in the vertical direction (y-axis) or horizontal direction (x-axis) yield that

$$F_1 = 0 \tag{3}$$

$$F_3 = 0 \tag{4}$$

which is impossible because we know that when someone stands on the bridge there will be some amount of force in every member. Now we know that in the real world we could build a structure like that shown on the right hand side of Figure 11. The way this is possible is the screws take up large amounts of load as opposed to the two-force members, so now you are completely reliant on the material properties of the screw, Figure 12.

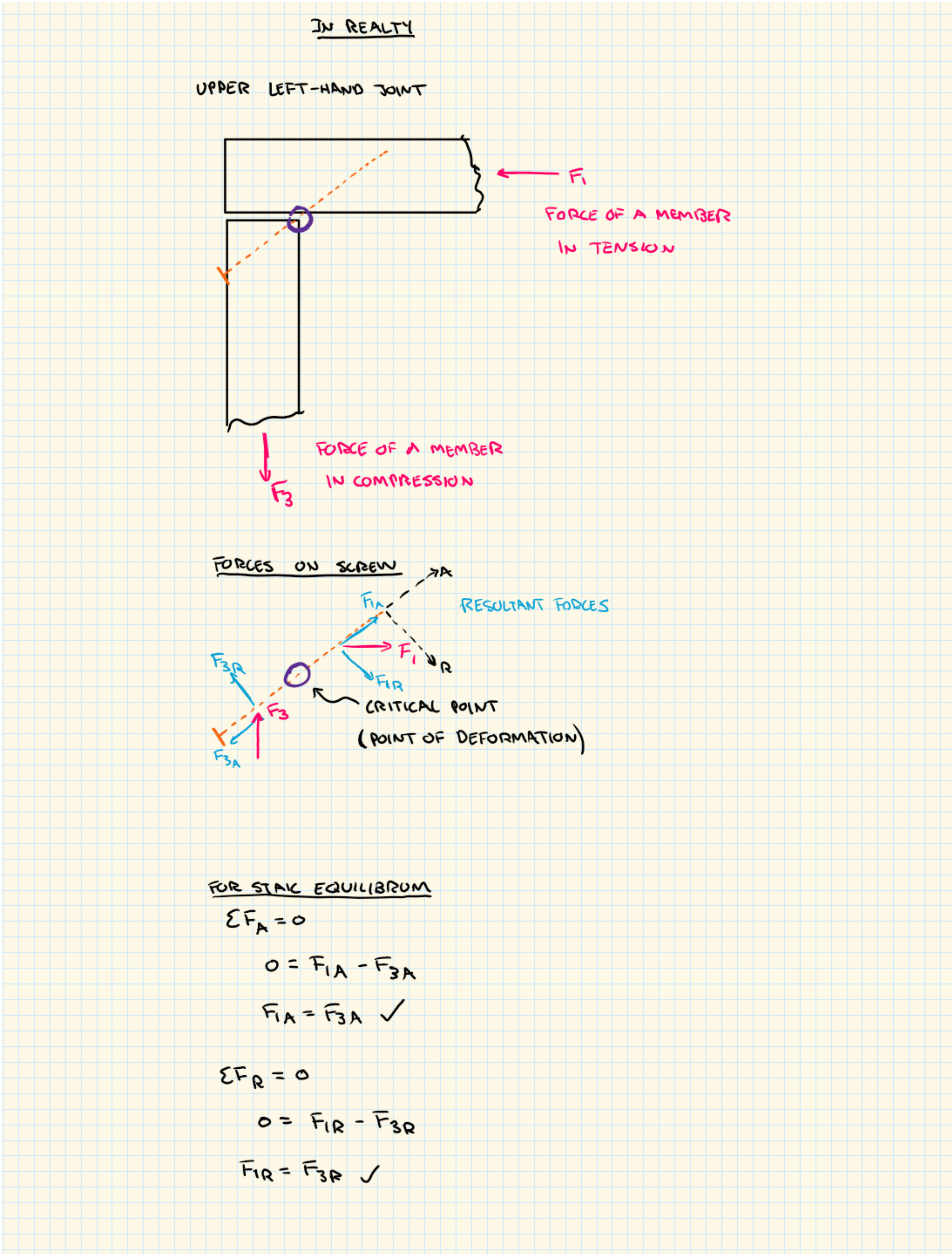


Figure 12. The scenario in which the truss is built incorrectly, and the screw has to carry the load

In Figure 12 the screw holding the two members together is illustrated in orange. In purple is the part of the screw between the two pieces that would break upon excessive loading. In the second illustration we can see the forces imposed on the screw, and below that the equations show that,

$$F_{1A} = F_{3A} \tag{5}$$

$$F_{1R} = F_{3R}$$

where A and R denote axially and radially respectively. This is just another coordinate system used to assist in the algebra, similar to X and Y. These show how yes static equilibrium is being achieved but entirely at the hands of the screw. The results are large loads within the screw. So for the screw to stay clear of it's yield point (Appendix B), where it starts to break, you have to use a diameter of around half an inch, which leads to many other difficulties when building. If small screw were used with the incorrect design, it would undergo plastic deformation, hence the truss would laterally deform turning the rectangle into a parallelogram.

Implementation

The first step was setting the abutments correctly. The procedure was the same as what was done for Bridge One and Three. Then all the subassemblies, the center section and trusses were assembled off site. The center sections pieces were cut using a chop saw and then laid onto a template, which was a piece of plywood with nominal values and orientations sketched out. With the pieces in place, they were clamped to the piece of plywood, so they didn't move when inserting fasteners.

Figure 13. Center Brace section laid on plywood template

Larger 8-inch timberlocs were used, since 6 inches wasn't enough for a secure connection in the 4x6 lumber. The same methodology was used for the truss sections, although a different template was needed, again 8-inch timer locs were used. The challenge when making the subassemblies was trying the prevent the 8-inch Timberlocs from sucking lumber pieces out of place, because an 8-inch timberloc can transmit a large amount of force. The way this was mitigated was a combination of clamps, and small 3-inch GRK screws through the bottom of the plywood and into a piece in the assembly. The screw layout used can be seen in Appendix C. Then, it was taken apart, and the pieces were all stained. Since the screw holes were already there, the assemblies were easily refastened, Figure 14.

Figure 14. Trussing sections assembled

After letting the stained subassemblies dry it was time for assembly. Scrap pieces of timber were laid on the ground to make 3 stacks, each one acting as staging support, Figure 15.

Figure 15. Ari assembling the different sections off site

The supports were laid to be roughly level and all the same height off the ground. The center section was laid on the center of the three supports, parallel to the support. Then one railing section at a time was lifted on the supports so it was sitting perpendicular to the center section, the way the bridge would be installed. The two sections could be clamped flush, Figure 15. Then instead of connecting these sections with timberlocs, as initially planned, the decision was made to instead drill a hole through the two railings and center section. Then, a ½-inch piece of threaded rod could then be inserted through the holes and fitted with a washer and nut on each side. A ½-inch piece of steel in shear breaks at about 13,600 lbf, a ¼-inch same grade steel in shear breaks at 3,380 lbf. The timberloc is closer to ¼-inch steel. Once the sections were clamped, seen in Figure 15, a drill with a ½ auger bit was used to drill through the vertical lumber pieces being clamped together. It was important to focus on creating a hole that was plum here. The railing section was then separated from the center section. Dimple marks marked where the screw heads protruded and a paddle bit was used to counter sink those locations on the center section, helping to ensure a flush connection. Next the same process was carried out with the opposite section. However this time the auger used the existing hole, in the center section, as a start. This way the holes in the 3 different pieces were co-linear and the rod could snugly go through all the sections. Then the sections were labeled in areas that aren't visible in the final bridge, so that the bridge could be installed on site in the exact same way it was assembled. Finally, this process was repeated with the remaining two railings and other side of the center section.

Next it was time to install the bridge on site. All the materials were transported to the job site. To install the bridge, I had to support the different sections similar to how they were during the assembly. To accomplish this over a creek bed a temporary staging scaffold was constructed out of 2x4 lumber and extra screws, seen in Figure 16.

Figure 16. Temporary staging scaffolding supporting bridge sections being connected

Four of the 2x4's were cut at an acute angle to create a point that could be hammered into the clay in the creek bed to serve as posts. Beams were then screwed into these posts at a height flush to the top of the abutments so that the railings were level, and all sections were at the correct height. The center section was placed in the center and then the corresponding railing sections were placed in their respective spots, and clamped together, Figure 16. The threaded rods were inserted through the sections, and the washers and nuts were placed onto the rods and tightened. Then the bottom tie rods were placed through the HD3B's, nuts were threaded on, and then torqued down to tension the rod. Then, 8-inch timberlocs were screws through the ends of the railings that overlap the abutments. This helped to strengthen the bridge by securing the ends flush to the abutments, plum, co-linear to the opposing railing, and square to the theoretical rectangle that makes the bridge.

With the main structure done it was time to place the 2x6 decking that would make up the board walk. Starting in the center and working to the edges 3.5-inch GRK decking screws were used to screw each board to the ledges on which they sat. Two screws on each side (a total of 4 per board) were screwed at an angle so that the head of the screw stayed away from the edge of the board, preventing splitting. Finally railing caps were added to create the final bridge seen in Figure 17.

Figure 17. Finished bridge

Railing caps were placed symmetrically on the tops of the railings. This was a change from the initial design which had two kingposts that stick up in the middle, the intent was to add more structure to the railings. That is exactly what the railing caps do, in the same manner as Bridge One and Three.

Appendices:

Appendix A: Supporting Hand Calculations

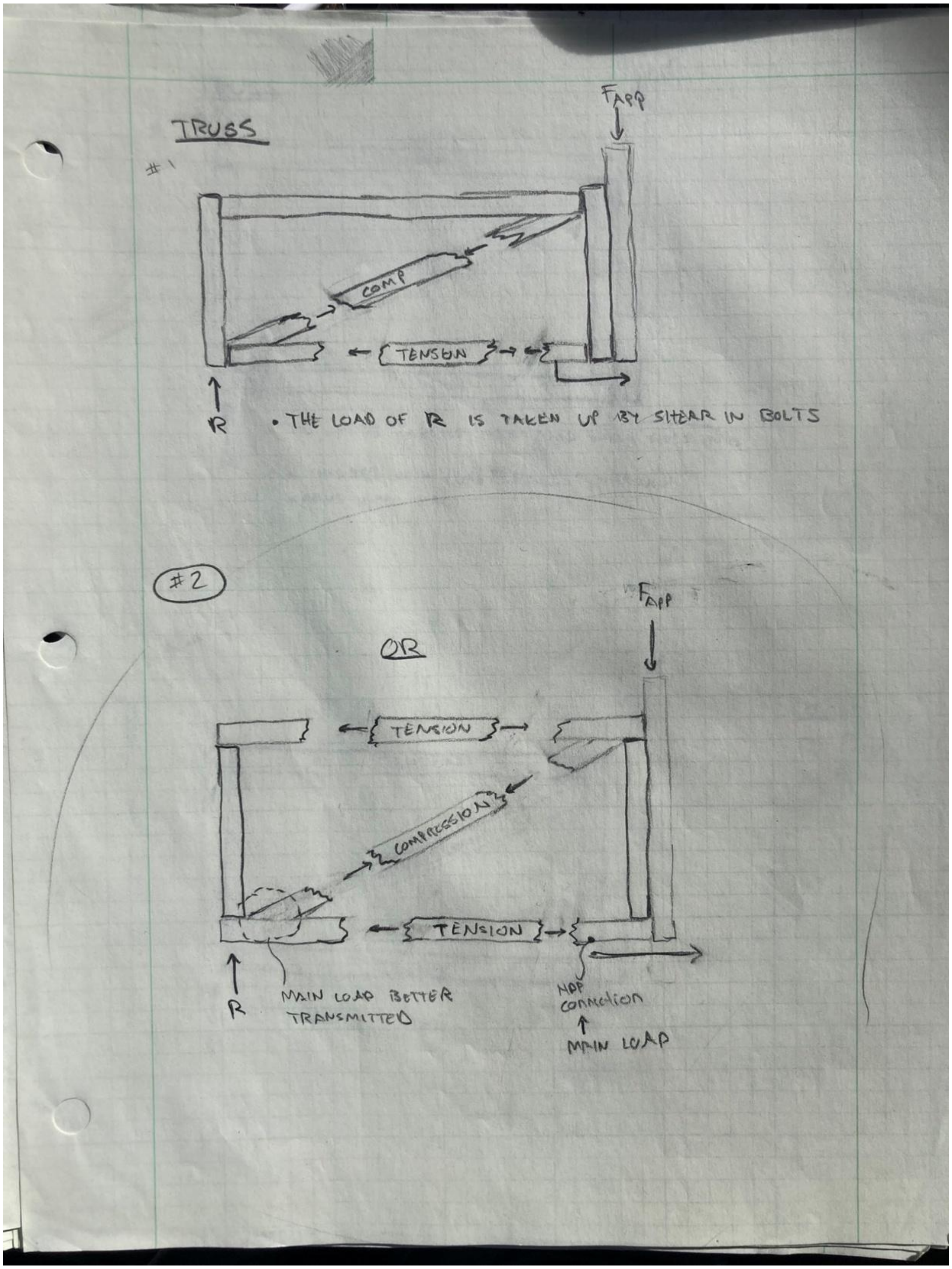
Appendix B: Hand Calculations for Screws

Appendix C: Screw Layout

Appendix A

Supporting Hand Calculations

Hand Calculations were performed to roughly estimate the strength of the center brace, which was implemented in all the designs, making it structurally very important. There are also rough sketches of varying designs, to help facilitate the selection of the best design.


TRUSS
#1
FAPP
COMP
TENSION
R
• THE LOAD OF R IS TAKEN UP BY SHEAR IN BOLTS
#2
OR
FAPP
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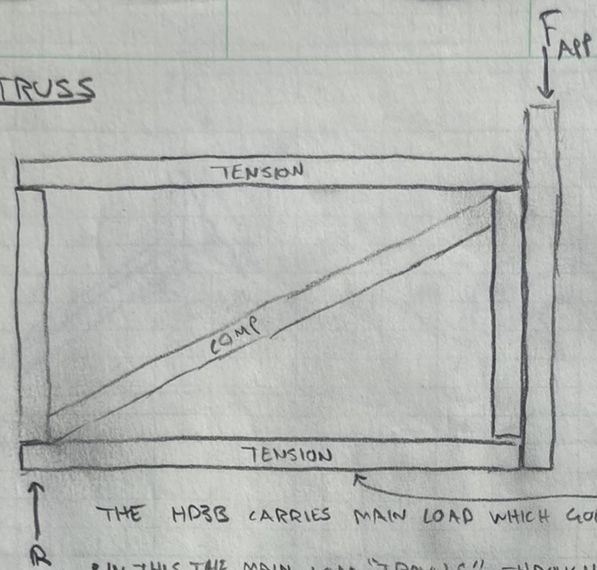
R
MAIN LOAD BETTER TRANSMITTED
connection
MAIN LOAD

TRUSS

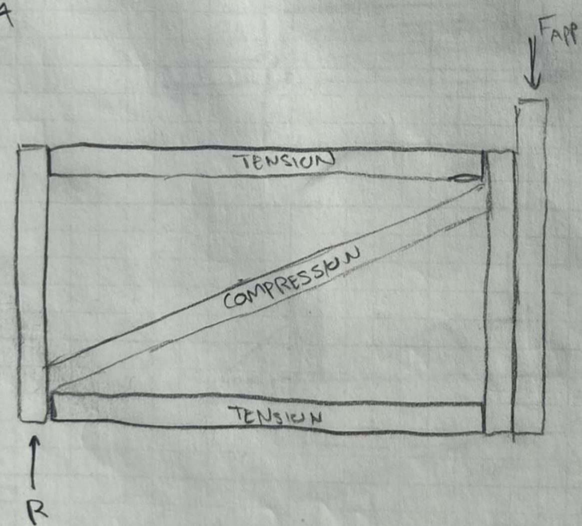
#3



THE HD3B CARRIES MAIN LOAD WHICH GOES INTO

- IN THIS THE MAIN LOAD "TRAVELS" THROUGH SCREWS INTO DIAG

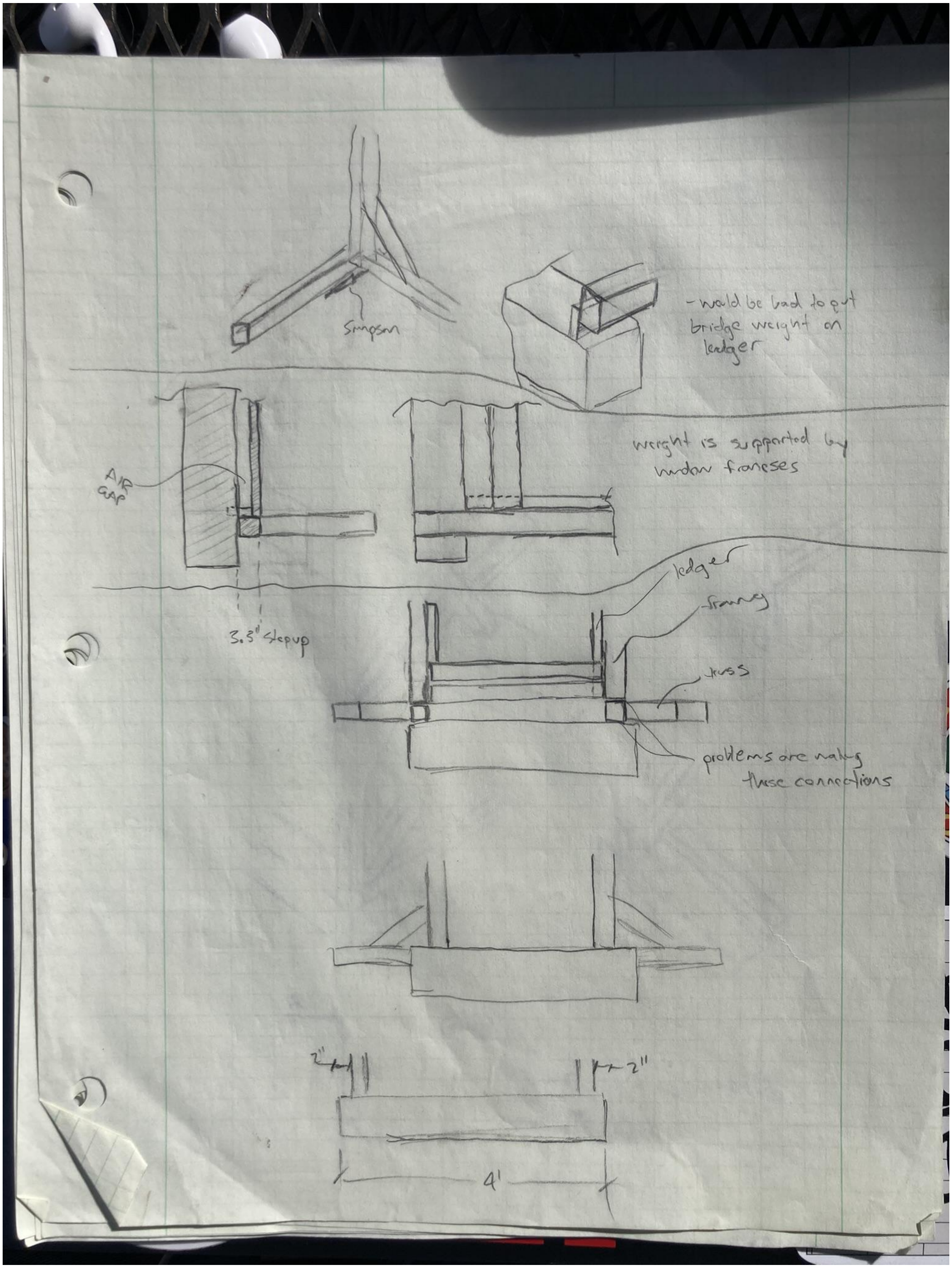
#4

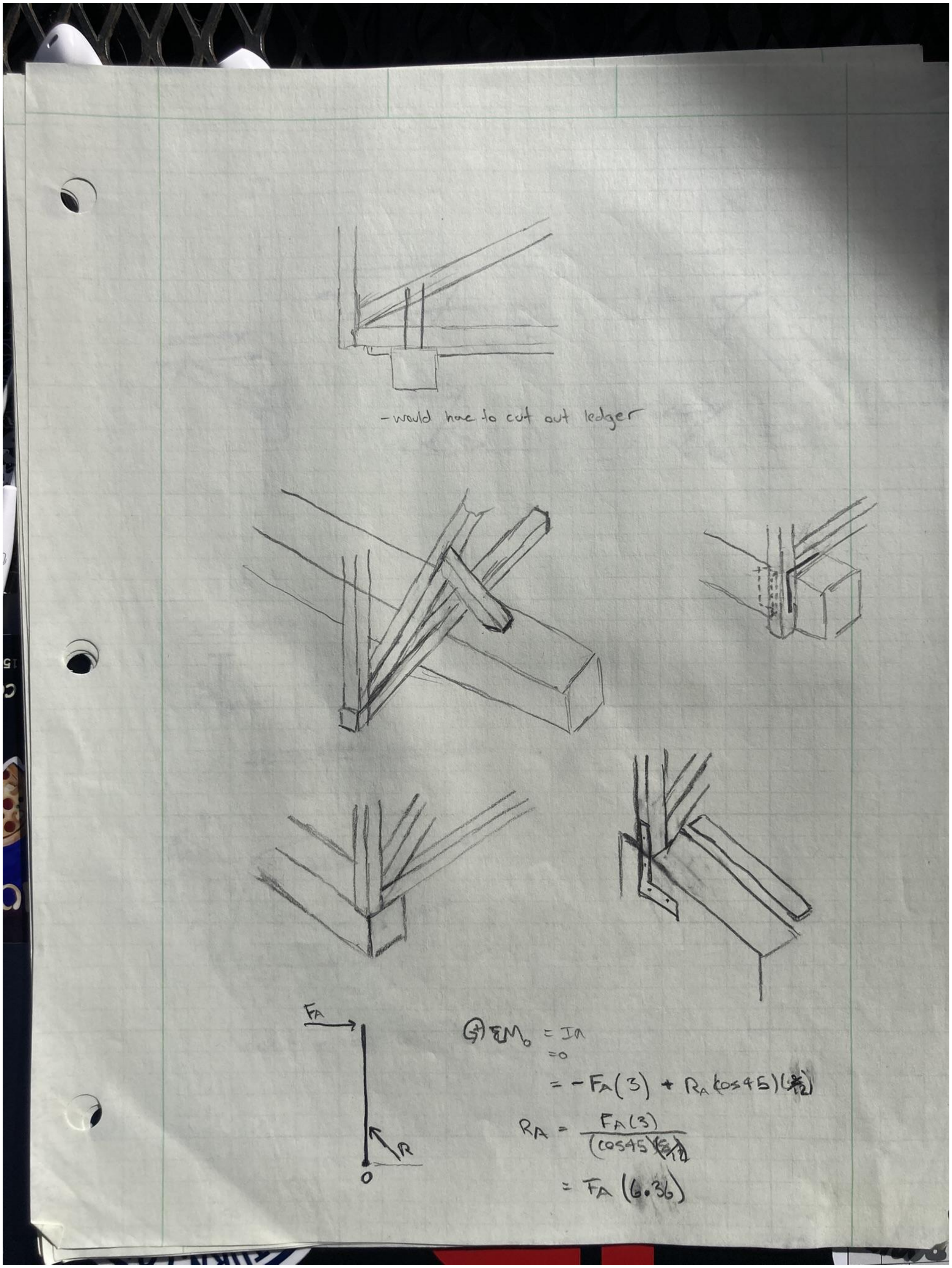


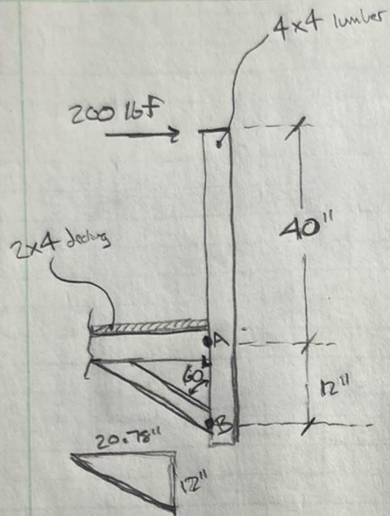
NOTE

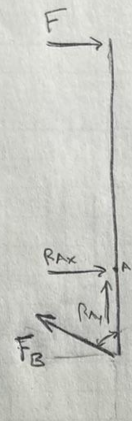
$R = F_{APP}/2$

By symmetry


Simpson
- would be bad to put bridge weight on ledger
AIR GAP
weight is supported by window framing
3.3" stepup
ledger
framing
truss
problems are making these connections
2"
2"
4'


- would have to cut out ledger
F_A
R
O
ΣM_o = Iα
= 0
= −F_A(3) + R_A cos45 (8/12)
R_A = F_A(3) / (cos45)(8/12)
= F_A(6.36)





200 lbF $\left(\frac{40}{12}\text{ ft}\right) \Rightarrow$ 666 ft-lb

(+) $\Sigma M_A = I\alpha^{\,0}$

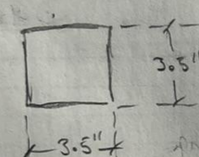
$0 = -666\text{ ft-lb} - F_B \cos 60 (1\text{ ft})$

F_B = 1332 lbF in compression

FS = 2 - Cond for 400 lbF

F_B = 2664 lbF

<u>4x4 lumber</u>



<u>ASSUME</u>

- Paralell to Grain
- Strut NOT a slender column
  - → Wont exceed 8'

<u>TENSION</u>

σ_{al} = 525 lbf/in^2

$F_{al} = (\sigma_{al})(A)$

$= (525\text{ psi})(12.25\text{ in}^2)$

= 6431 lb

<u>COMPRESSION / BUCKLING</u>

σ_{al} = 1150 psi

F_{al} = 14,088 lbF

$F'_c = F_c \cdot C_p \Rightarrow$ 710 psi

(F_c: allowable comp stress; C_p: column stab factor)

So F_{al} = 8710 lb

<u>EVELUR COLUMN STABILITY</u>

$$P_{cr} = \frac{\pi^2 E I}{(KL)^2}$$ for colum of ≈8' & more

As L dec from 4' this val will inc so this is limiting case

k = 0.5 - Both ends fixed

L = 4 ft

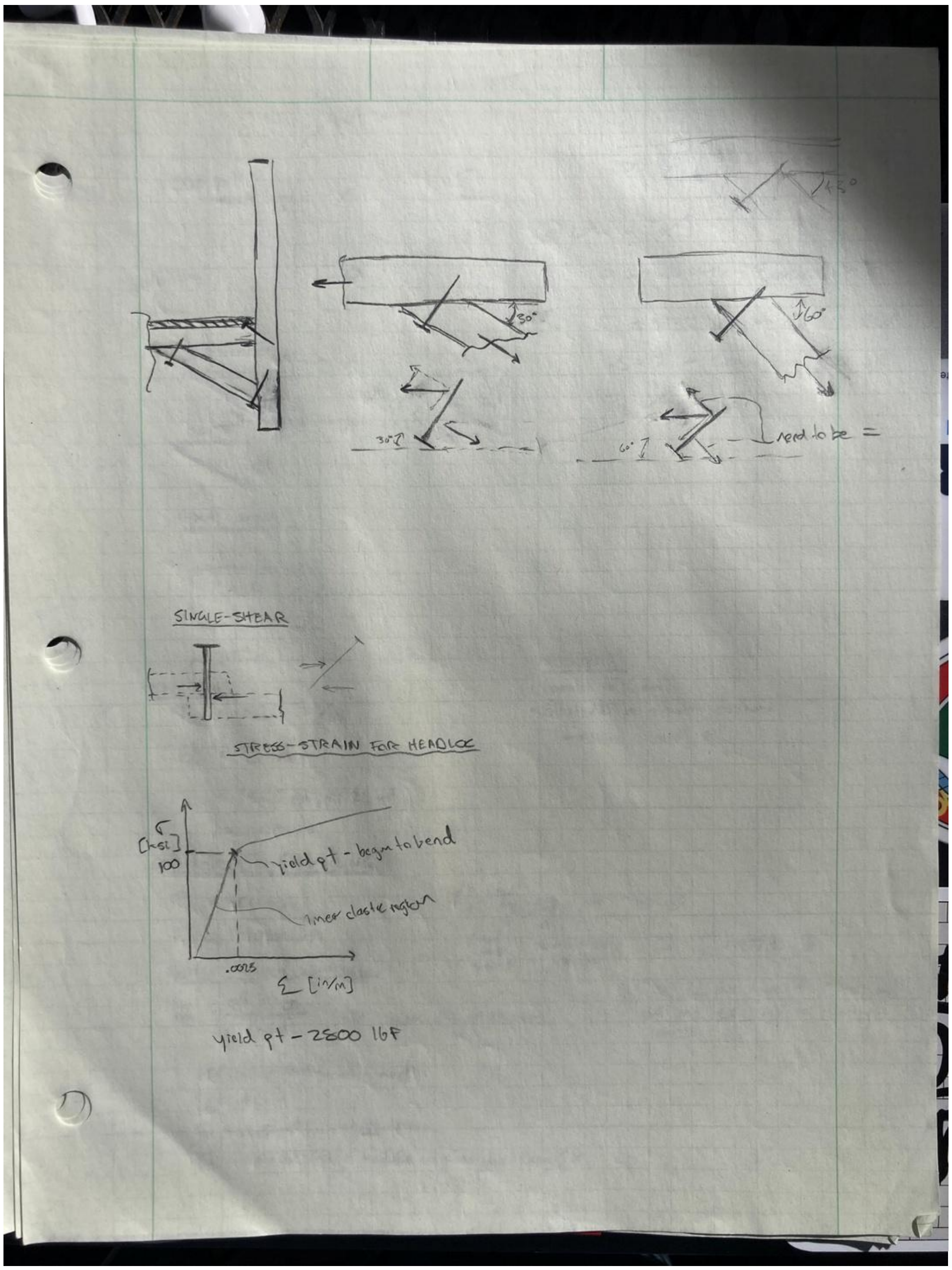
I = 12.5 in^4 - MOI - Area

E = 1.6·10^6 psi - Modulus of elas for Doug fir

Appendix B

Hand Calculations for Screws

This was a rough calculation performed to help justify the screw layouts. It illustrates how the loads are transmitted to a screw and then how the screw would begin to deform and break (stress-strain curve) under loading.

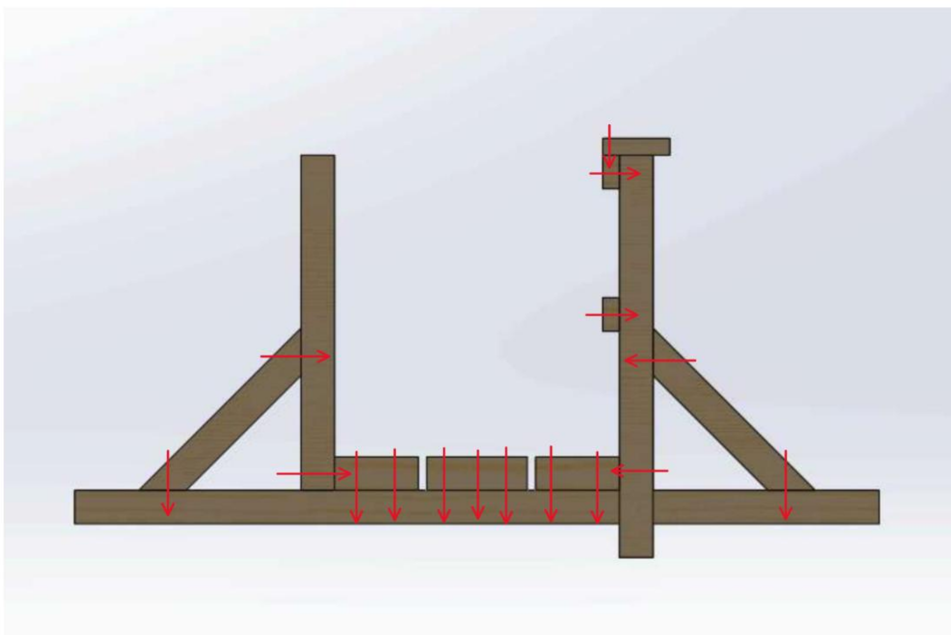


Appendix C

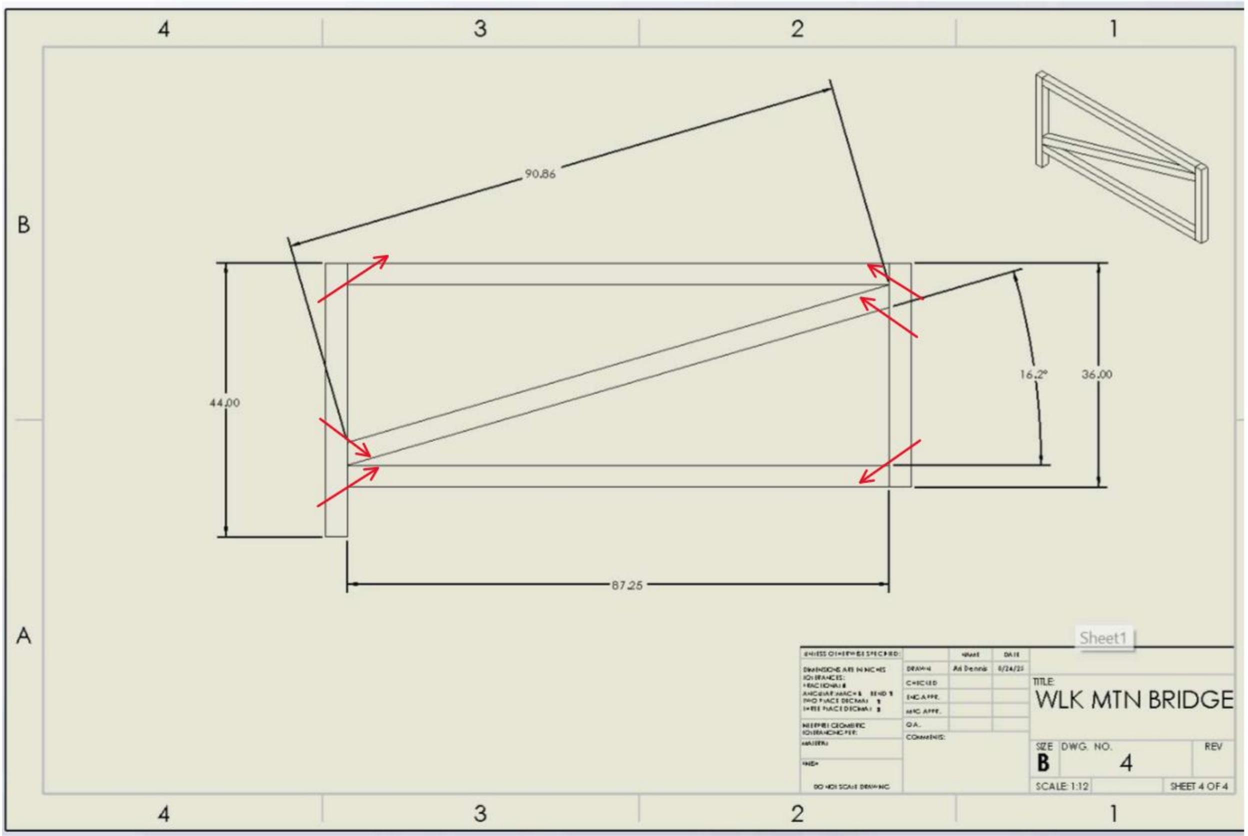
Screw Layout

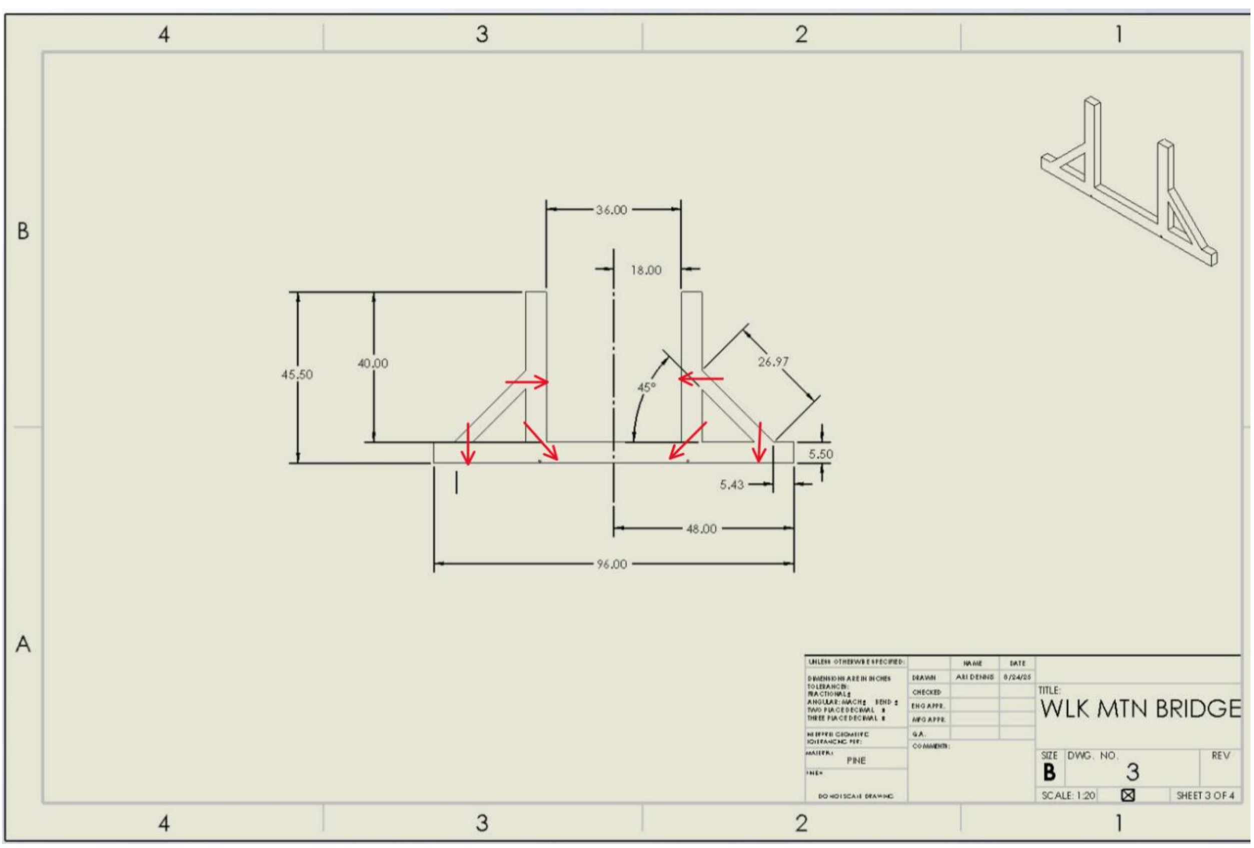
The Screw layout is a critical element in the design and implementation, illustrated below by red arrows showing orientation and direction. The way the screws are inserted into the wood has a large impact on the strength of the connection and structure. Throughout the entire project all screws were installed such that they passed through enough wood in each of the respective pieces. Also, the screws were installed so that they were as close to perpendicular to the grain of the wood in each. Another consideration is that there are finite number of ways screws can be inserted because of workability: can the tools at hand be used or is something in the way, will the screw be accessible again, is there anything in the path of the screw such as another screw, etc.

BRIDGE 1 & 3



NOTE: BRIDGE IS SYMETRICAL, SOME ELEMENTS REMOVED FOR CLARITY


4
3
2
1
B
A
90.86
44.00
16.2°
36.00
87.25
Sheet1
DRAWN
Ari Dennis
CHECKED
TITLE:
WLK MTN BRIDGE
SIZE
DWG. NO.
REV
B
4
SCALE: 1:12
SHEET 4 OF 4


4
3
2
1
B
A
36.00
18.00
45.50
40.00
26.97
45°
5.50
5.43
48.00
96.00
DRAWN
ARI DENNIS
MATERIAL
PINE
TITLE:
WLK MTN BRIDGE
SIZE
DWG. NO.
REV
B
3
SCALE: 1:20
SHEET 3 OF 4