Yosemite Bridge

Team 13 Project Report

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Team Member 2:	Dante Vela
Team Member 3:	Jonathan Lu
Team Member 4:	Ryan Matsumoto

Overview of Prototype Bridge

Number of Joints	9
Number of Members	15
Weight (grams)	4.8 grams

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Section A - Bridge Design Description

A.1 - Designs Considered During Brainstorming

When our team first approached this problem, our goal was to build a bridge that fulfilled on the required design specifications, and which utilized a non-standard Howe or Pratt design. After initial research, we decided on two design possibilities: the Warren bridge or the K Truss bridge. The Warren bridge appealed to us because of its strength and simplicity, while the K Truss design offered a challenging level of complexity, breaking up the vertical members into smaller sections.

We performed our analysis on both sets of designs, examining how the bridges might look given our specifications and constraints, as well as how they might act under different loads.

<u>K-Truss Bridge Analysis</u>
We sketched and analyzed our K-Truss bridge design on the Johns Hopkins University (JHU) bridge designer. We built two scenarios, shown in Figure 1A and 1B, for the minimum and maximum safety ranges. We distributed the loads across the seven nodes equally, and the analysis was able to show us the members in tension (in red) and in compression (in blue).

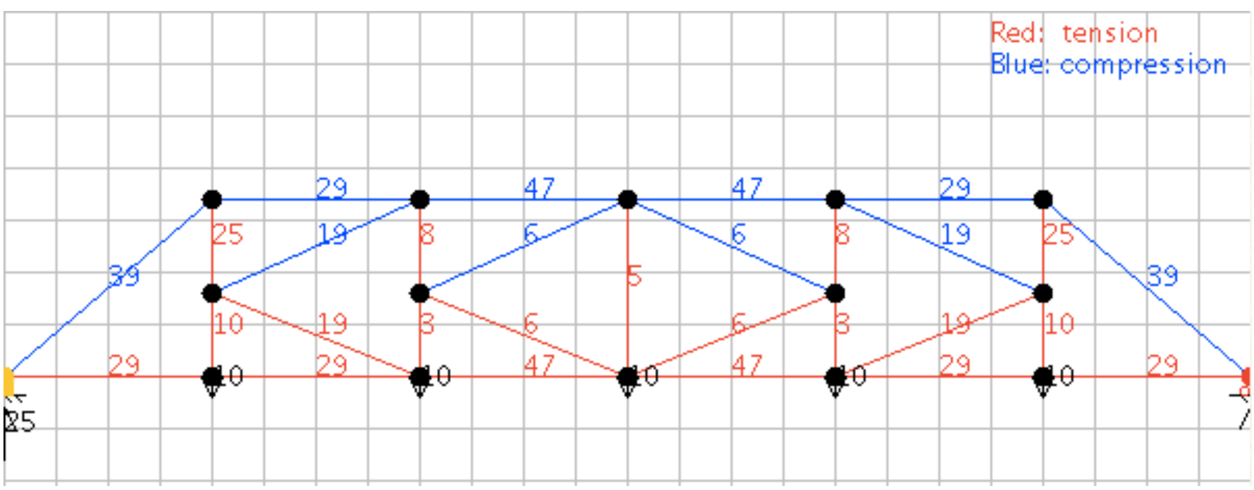


Figure 1A: K-Truss bridge analysis with 1.5 safety factor

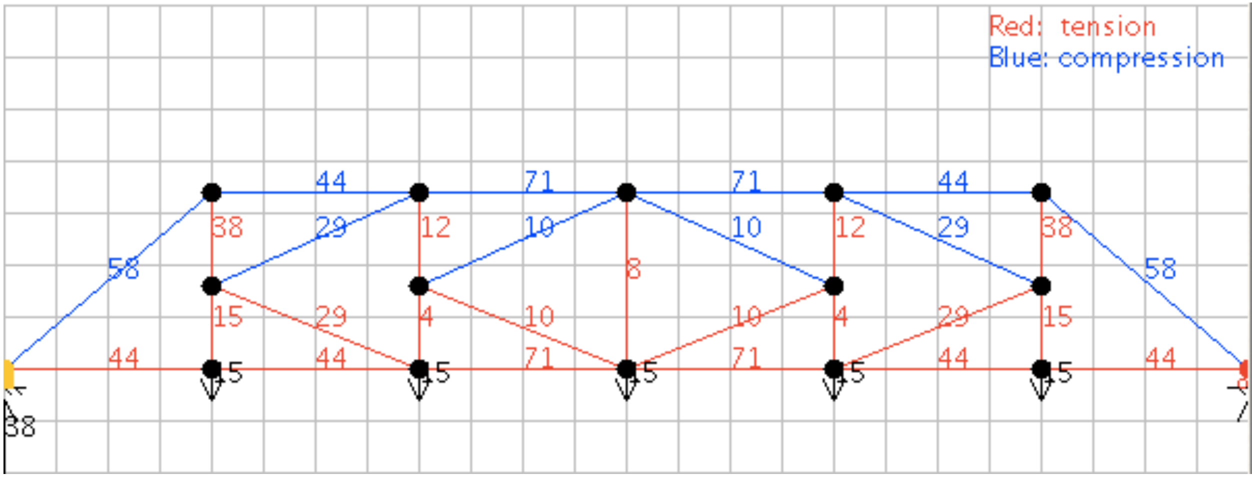


Figure 1B: K-Truss bridge analysis with 2.2 safety factor

While both analyses met our design specifications, it quickly became clear that this would be a complex bridge to build. We thus decided to focus our efforts on our Warren bridge analysis.

<u>Warren Bridge Analysis</u>

Our initial attempt as the Warren Bridge involved a design with four bottom members (see Figure 2). Our subsequent analysis showed that this design was too strong and would support loads greater than 145N. This design would also only have three laterals, and we ideally would have more cross members to support the bridge testing bed.

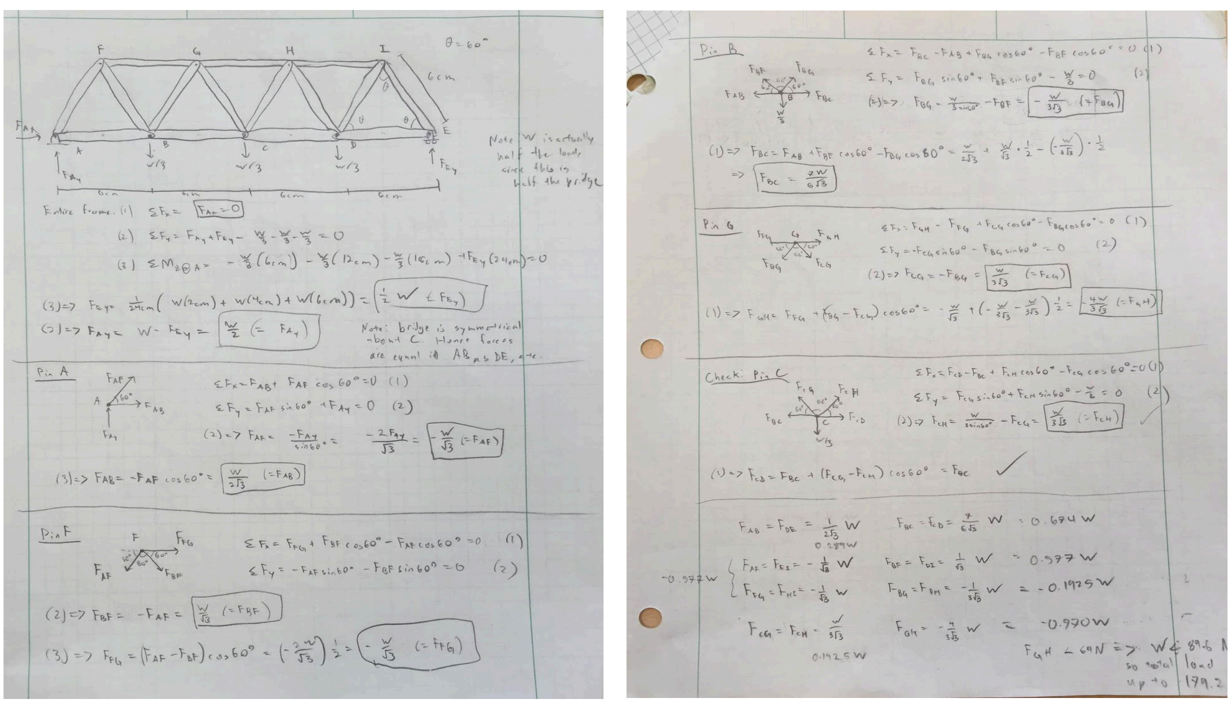


Figure 2: Initial four-member analysis of Warren bridge design

We subsequently tried a six-member Warren bridge design, but found in our initial attempt that the bridge came out too short in height to allow the testing bed to enter it for any span less than 25cm in length (see Figure 3, Appendix B).

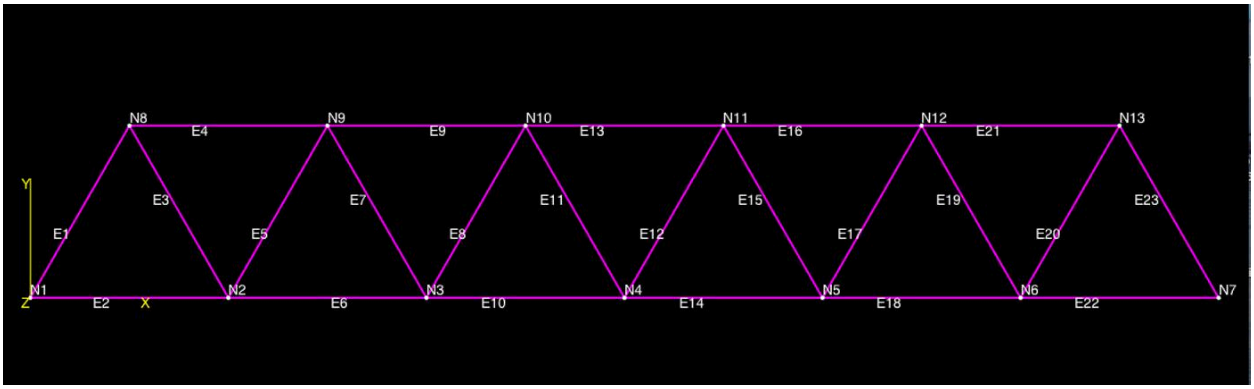


Figure 3: Initial six-member bridge design that was too short in height (h= 3.46cm)

We tried raising our six-member design to a height of 3.5cm (see Figure 4, Appendix C) while maintaining its length below 25cm, but found that the resulting design was too strong and significantly above our preferred failure load range of 130-135N.

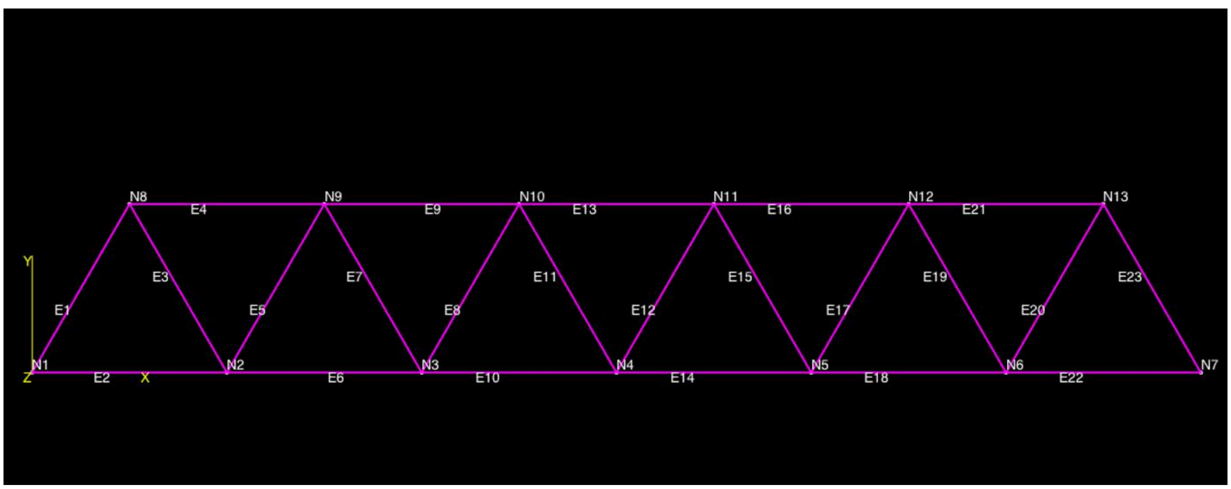


Figure 4: Raised six-member bridge design that was too strong

We decided to try a five-member bridge, since this also meant this might be easier to construct (see Figure 5, Appendix D). However, this design was even stronger than the 6-member raised Warren and with spans less than 25cm in length would not fail until loads significantly greater than 145N.

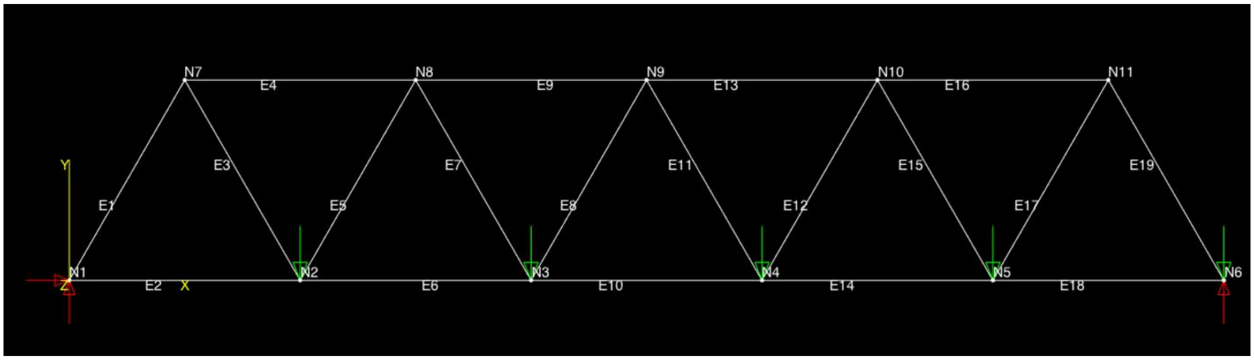


Figure 5: 5-member bridge design that was too strong

As such, to weaken it we tried flattening the design such that the height of the bridge would be exactly 3.5cm. While initially it appeared that this design would function, we failed to account for the balsa wood thickness in this design and the 5 member bridge was too short (see Figure 6, Appendix E).

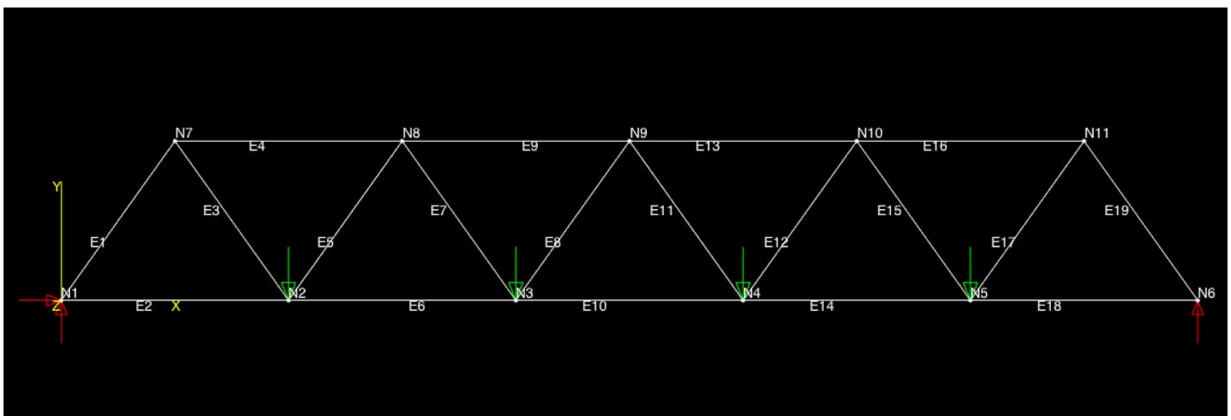


Figure 6: Flattened five-member Warren bridge design

If we wanted 3.5 cm of height for the inner dimension, the members would need to be farther apart. We modified the dimensions of the bridge to account for this difference, increasing the height to 3.8175cm but the adjusted span was too strong for spans less than 25cm in length (see Figure 7, Appendix F).

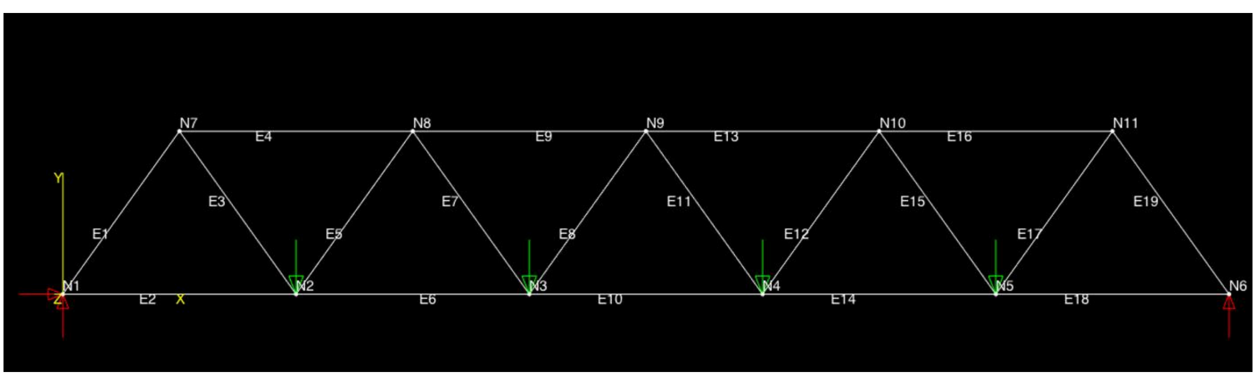


Figure 7: 5-Member Flattened Warren Re-Adjusted for Test Road Bed Insertion

Finally, we moved back to the four member design, which with modifications satisfied all our required specifications even when accounting for the balsa wood thickness (see Figure 8, Appendix G). Flattening this bridge design to a height of 3.8175cm yielded appropriate inner and outer height dimensions while also having desirable predicted failure loads for spans less than 25cm long.

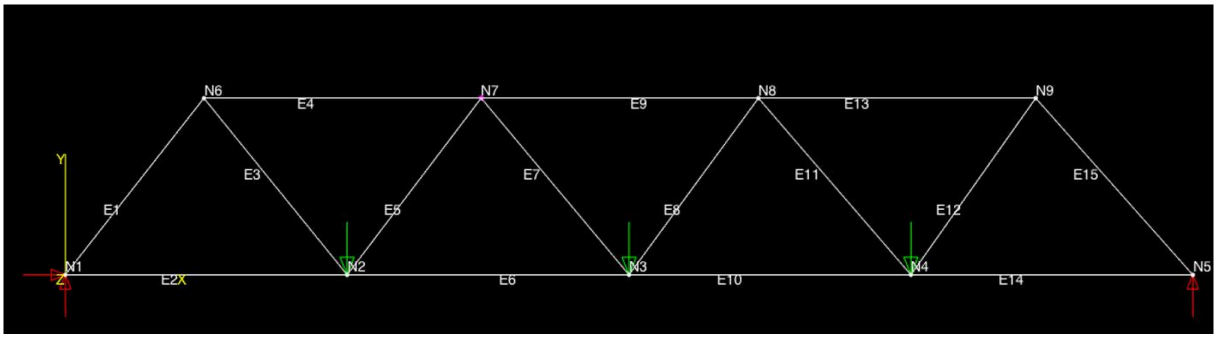


Figure 8: Final four-member Warren bridge design

Having completed our analysis for both designs, our main criteria for the selection of our final bridge design were as follows:

1. Ability to meet all given design specifications (e.g. falling within the correct dimensions and safety factor range)
2. Ease of construction

We were able to build designs of both the Warren and K-Truss bridge which met our given design specifications. What ultimately determined our final approach was our estimated ease of construction. The K-Truss bridge has far more joints than the Warren bridge, which would have been time consuming. We also consulted with Sheri during our design review session and reached the same conclusion. We therefore decided to proceed with the Warren bridge design for final construction.

A.2 - Detailed Description of Final Design

Our final design is a compressed Warren bridge with 4 base members and 15 members total (see Figure 7). Our span length is 24 cm, our inner height is 3.5 cm, our outer height is 4.135 cm, our inner width is 3.5 cm, and our outer width is 4.135 cm (all shown in the Design Specification Table). As you can see in our Bridge Diagram in A4, the compressed Warren bridge consists of 4 base members of equal length (6 cm) that are each the base of an isosceles triangle, with two diagonal members of length 4.27 cm at an angle of 55.01 degrees relative to the base members. At the top of our bridge are 3 top members, each of length 6 cm.

We tried to minimize our outer height (4.135 cm) while staying within bounds for the design target load range (99N - 145N) and minimum height for the test bed (3.5 cm inner height) so that we could aim for the top 25% of lightest bridges while also limiting the failure load to our desired range of 130 to 135N. We also chose the compressed Warren bridge design over the K Truss bridge design because it was simpler to build and had fewer joints. Our bridge design had many members that were similar, making construction more streamlined and efficient.

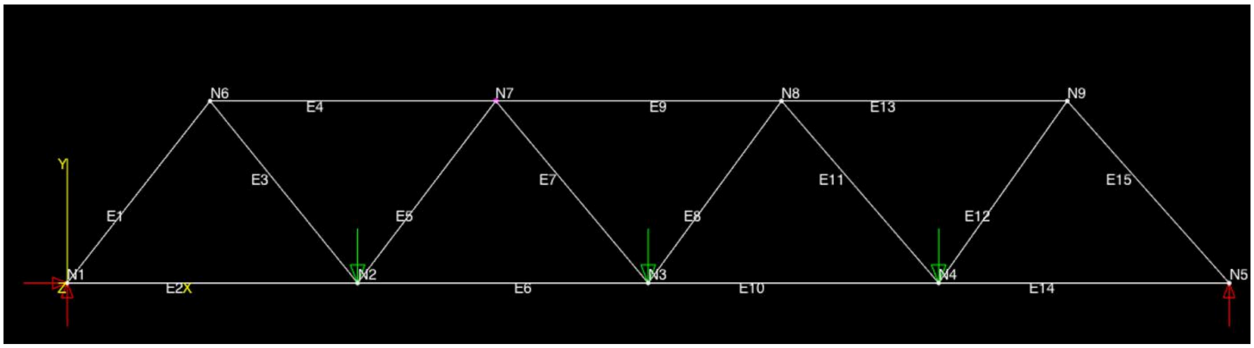


Figure 7: Final four-member Warren bridge design

A.3 - Design Specification Table

The specifications of our design are shown in Table 1 below.

Table 1: Design Specifications – Requirements and As Built

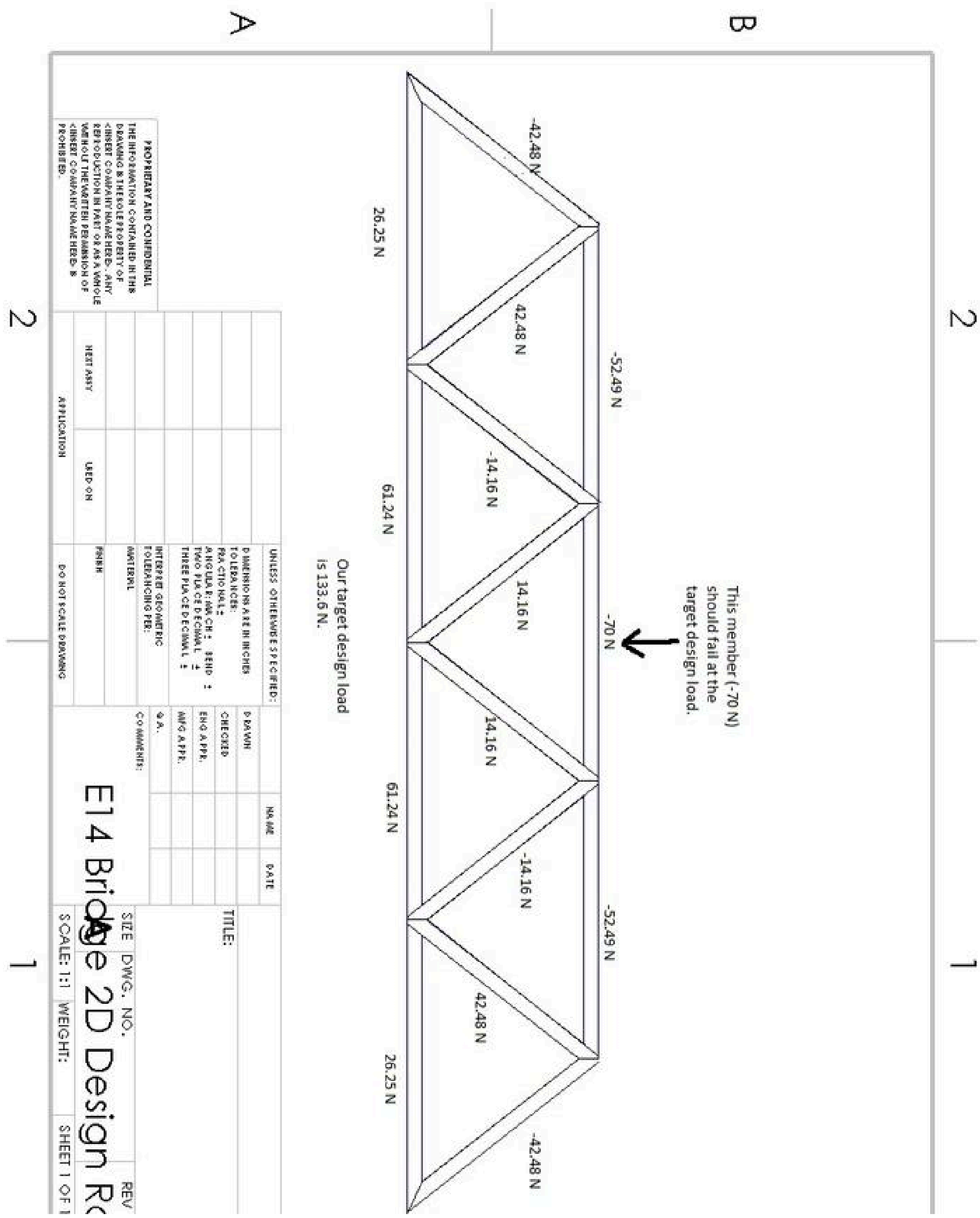
	Design Requirement	**Your Prototype Bridge (as built)**
Number of joints	Not specified	9
Number of members	Not specified	15
Span Length	minimum 24 cm, maximum 25 cm	23.1 cm (24 cm)
Height - Maximum (outer dimension)	10 cm, from deck to highest truss point	4.0 cm (4.135 cm)
Height – Minimum (inner dimension)	3.5 cm, for test road bed insertion	3.4 cm (3.5 cm)
Width - Maximum (outer dimension)	4.5 cm	4.135 cm
Width – Minimum (inner dimension)	3.5 cm, for test road bed insertion	3.5 cm
Weight – Maximum 20g	Top 25% contestant lightest bridge (+5 Bonus Points)	4.8g (9 g)**
Design approach	Non-standard Howe or Pratt design (+5 Bonus Points)	Compressed Warren
Design Target Load Range	Between 99 N – 145 N	133.6 N
Exact Failure Load	Test failure load	180.0 N

*Values in parentheses were the predicted values. Upon printing the Solidworks design the truss diagram was compressed to a 96% scale.

**Predicted weight based on total length of balsa wood used and balsa wood linear density, as well as quantity glue used. Actual weight is less likely due to the glue drying and thus loss of water mass.

A.4 - Bridge Diagram

Note: The bridge diagram below is not exactly to scale here, as it would not fit on the page with the accompanying label in a realistic scale. As such, the diagram is also provided accurately to scale as Appendix H.



Section B - Analysis and Construction of Bridge

B.1 - Description of Analysis Process

Dante began the analysis with written method of joints truss analysis for a Warren Bridge with 4 bottom members (ie 4-Member Warren). See Appendix A.

Ben then used Mastan2 to evaluate 6-Member Warren (Appendix B), 6-Member Warren Raised (Appendix C), 5-Member Warren (Appendix D), 5-Member Flattened (Appendix E), 5-Member Re-Adjusted Flattened for Test Road Bed Insertion (Appendix F), 4-Member Flattened (Appendix G). Dante also performed written method of joints analyses on the 5-Member Flattened Warren and 5-Member Re-Adjusted Flattened Warren designs.

While Dante and Ben were performing these analyses, Jonathan and Ryan conducted analysis of various potential K-truss designs using the John Hopkins University (JHU) software. After a few iterations they achieved a K-truss design that would satisfy the design requirements (see A1 above).

Dante then confirmed the 4-Member Flattened (Appendix G) with written method of joints analysis. Please see the member force table for a summary of the findings for force on each member.

B.2 - Member Force Table (with Factor of Safety)

The member force table for our bridge design is show below in Table 2.

Table #2 Member force table of member loads for applied load of 133.6 N (SF 2.02).
Shaded row indicates member predicted to fail at applied load.

Member	Load	Tension or Compression	Member Length	Failure Mode	Load Capacity
E1	-42.48	C,-	4.27 cm	Crushing	70.0 N
E2	26.25	T,+	6.00 cm	Yield	735.0 N
E3	42.48	T,+	4.27 cm	Yield	735.0 N
E4	-52.49	C,-	6.00 cm	Crushing	70.0 N
E5	-14.16	C,-	6.00 cm	Crushing	70.0 N
E6	61.24	T,+	6.00 cm	Yield	735.0 N
E7	14.16	T,+	4.27 cm	Yield	735.0 N
E8	14.16	T,+	4.27 cm	Yield	735.0 N
E9	-70	C,-	6.00 cm	Crushing	70.0 N

E10	61.24	T,+	6.00 cm	Yield	735.0 N
E11	-14.16	C,-	4.27 cm	Crushing	70.0 N
E12	42.48	T,+	4.27 cm	Yield	735.0 N
E13	-52.49	C,-	6.00 cm	Crushing	70.0 N
E14	26.25	T,+	6.00 cm	Yield	735.0 N
E15	-42.48	C,-	4.27 cm	Crushing	70.0 N

B.3 - Description of Construction Process

We began our construction process by printing out two of our to-scale SolidWorks designs. (After completing bridge construction we realized the designs had been printed at 96% to scale due to printer auto-scaling to fit margins). We stuck them on our foam board with tape, as shown in Figure 8, so that we could work on them simultaneously.

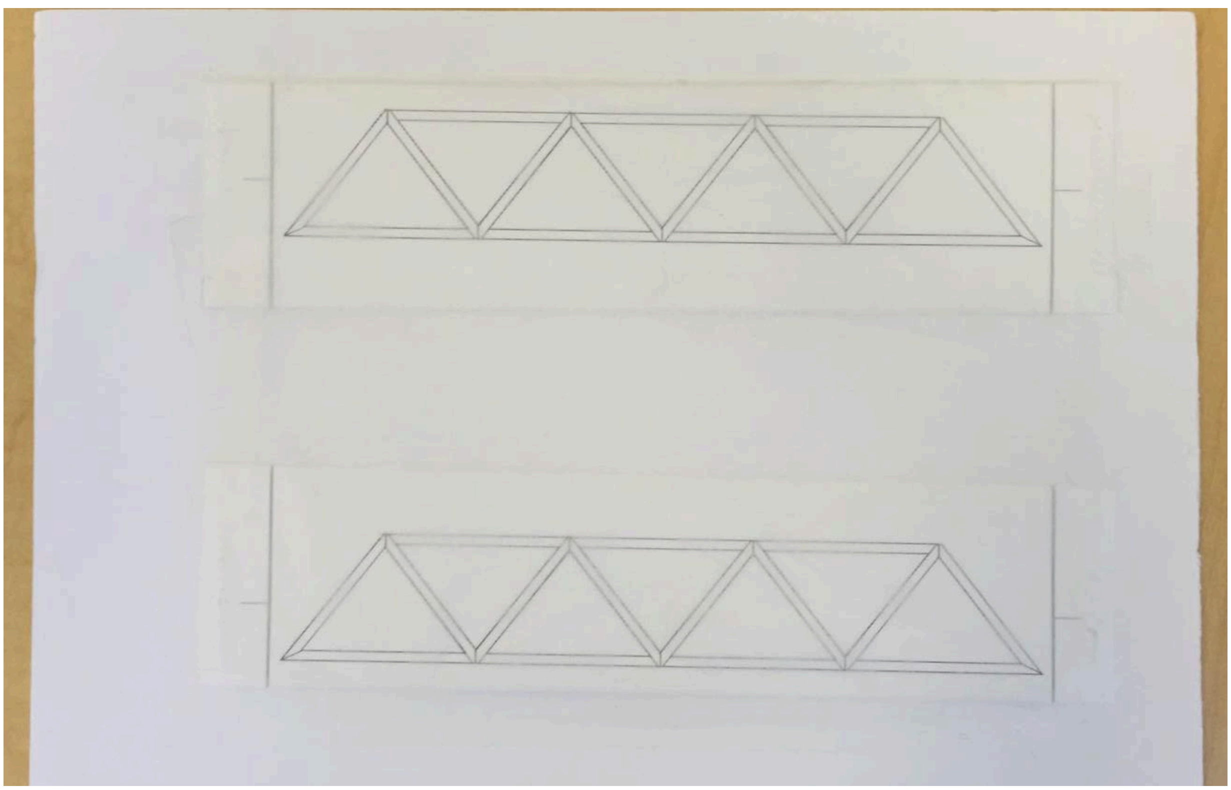


Figure 8: Sticking the SolidWorks designs onto our foam board

We then laid a layer of thin wax paper over our to-scale drawings and used them as a basis to begin marking our balsa wood strips and making the appropriate cuts (see Figure 9).

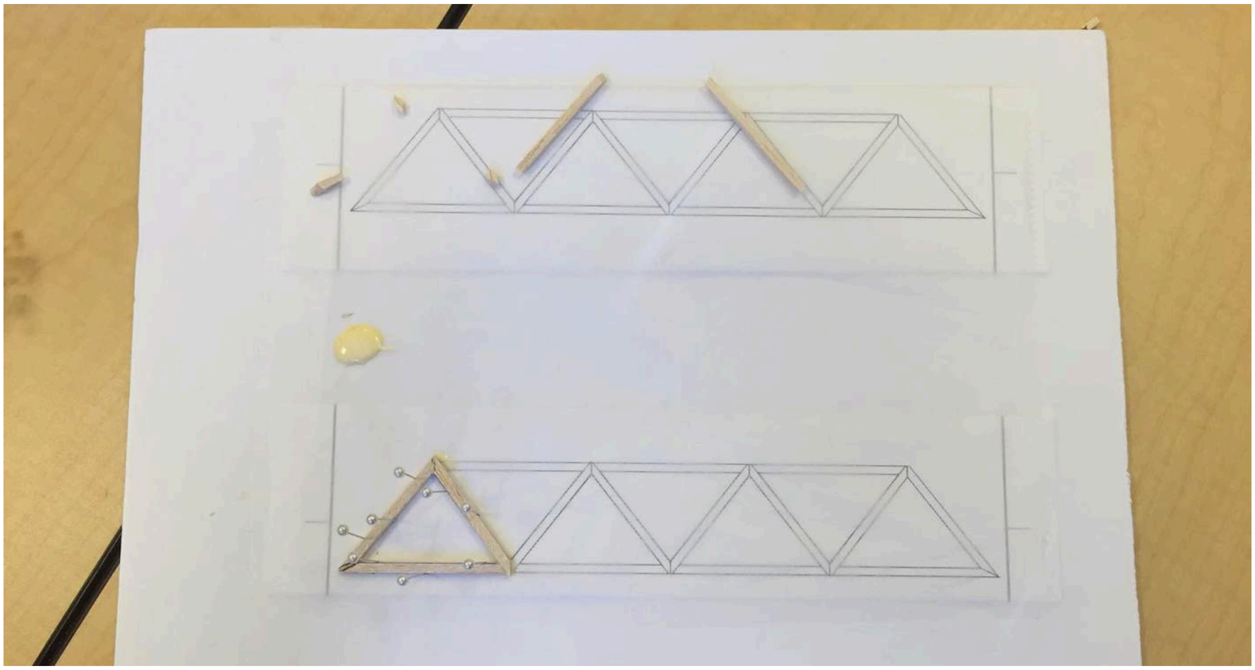


Figure 9: Wax paper over the drawings and laying out the members

We used a black pen to mark the exact angles at which the members should be cut, using an x-acto knife to cut our members (see Figure 10).

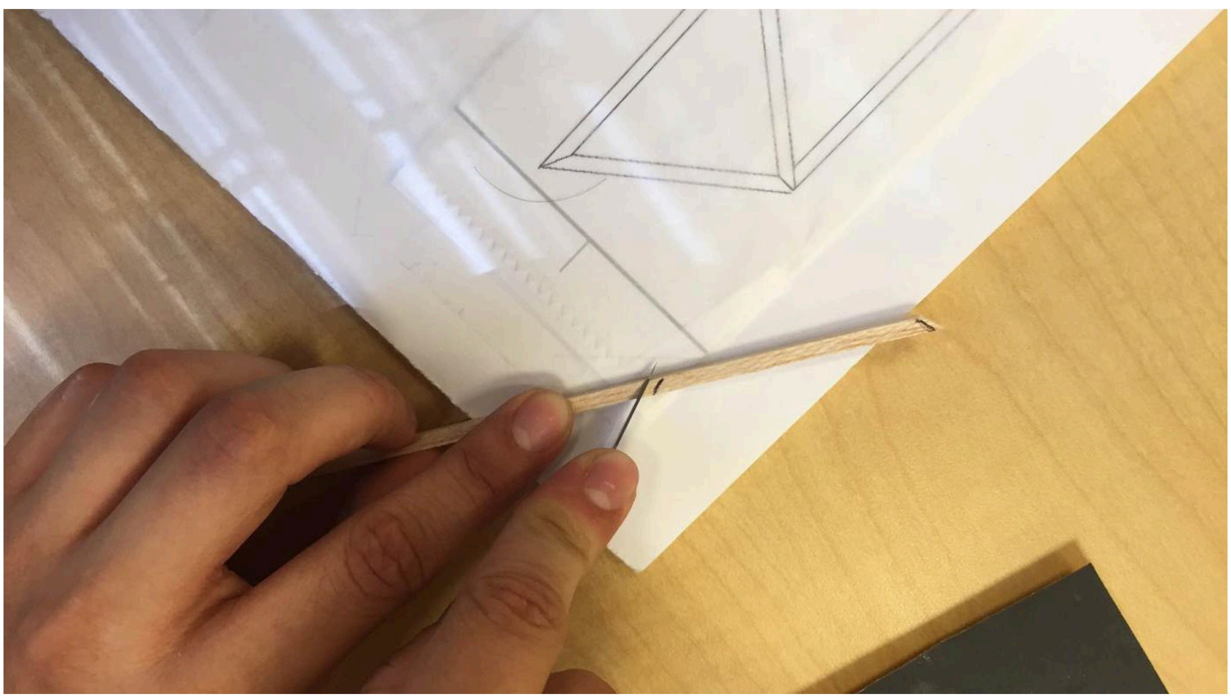


Figure 10: Using the x-acto knife to precisely cut our members

After cutting each member, we sanded them down to ensure flushed edges for each member as well as precise angles. As we assembled our bridge, we used pins to hold the glued members in place (see Figure 10).

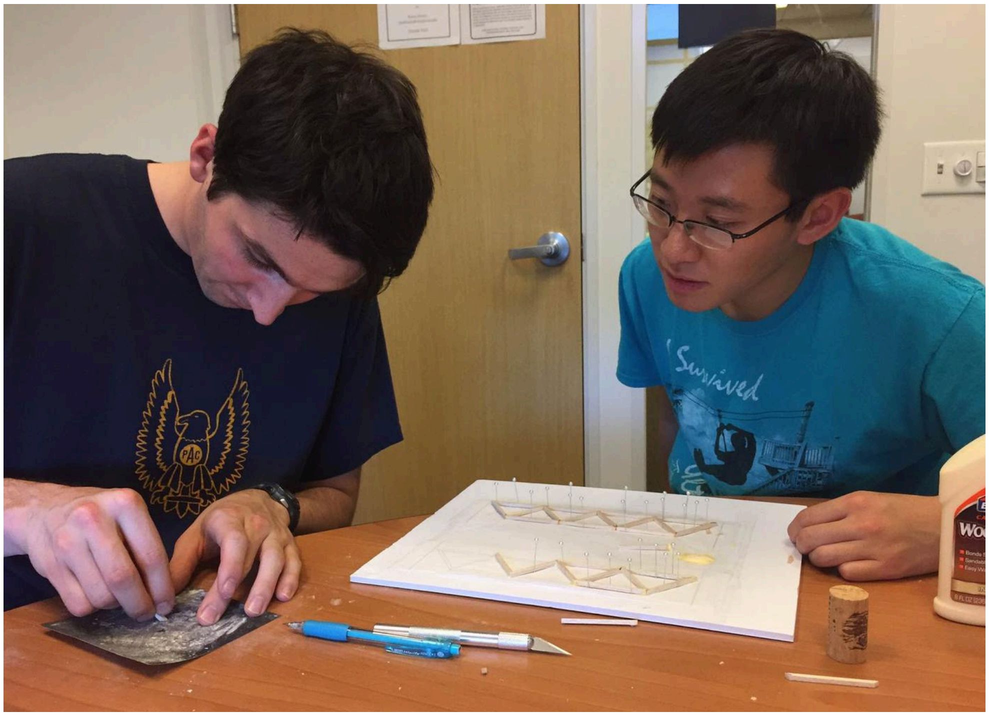


Figure 10: Sanding the members down and holding them in place with pins

We then cut our cross members, as seen in Figure 11 below.

Figure 11: Cutting our cross members

The next step was two use the cross-members to glue the two sides of the bridge together, and secure the joints with card stock gussets (see Figure 12).

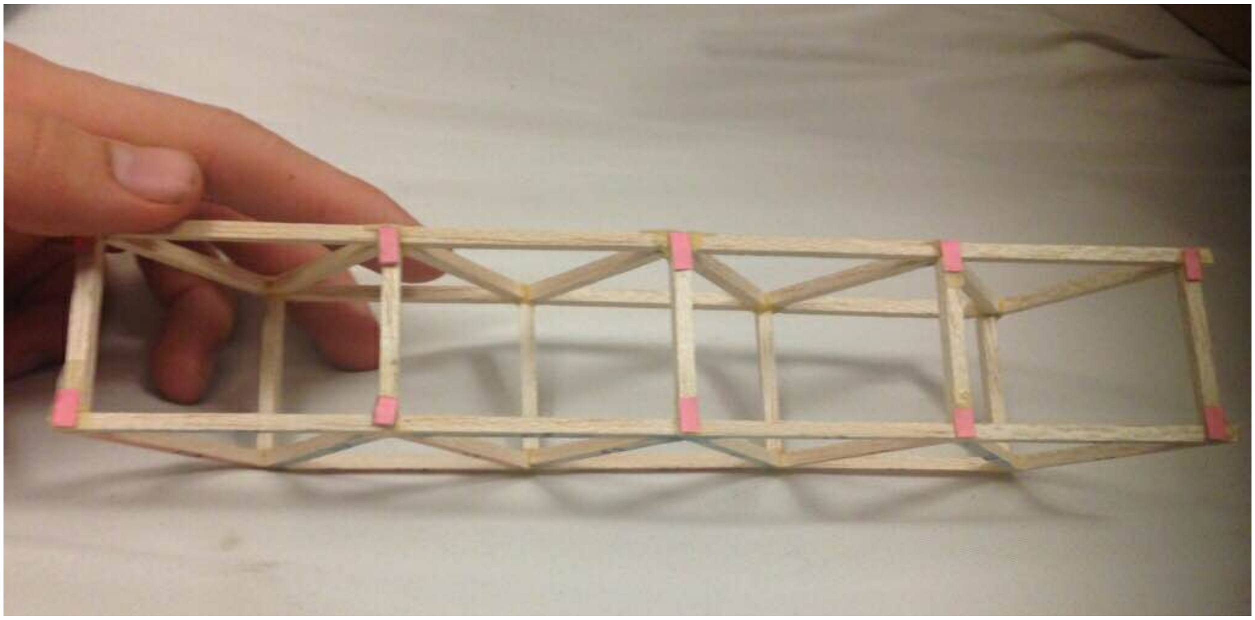


Figure 12: Securing the joints with card stock gussets

Finally we collared the members red or blue to indicate which ones were in tension vs. compression (see Figure 13).

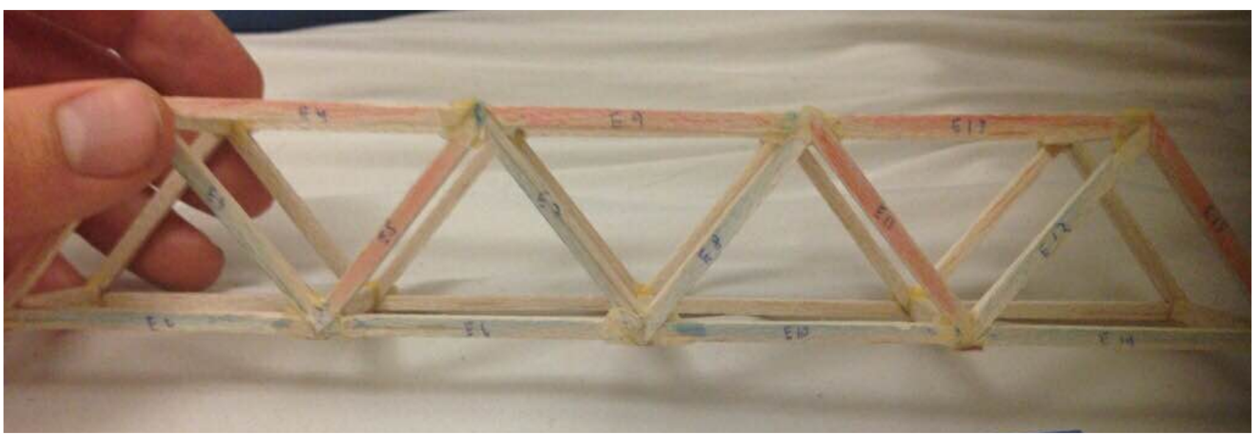


Figure 13: Colored members indicating tension vs. compression.

Section C - Testing Results & Failure Analysis

C.1 – Testing Process and Failure Load

On test day, we straddled our bridge across the testing device so that each side of our bridge rested on a different side. A test road bed with dimensions 3.0cm x 3.0cm x 21.0cm (width x height x length) was placed inside the bridge with hooks extending below the road bed surface. The four different hooks hung at the following lengths (from the end of the road bed): 6.7cm, 9.2cm, 11.8cm, and 14.3cm. The force gauge was connected to the hooks and when testing began, force was applied with a crank (and measured) until the bridge failed structurally. The crank pulled down on strings attached to the hooks, applying a downward force on the bridge.

Our bridge's failure load on test day was 180N, above our target failure load of 133.6N. Our bridge was able to achieve 66N, 99N, and 145N of force. We also measured the mass of our bridge, which was 4.8 grams, one of the lowest in the class. We are very proud of this because we aimed to minimize the mass to minimize the amount of balsa wood we needed (which would translate into lower costs in the real world).

C.2 – Method of Failure

Once the total load on the bridge reached 180N, a member detached at a joint. While our bridge did hold out for a safety factor of 1.5, it failed to fail at a safety factor below 2.2. This is probably because the compressive load capacity we were suggested to design for (70N) was not correct - calculations show that the compressive yield strength for balsa wood to be above 8MPa * (3.175mm)^2 ≈ 80N even for a very conservative compressive ultimate strength of 8MPa (recall that the average tested value is 35MPa for the balsa wood we used). Our bridge was designed for the member under most compression to be under a load of about 76N when the total load on the bridge reached 145N, which is less than the conservative 80N and much less than the supposed average of about 350N. The tension loads, of course, came nowhere close to maximum tensile load of balsa wood of about 735N, so we did not consider this failure mode.

Our bridge did not fail in the manner we expected it to. We anticipated a failure mode of crushing at member E9. Instead, member E6 disconnected from E5, signaling a glue failure. This is probably due to inexact construction of joints, leading to an improperly glued member. The connection between these members survived the lower loads because the glue was strong enough, but once the tension in E6 became large enough, the glue connection yielded. In particular, the angles of members were very tedious to get down to our exact design specification. Furthermore, it was difficult to sand surfaces of members to flat surfaces. Often, members were sanding too short to use in pursuit of flat, perfectly angled edges, requiring us to cut a new piece for that member and restart. Both of these difficulties would lead to gaps in bridge members and hence weaken the glue connection between them.

We also noticed we had one particularly hard piece of balsa wood (it was very difficult to cut, as opposed to other pieces). We created a few members from this piece before abandoning it due to difficulty in cutting, and used these members on the same side of the bridge where we experienced the failure. It is quite possible that these hard members led to a different distribution of forces and differential rates of deformation, which would in turn lead to this unexpected failure.

C.3 – Suggestions for Improvement

There are several ways in which we could improve the design, construction, and testing processes to satisfy the project goals and requirements. In terms of design, we could have adjusted our model to account for the true strength of the balsa wood. It was given that Young's modulus of compression of the provided balsa wood was on average 35 MPa, with some weaker elements that were only 8-10 MPa, which for the cross-sectional area of (3.175*10^-3m)^2 yields compressive strengths of 350N and 80-100N, respectively. Despite these values, we were instructed to design to a compressive strength of 70N. We did so and designed our bridge to fail at a load of 133.6N. However, since our bridge withstood up to 180.0N it thus corresponds to a member compressive strength of 94.3N, and it is likely that the true Young's modulus was at least 9.43 MPa. Thus, in future bridge designs we could improve our design by testing our given samples of balsa wood more thoroughly and homogenizing the material so that we can better control when our bridge will fail.

We could also optimize our construction process. Firstly, the SolidWorks diagrams could have been printed to scale so that our bridge dimensions better matched those mandated by the project handout. Also, as mentioned above we could use more homogenous balsa wood that yields a consistent compressive strength among the different members. Since one of our joints and not one of our members was the cause of failure, we could improve our joint making. More accurate and precise cutting, filing, and gluing of the members would have yielded stronger joints that aligned more uniformly with less gaps between the different members. Stronger glue may also have been useful.

Finally, in testing our material the force could have been applied more gradually. By cranking the handle too quickly the force spiked, potentially leading to a greater failure load than is accurate.

Section D - Summary of Project Processes

D.1 - Description of Work Process and Schedule

Our overall work process and schedule went largely according to plan, and went as follows:

1. Planning and brainstorming
   - Date: October 22
   - Time spent: 1 hour
   - Description: We met for an hour on October 22 to create a plan of action. We decided to split up into pairs, each working on one design. Ben and Dante worked on the Warren bridge design, while Jonathan and Ryan worked on the K-Truss bridge design. At this meeting, we also laid out our timetable for the subsequent two weeks, plotting out key deadlines and meeting times.
2. Completion of two designs
   - Duration: October 23 – 29
   - Time spent: 5 hours
   - Description: We spent a significant amount of time acquainting ourselves with Mastan2 in order to prepare our bridge designs, totalling about 3 hours to get our bearings and two hours to complete each of the designs and analyses.
3. Pre-review bridge design meeting
   - Date: October 29
   - Time spent: 1.5 hours
   - Description: At this meeting, we were able to meet with our mentor, Dr. Sheppard, to present our two designs and supporting analyses. With Dr. Sheppard's feedback, we were able to have a productive discussion about which approach to take, and ultimately decided on the Warren bridge design, the reasons for which are explained in Section A.
4. Bridge construction
   - Date: November 1-2
   - Time spent: 12 hours
   - Description: We met for a consecutive 8 hours on Sunday to construct our bridge. This involved 2.5 hours of finalizing our design on SolidWorks and double-checking with hand calculations. The remaining time was spent cutting, sanding and glueing the two sides of our bridges together. We left the bridge sides to dry overnight, and met again for four hours on Monday to add the cross-members, gussets, and final sanding.
5. Writing of first draft report

- Date: November 1
- Time: 5 hours
- Description: While Ryan, Dante and Ben focused on bridge building, Jonathan worked on the first draft of the report, completing Sections A, B, D and E.

6. Bridge testing
   - Date: November 3
   - Time: 2 hours
   - Description: Our team was able to put our bridge on the testing apparatus and stress test our bridge model to find the force at which it failed.
7. Completion of report
   - Date: November 4
   - Time: 3.5 hours
   - Description: Given our testing results the day before, our team met to complete the final portions of the report, namely Section C: Testing Results & Failure Analysis, and Section D.3: Reflections on Process and Results.

D.2 - Description of Individual Contributions

<u>Ben Chuter</u>

Primary Role: Mastan Man

I began working on this project by exploring and analyzing a variety of potential truss designs using the JHU online software. After our group decided to focus on the K-truss and Warren-truss designs, I conducted analyses on the different versions of the Warren truss described above using Mastan2. Upon completion of the final design analysis, I helped write the project report, working mostly on section B and the appendices. I also assisted bridge construction, mostly with cross-member cutting and gusset creation and attachment but also in glueing and sanding. As with other members of the group, I helped write part C and perform final edits.

My three strongest attributes would be doing an equal share of the work, being fully engaged in discussions during meetings, and encouraging the group to complete the project on a timely basis. I have consistently put in work since the beginning of this project to its completion, trying to anticipate and overcome any potential obstacles proactively. I have also engaged in group meetings and been fully attentive, participating in discussions and lending my thoughts towards the design and building decisions. I also helped our group establish a timeline for completion for various milestones of the project to allow us to finish on time.

However, I feel that I could have better taken a leadership role in some aspects of the project, communicated ideas more clearly and effectively and better helped the group overcome difficulties. I think our group might have saved some time and effort if we'd had more leadership and been more decisive about certain design and building decisions. At the same time, I feel that sometimes I fail to communicate my ideas well, which can prevent me from taking on a leadership role, which would have had benefits described above. Finally, when difficulties arose as it became known that our bridge was scaled incorrectly due to the to-scale diagrams not actually being to-scale, I think I could have been a more calming influence. I should not have hesitated to acknowledge that this assignment is a team project where the responsibility for error falls equally on everyone's shoulders. I could have easily made the same mistake if I had made the diagrams.

Dante Vela

Primary Role: Mathemagician

Most of my contributions in this project involved the bridge - from deciding on and modifying the design and analyzing the bridge's truss members by hand, to cutting and sanding the actual members for construction.

My best team player attribute was probably contributing useful ideas that helped the group succeed (f), such as the bridge design and modifications to it. I also delivered work when promised (h), like performing by-hand verifications on designs in order to approve them for other teammates to work on them. I would also say I was good at communicating ideas clearly/effectively (i), so that teammates would know my rationale behind certain decisions.

In terms of areas I could improve, I believe I could have more fully engaged myself in discussions (c), as I was often silent until the subject changed to something more relevant. I could have also taken up more of a leadership role (d), or encouraged my group to complete the project on a timely basis (g), but I do believe myself to be more of a follower (we can't all be leaders), and the teammates who did preoccupy themselves in these areas were effective anyway.

Jonathan Lu

Primary Role: Report Writer

My three strongest attributes are 1) delivering work with promised/needed, 2) took a leadership role in completing the report, and 3) encouraged the group to complete the project on a timely basis. With respect to 1), we established a good process where we either set concrete deadlines and deliverables, or set aside time to work together or different aspects of the project. For 2), I took a leadership role in completing the report, drafting the write-ups. For 3, I helped the group to put together a solid timetable to get our work completed efficiently and on time.

To improve, I could be 1) more engaged in discussions during meetings, 2) help the group overcome difficulties, 3) contribute more useful ideas. For 1), I could have been more proactive in voicing my opinion and helping to push the decision-making process along. For 2), I could have more proactively helped with our familiarization with Mastan2 and SolidWorks, and for 3), I could have helped more when we were figuring out how to solve various design challenges to meet our required specifications.

Ryan Matsumoto

Primary Role: SolidWorks Wizard

During this project, I produced the 2D to scale drawing of our bridge side using SolidWorks. I also took a lead role in bridge construction, following the video and keeping everyone on track. During bridge construction I glued together many of the members at joints, including cross members.

My three strongest attributes were 1) Contributed useful ideas that helped the group succeed, 2) Delivered work when promised/needed, and 3) Communicated ideas clearly/effectively. With respect to 1), I spearheaded an effort to adjust our design once I realized that we had not taken into account the width of the balsa wood and how it adjusted our bridge dimensions. For 2), I finished the 2D to scale drawing and gluing of bridge members in a timely manner. For 3), I effectively communicated to my teammates my ideas about how our bridge design could be adjusted to satisfy the height/width requirements.

To improve, I could have 1) Taken more of a leadership role in some aspects of the project, 2) Be more fully engaged in discussions during meetings and 3) Helped group overcome differences to reach effective solutions. For 1), I could have taken a more prominent role in keeping the team on track and formulating our schedule for completing the project. For 2), I could have been more involved in some of our discussions about the mathematical mechanics of our bridge design. For 3), I could have contributed more of my own ideas when we were debating which bridge design to pursue.

D.3 - Reflections on Process and Results

Upon reflection, our team would largely follow the same process and design that we undertook in this project, with a few exceptions. With respect to design, when we printed out our SolidWorks designs, the printer shrunk our design to 96% of the original, without us knowing. Thus when we assembled the bridge, our final design was slightly short. In the future, we would correct for this by conducting a simple check that the printer produced our drawings to-scale. In terms of process, our bridge failed largely due to a weakness in one of our joints, and not due to a failure in the member that we were expecting. Thus we could focus more on making sure our joints were better glued together.

Aside from these changes, we would also make sure to adjust for the true strength of the balsa wood in our design. The tested values of the balsa wood Young's modulus suggest that balsa wood was actually much stronger than what was indicated in the design specifications. This discrepancy means that it would likely fail at a higher load than what we had originally calculated with the given compressive strengths. Indeed, during the experiment, our bridge failed at 180N, significantly higher than the target 133.6N. Thus to arrive at a more accurate failure load, we would be more precise with the value of the material strength we were using.

We had several main takeaways from this project. First, we learned that with the right structure, dimensions and calculations, it is possible to build surprisingly light structures capable of carrying large loads. In fact, our bridge had a 4000:1 strength to weight ratio despite the fact that we intentionally weakened it by flattening the Warren design. We also learned that software can be very helpful to the design process, particularly when there is a need for iterative calculations. Mastan2 and the JHU Bridge Designer proved invaluable in allowing us to complete our force analysis and revise our bridge to meet all our desired design specifications. SolidWorks also was an effective way to create to-scale diagrams. Finally, we've all emerged from this project with a better understanding of how to work effectively in a team, and more importantly, learn different perspectives during the process of working in a group.

Section E - Business Model Canvass

Yosemite Bridge Competition

Key Partners

Who are your Key Partners? Who are your Key Suppliers?

The key partners we need to involve to deliver this bridge project are:

1) Relevant departments of Yosemite Park and the National Park Service
2) Specialists in surveyance and geology to understand the geotechnical landscape of the bridge site
3) Construction counterparts who can provide heavy machinery including bulldozers, excavators, formworks etc.
4) Relevant government regulators who will perform final inspections of the

Key Activities

What Key Activities do your Value Propositions require?

Key Resources

What Key Resources do your Value Propositions require?

Value Proposition

What customer value do you deliver? Which customer needs are you satisfying? Which one of your customer's problems are you helping to solve?

Through this project, the main customer value we are delivering is to enhance the experience of park visitors in Yosemite. The timber-build bridge crossing the Tuolumne River was built in the 1970s and is in desperate need for replacement. The location is one of the most popular areas in the park, and the surrounding alpine meadow is the starting point for many wilderness treks. Without the bridge, tourists won't be able to cross the Tuolumne River. By replacing the bridge, we'll be repairing a major park attraction and enhancing the experience for hundreds of thousands of visitors.

Customer Relationships

What type of relationship does each of your Customer Segments expect you to establish and maintain with them? How are they integrated with the rest of our business model?

Channels

Through which Channels do our Customer Segments want to be reached?

Customer Segments

For whom are you creating value? Who are your most important customers?

We have multiple customer segments for whom we are creating value. First are the Yosemite Park visitors, who will benefit when this bridge completes one of the park's most popular trails. We're also catering to Yosemite Park and the NPS, who are welcoming bidders to redevelop the Glen Aulin Bridge. We are also indirectly serving the SBA, which is providing the grant for this project. All three of these stakeholders are important, but perhaps the most important is the park's visitors, for whom this is ultimately being built.

bridge Our key suppliers include: 1) Materials providers: manufacturing companies that will provide us with the raw materials needed to build the bridge		Our direct customer is the Yosemite Park and National Park Service (NPS). These governmental bodies are the ones which are commissioning the project. Our value add to them is to help them solve the problem of the bridge fallen into disrepair and to help Yosemite Park provide a top notch experience for its visitors. What makes us unique is that we are a "mom and pop" operation and can help relieve some of the financial burden from the NPS by receiving funding from the Small Business Association (SBA).		

Cost Structure

What are the most important costs inherent in your business model?

The main costs inherent in our business model might include:

- Abutments
- Superstructure
- Engineering
- Construction
- Labor

Revenue Streams

For what value are your customers really willing to pay? How are they currently paying?

The financial support for this project is coming from a grant from the SBA, which recently announced a $10 million grant program to benefit small businesses working in infrastructure.

The bridge itself will not be a revenue generator, but visitors must pay a park entrance fee to enjoy Yosemite Park, an experience that includes the use of the new bridge.

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Engineering Innovation: Bridge Designer. John Hopkins University. Retrieved November 1, 2015.

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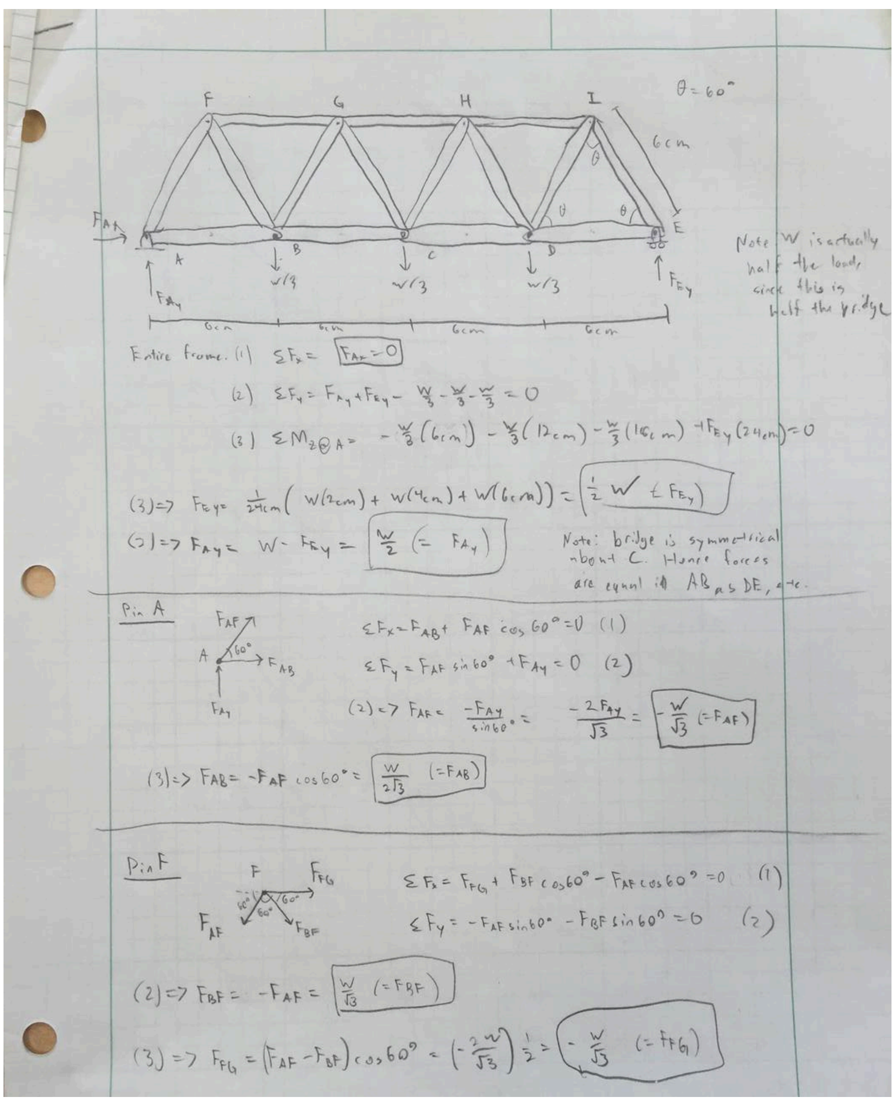
SolidWorks [Computer software]. (2015). Retrieved from Stanford Networks.

Ziemian, Ronald D., and William McGuire. (2015). Mastan2 [Computer software]. New York: John Wiley.

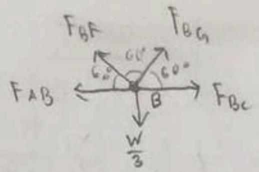
Appendices

<u>Supporting Calculations</u>

Appendix A: 4-Member Warren Analysis



Pin B



$\Sigma F_x = F_{BC} - F_{AB} + F_{BG}\cos 60° - F_{BF}\cos 60° = 0$ (1)

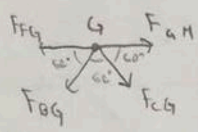
$\Sigma F_y = F_{BG}\sin 60° + F_{BF}\sin 60° - \frac{W}{3} = 0$ (2)

$(2) \Rightarrow F_{BG} = \frac{W}{3\sin 60°} - F_{BF} = \boxed{-\frac{W}{3\sqrt{3}} \;(= F_{BG})}$

$(1) \Rightarrow F_{BC} = F_{AB} + F_{BF}\cos 60° - F_{BG}\cos 60° = \frac{W}{2\sqrt{3}} + \frac{W}{\sqrt{3}}\cdot\frac{1}{2} - \left(-\frac{W}{3\sqrt{3}}\right)\cdot\frac{1}{2}$

$\Rightarrow \boxed{F_{BC} = \frac{7W}{6\sqrt{3}}}$

Pin G



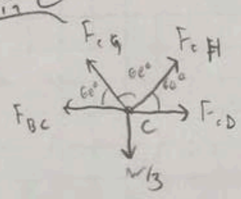
$\Sigma F_x = F_{GH} - F_{FG} + F_{CG}\cos 60° - F_{BG}\cos 60° = 0$ (1)

$\Sigma F_y = -F_{CG}\sin 60° - F_{BG}\sin 60° = 0$ (2)

$(2) \Rightarrow F_{CG} = -F_{BG} = \boxed{\frac{W}{3\sqrt{3}} \;(= F_{CG})}$

$(1) \Rightarrow F_{GH} = F_{FG} + (F_{BG} - F_{CG})\cos 60° = -\frac{W}{\sqrt{3}} + \left(-\frac{W}{3\sqrt{3}} - \frac{W}{3\sqrt{3}}\right)\frac{1}{2} = \boxed{-\frac{4W}{3\sqrt{3}} \;(= F_{GH})}$

Check: Pin C



$\Sigma F_x = F_{CD} - F_{BC} + F_{CH}\cos 60° - F_{CG}\cos 60° = 0$ (1)

$\Sigma F_y = F_{CG}\sin 60° + F_{CH}\sin 60° - \frac{W}{3} = 0$ (2)

$(2) \Rightarrow F_{CH} = \frac{W}{3\sin 60°} - F_{CG} = \boxed{\frac{W}{3\sqrt{3}} \;(= F_{CH})}$ ✓

$(1) \Rightarrow F_{CD} = F_{BC} + (F_{CG} - F_{CH})\cos 60° = F_{BC}$ ✓

$F_{AB} = F_{DE} = \frac{1}{2\sqrt{3}} W$ (0.289W) $\quad F_{BC} = F_{CD} = \frac{7}{6\sqrt{3}} W = 0.674W$

-0.977W $\begin{cases} F_{AF} = F_{EI} = -\frac{1}{\sqrt{3}} W \\ F_{FG} = F_{HI} = -\frac{1}{\sqrt{3}} W \end{cases}$ $\quad F_{BF} = F_{DI} = \frac{1}{\sqrt{3}} W = 0.577W$

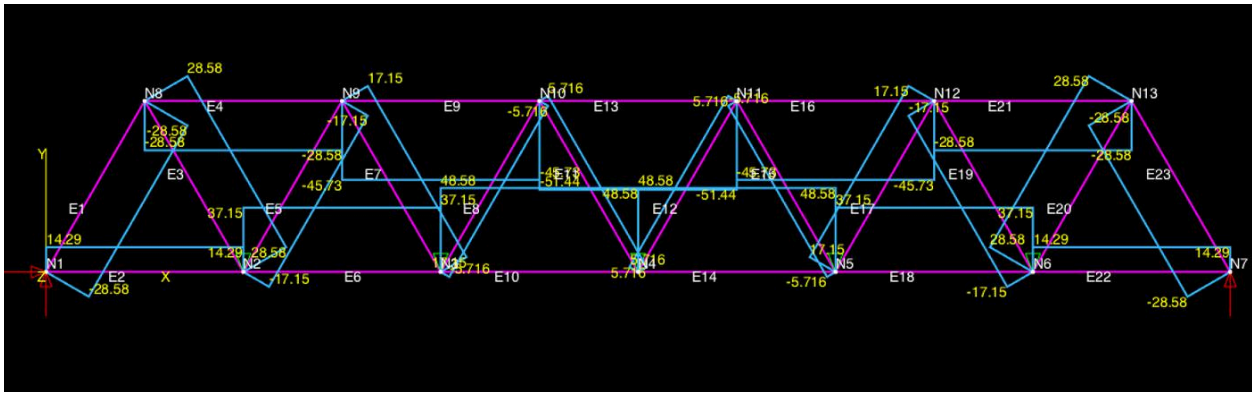
$F_{BG} = F_{DH} = -\frac{1}{3\sqrt{3}} W = -0.1925W$

$F_{CG} = F_{CH} = \frac{W}{3\sqrt{3}}$ (0.1925W) $\quad F_{GH} = -\frac{4}{3\sqrt{3}} W = -0.770W$

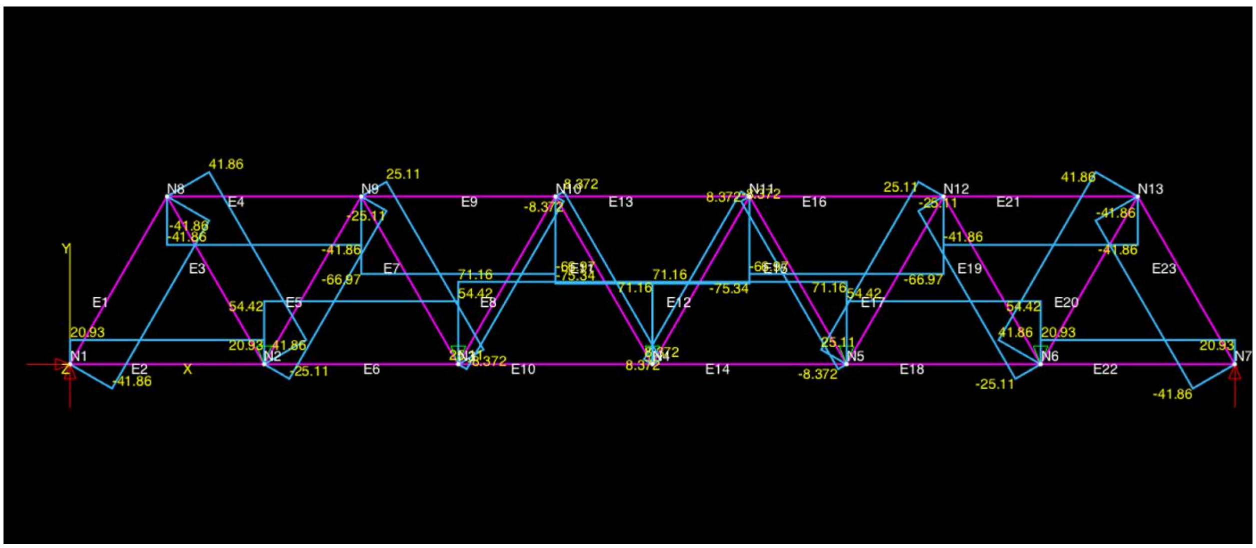
$F_{GH} < 69N \Rightarrow W \leq 89.6$ N

Appendix B: 6-Member Warren Analysis

SF = 1.5

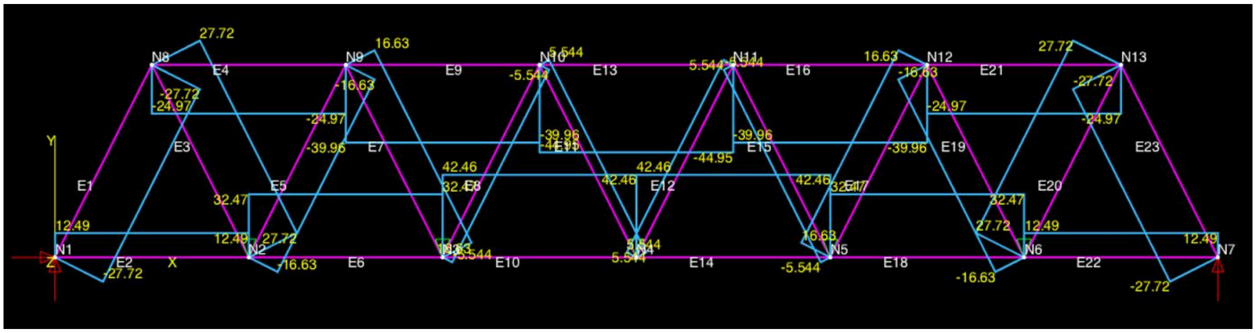


SF = 2.2

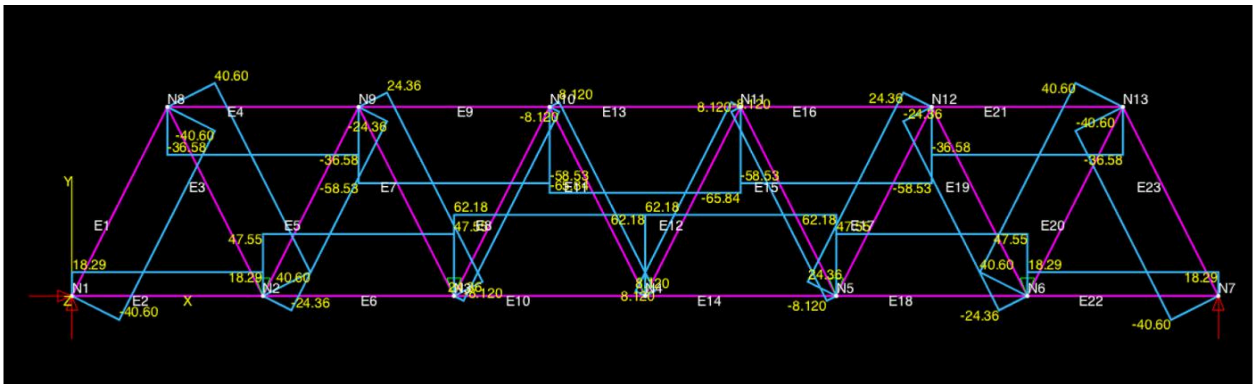


Appendix C: 6-Member Warren Raised

SF = 1.5

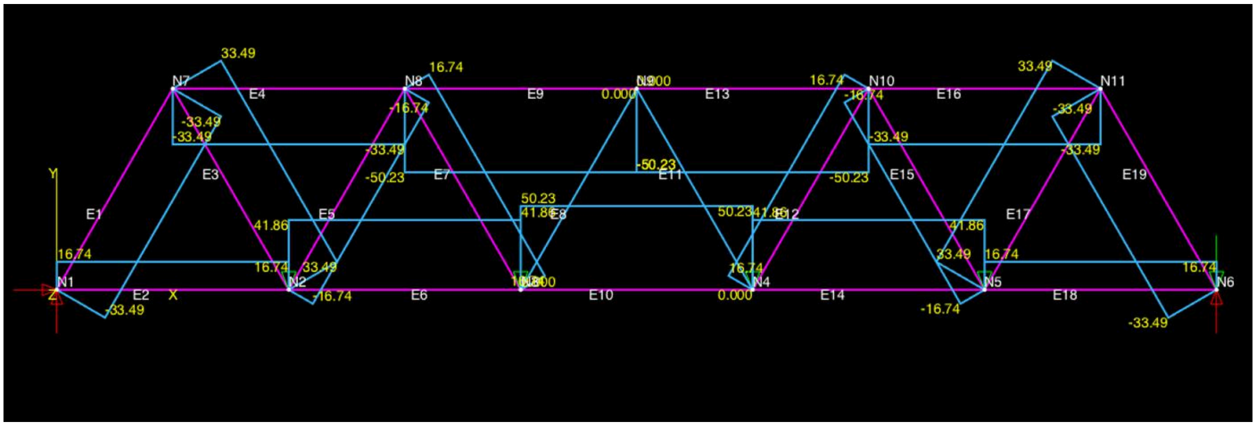


SF = 2.2

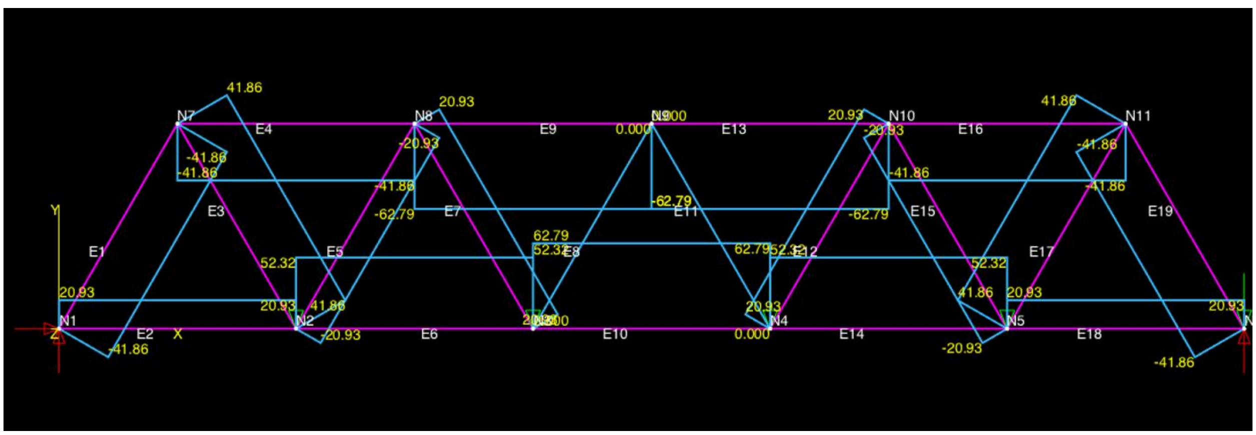


Appendix D: 5-Member Warren

SF = 1.5

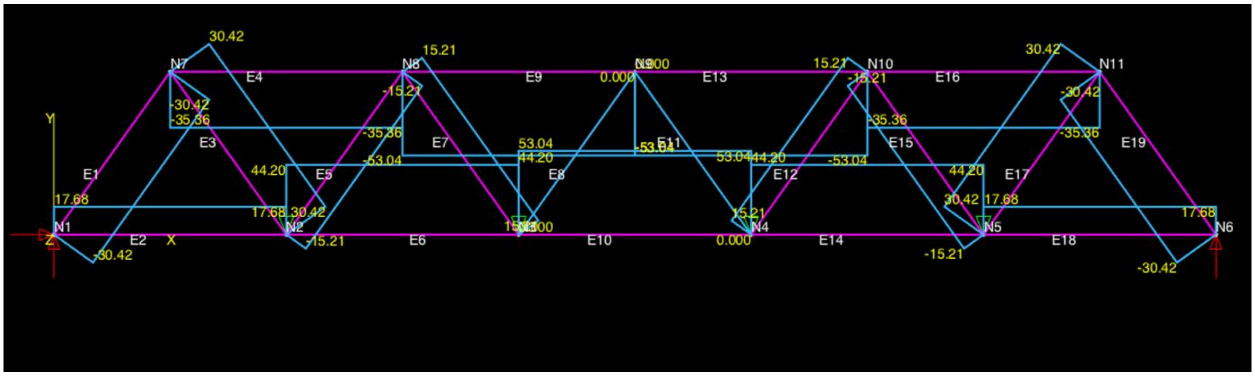


SF = 2.2

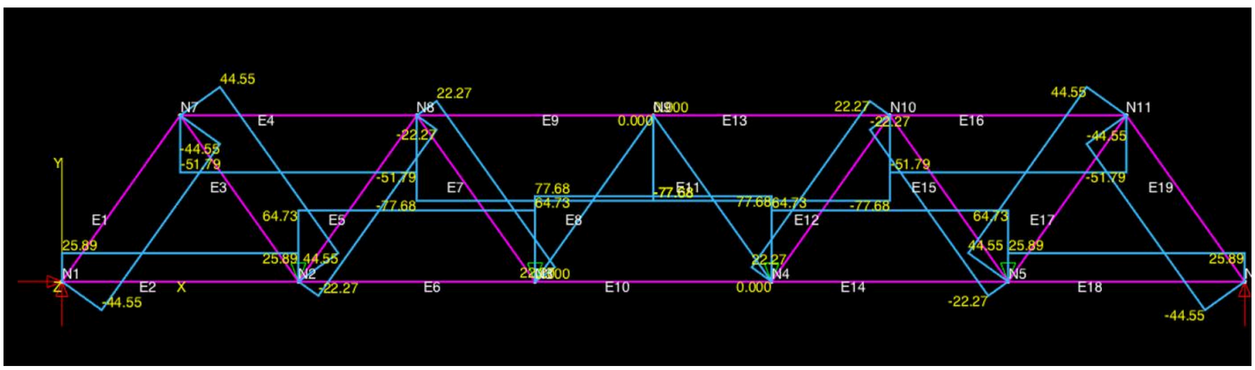


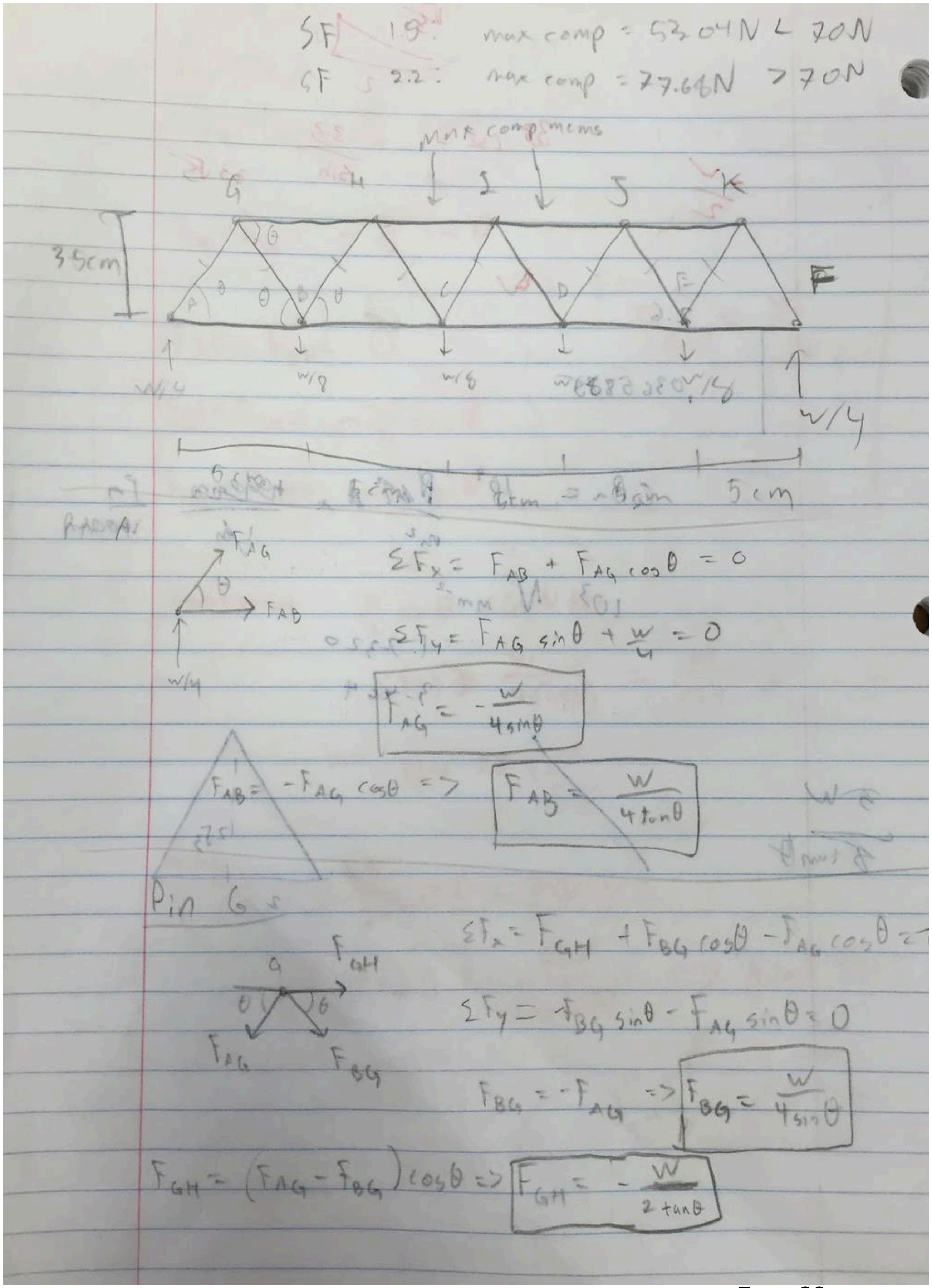
Appendix E: 5-Member Flattened

SF = 1.5



SF = 2.2




SF 1.9: max comp = 53.04N < 70N
SF 2.2: max comp = 77.64N > 70N
max comp mems
G
H
I
J
K
35cm
θ
A
B
C
D
E
F
w/4
w/8
w/8
w/8
w/4
5 cm
F_AG
θ
F_AB
w/4
ΣF_x = F_AB + F_AG cos θ = 0
ΣF_y = F_AG sin θ + w/4 = 0
F_AG = - w / 4 sin θ
F_AB = - F_AG cos θ =>
F_AB = w / 4 tan θ
Pin G
G
F_GH
θ
θ
F_AG
F_BG
ΣF_x = F_GH + F_BG cos θ - F_AG cos θ = 0
ΣF_y = - F_BG sin θ - F_AG sin θ = 0
F_BG = - F_AG => F_BG = w / 4 sin θ
F_GH = (F_AG - F_BG) cos θ => F_GH = - w / 2 tan θ

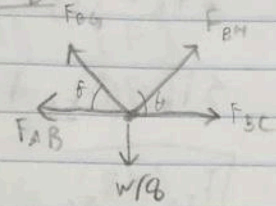
99

$w = 145$

51.975

76.125

Pin B



$$\Sigma F_x = F_{BC} - F_{AB} + (F_{BH} - F_{BG})\cos\theta = 0$$

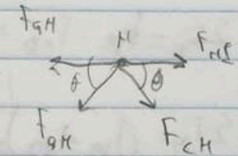
$$\Sigma F_y = (F_{BH} + F_{BG})\sin\theta - \frac{W}{8} = 0$$

$$F_{BH} = \frac{W}{8\sin\theta} - F_{BG} = -\frac{W}{8\sin\theta} \quad (= F_{BH})$$

$$F_{BC} = F_{AB} + (F_{BG} - F_{BH})\cos\theta = 0$$

$$= \frac{W}{4\tan\theta} + \left(\frac{W}{4\sin\theta} + \frac{W}{8\sin\theta}\right)\cos\theta = \frac{5}{8}\frac{W}{\tan\theta} \quad (= F_{BC})$$

Pin H



$$\Sigma F_x = F_{HI} - F_{GH} + (F_{CH} - F_{BH})\cos\theta = 0$$

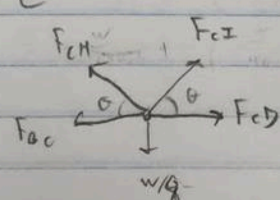
$$\Sigma F_y = (F_{CH} + F_{BH})\sin\theta = 0$$

$$F_{CH} = -F_{BH} \Rightarrow F_{CH} = \frac{W}{8\sin\theta}$$

$$F_{HI} = F_{GH} + (F_{BH} - F_{CH})\cos\theta = -\frac{W}{2\tan\theta} + \left(-\frac{W}{8\sin\theta} - \frac{W}{8\sin\theta}\right)\cos\theta$$

$$F_{HI} = \frac{-3}{4}\frac{W}{\tan\theta}$$

Pin C



$$\Sigma F_x = F_{CD} - F_{BC} + (F_{CI} - F_{CH})\cos\theta = 0$$

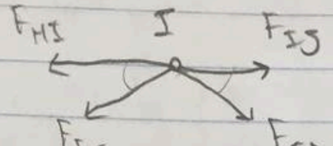
$$\Sigma F_y = (F_{CI} + F_{CH})\sin\theta - \frac{W}{8} = 0$$

$$F_{CI} = \frac{W}{8\sin\theta} - F_{CH} = 0$$

$$F_{CD} = F_{BC} + (F_{CH} - F_{CI})\cos\theta = \frac{5W}{8\tan\theta} + \frac{W}{8\tan\theta}$$

$$F_{CD} = \frac{3}{4}\frac{W}{\tan\theta}$$

Pin I



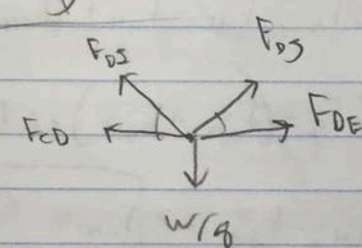
$$\Sigma F_x = F_{IJ} - F_{HI} + (F_{ID} - F_{IC})\cos\theta = 0$$

$$\Sigma F_y = (F_{ID} + F_{IC})\sin\theta = 0$$

$$F_{ID} = -F_{IC} = 0$$

$$F_{IJ} = F_{HI} \checkmark$$

Pin D



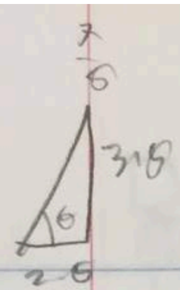
$$\Sigma F_x = F_{DE} - F_{CD} + (F_{DJ} - F_{DI})\cos\theta = 0$$

$$\Sigma F_y = (F_{DJ} + F_{DI})\sin\theta - \frac{W}{8} = 0$$

$$F_{DJ} = \frac{W}{8\sin\theta} = F_{CH} \checkmark$$

$$F_{DE} = F_{CD} + (F_{DI} - F_{DJ})\cos\theta$$

$$\frac{3}{4}\frac{W}{\tan\theta} + \left(-\frac{W}{8\sin\theta}\right)\cos\theta = \frac{5}{8}\frac{W}{\tan\theta} = F_{BC} \checkmark$$

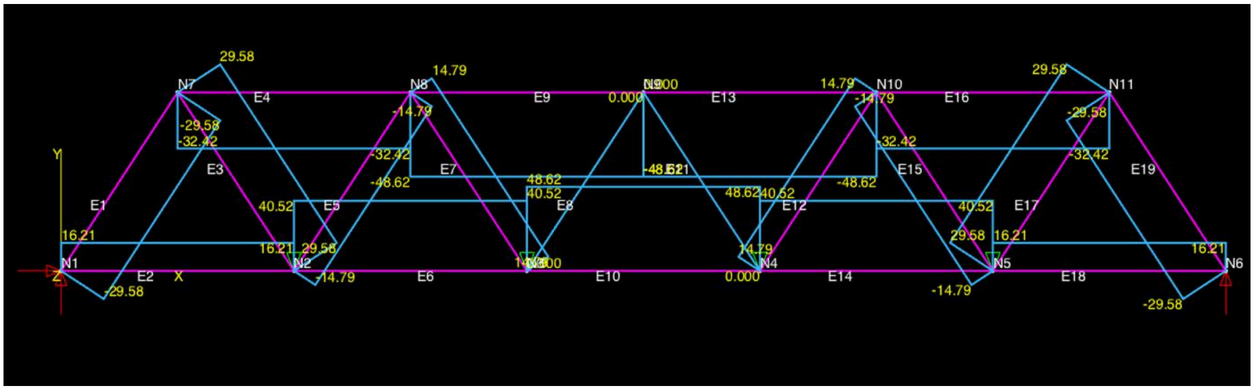


$-\frac{3}{4} \frac{w}{\tan\theta}$

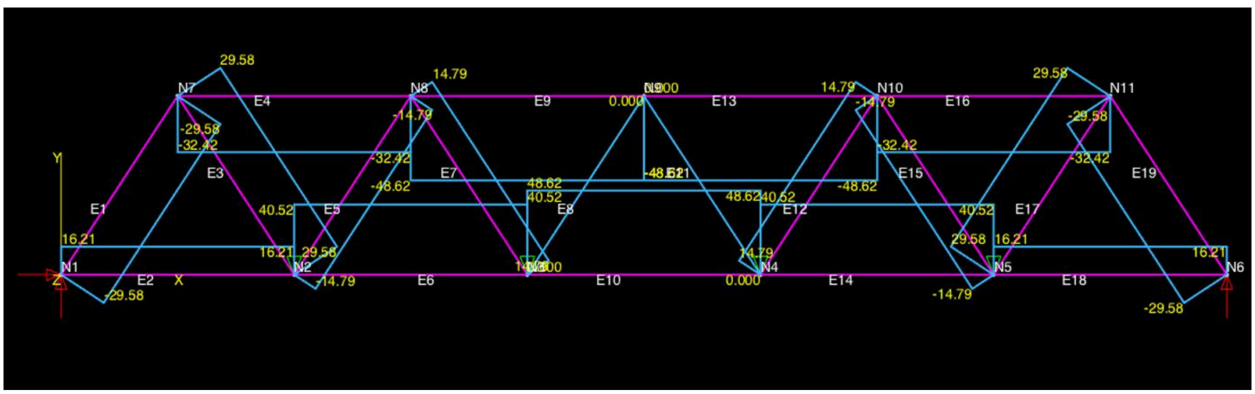
AB (EF)
BC (DE)
CD
AG (KF)

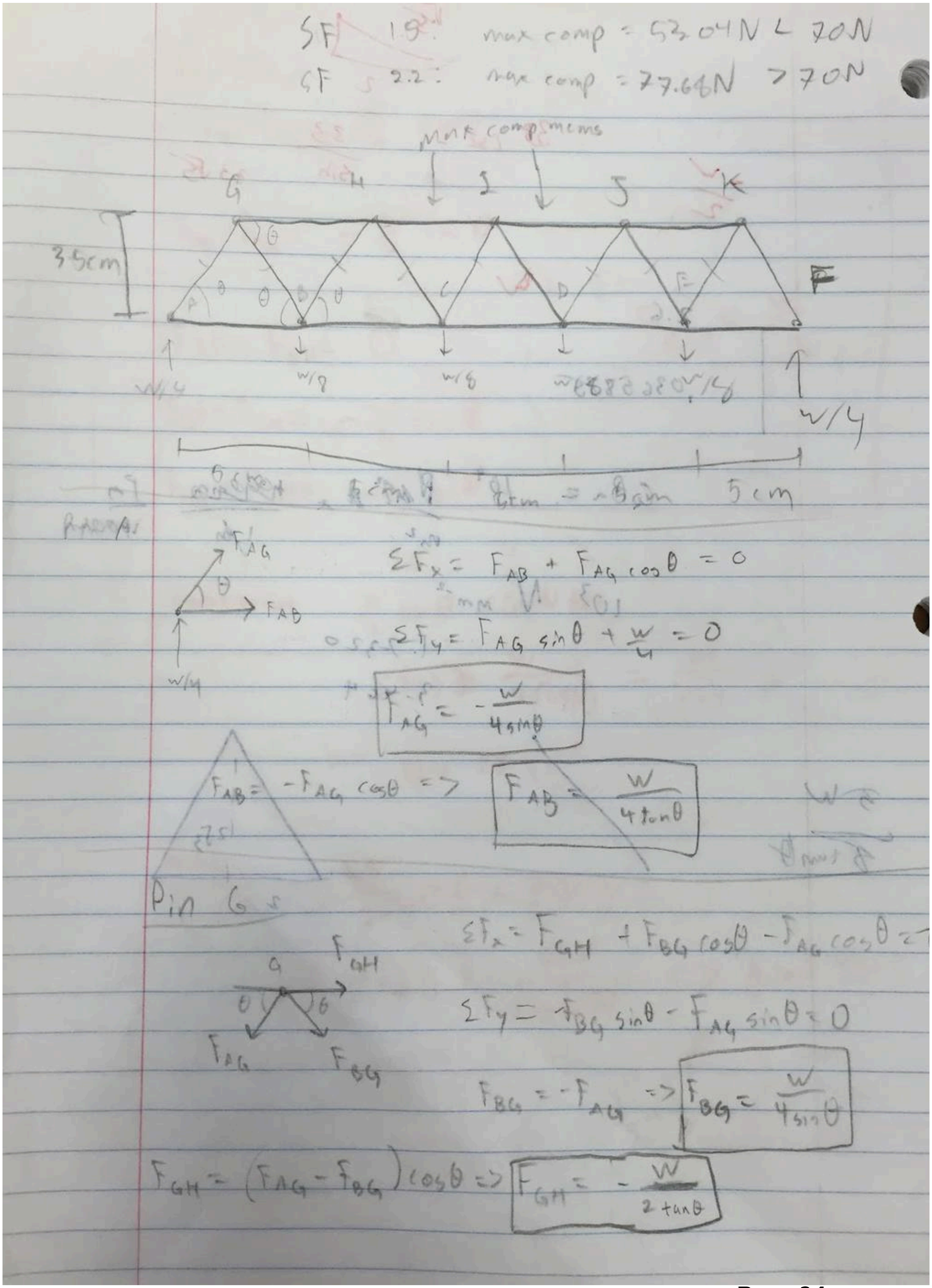
Appendix F: 5-Member Re-Adjusted Flattened for Test Road Bed Insertion

SF = 1.5



SF = 2.2




SF 1.9: max comp = 53.04N < 70N
SF 2.2: max comp = 77.64N > 70N
max comp mems
G H I J K
35cm
A B C D E F
w/4 w/8 w/8 w/8 w/8 w/4
5 cm
F_{AG} F_{AB} w/4
$\Sigma F_x = F_{AB} + F_{AG}\cos\theta = 0$
$\Sigma F_y = F_{AG}\sin\theta + \frac{w}{4} = 0$
$F_{AG} = -\frac{W}{4\sin\theta}$
$F_{AB} = -F_{AG}\cos\theta \Rightarrow F_{AB} = \frac{W}{4\tan\theta}$
Pin G
$\Sigma F_x = F_{GH} + F_{BG}\cos\theta - F_{AG}\cos\theta =$
$\Sigma F_y = -F_{BG}\sin\theta - F_{AG}\sin\theta = 0$
$F_{BG} = -F_{AG} \Rightarrow F_{BG} = \frac{W}{4\sin\theta}$
$F_{GH} = (F_{AG} - F_{BG})\cos\theta \Rightarrow F_{GH} = -\frac{W}{2\tan\theta}$

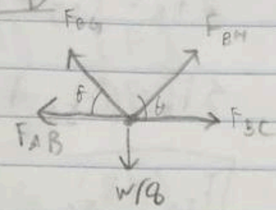
99

$w = 145$

51.975

76.125

Pin B



$$\Sigma F_x = F_{BC} - F_{AB} + (F_{BH} - F_{BG})\cos\theta = 0$$

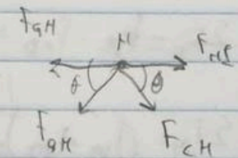
$$\Sigma F_y = (F_{BH} + F_{BG})\sin\theta - \frac{W}{8} = 0$$

$$F_{BH} = \frac{W}{8\sin\theta} - F_{BG} = \boxed{-\frac{W}{8\sin\theta} \quad (= F_{BH})}$$

$$F_{BC} = F_{AB} + (F_{BG} - F_{BH})\cos\theta \rightarrow 0$$

$$= \frac{W}{4\sin\theta} + \left(\frac{W}{4\sin\theta} + \frac{W}{8\sin\theta}\right)\cos\theta = \boxed{\frac{5}{8}\frac{W}{\tan\theta} \quad (= F_{BC})}$$

Pin H



$$\Sigma F_x = F_{HI} - F_{GH} + (F_{CH} - F_{BH})\cos\theta = 0$$

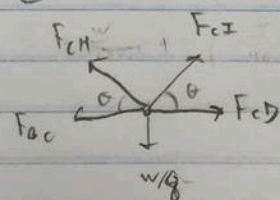
$$\Sigma F_y = (F_{CH} + F_{BH})\sin\theta = 0$$

$$F_{CH} = -F_{BH} \Rightarrow \boxed{F_{CH} = \frac{W}{8\sin\theta}}$$

$$F_{HI} = F_{GH} + (F_{BH} - F_{CH})\cos\theta = -\frac{W}{2\tan\theta} + \left(-\frac{W}{8\sin\theta} - \frac{W}{8\sin\theta}\right)\cos\theta$$

$$\boxed{F_{HI} = \frac{-3}{4}\frac{W}{\tan\theta}}$$

Pin C



$$\Sigma F_x = F_{CD} - F_{BC} + (F_{CI} - F_{CH})\cos\theta = 0$$

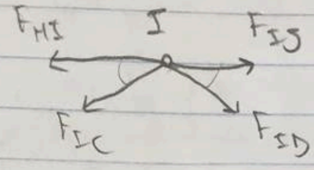
$$\Sigma F_y = (F_{CI} + F_{CH})\sin\theta - \frac{W}{8} = 0$$

$$F_{CI} = \frac{W}{8\sin\theta} - F_{CH} = 0$$

$$F_{CD} = F_{BC} + (F_{CH} - F_{CI})\cos\theta = \frac{5W}{8\tan\theta} + \frac{W}{8\tan\theta}$$

$$\boxed{F_{CD} = \frac{3}{4}\frac{W}{\tan\theta}}$$

Pin I



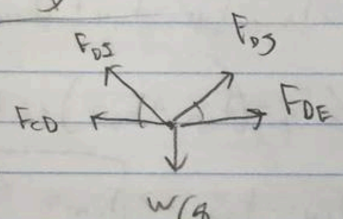
$$\Sigma F_x = F_{IJ} - F_{HI} + (F_{ID} - F_{IC})\cos\theta = 0$$

$$\Sigma F_y = (F_{ID} + F_{IC})\sin\theta = 0$$

$$F_{ID} = -F_{IC} = 0$$

$$F_{IJ} = F_{HI} \checkmark$$

Pin D



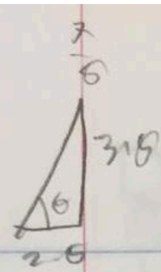
$$\Sigma F_x = F_{DE} - F_{CD} + (F_{DJ} - F_{DI})\cos\theta = 0$$

$$\Sigma F_y = (F_{DJ} + F_{DI})\sin\theta - \frac{W}{8} = 0$$

$$F_{DJ} = \frac{W}{8\sin\theta} = F_{CH} \checkmark$$

$$F_{DE} = F_{CD} + (F_{DI} - F_{DJ})\cos\theta$$

$$\frac{3}{4}\frac{W}{\tan\theta} + \left(-\frac{W}{8\sin\theta}\right)\cos\theta = \frac{5}{8}\frac{W}{\tan\theta} = F_{BC} \checkmark$$

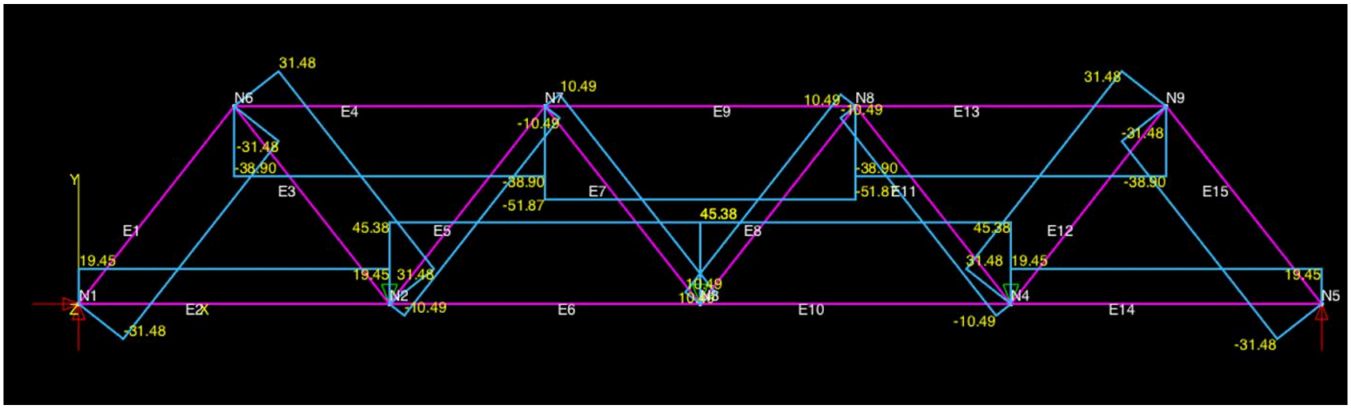


$-\frac{3}{4} \quad \frac{w}{\tan\theta}$

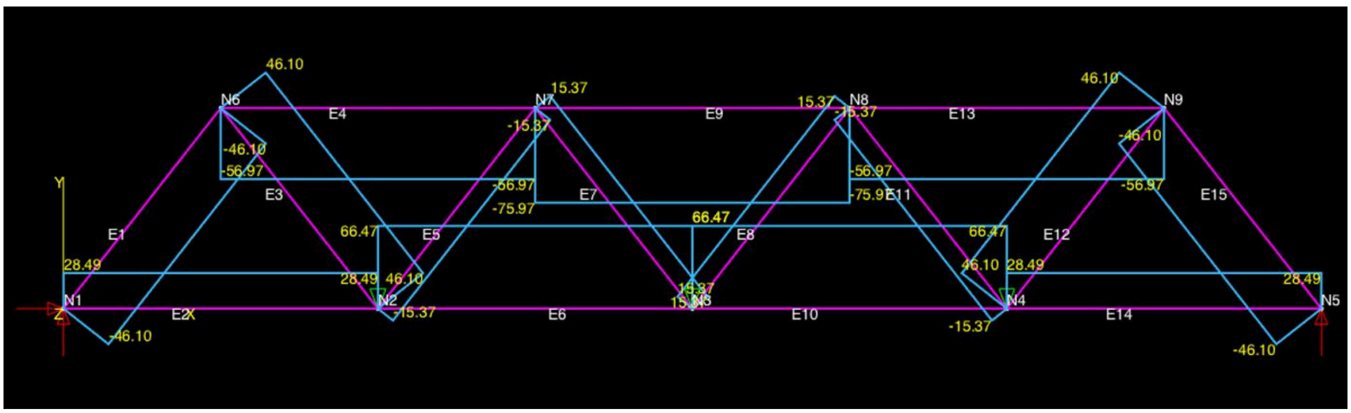
AB (EF)
BC (DE)
CD
AG (KF)

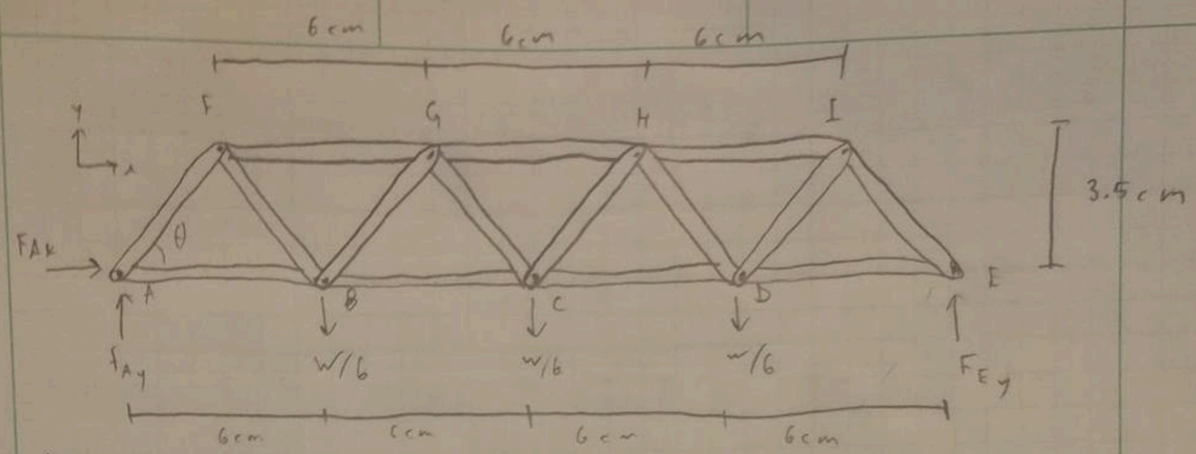
Appendix G: 4-Member Flattened

SF = 1.5



SF = 2.2





Assumptions: Massless, rigidless structure
- Supports $\frac{1}{2}W$ as load
- Pin at A, frictionless roller at E
- All forces on members drawn as tension

System: Entire structure

$\Sigma F_x = \boxed{F_{Ax} = 0}$ (immediate)

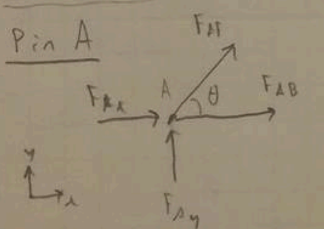
$\Sigma F_y = F_{Ay} + F_{Ey} - \frac{W}{6} - \frac{W}{6} - \frac{W}{6} = 0$ (1)

$\Sigma T_{z@A} = -\frac{W}{6}(6cm) - \frac{W}{6}(12cm) - \frac{W}{6}(18cm) + F_{Ey}(24\ cm) = 0$ (2)

(2) => $F_{Ey} = \frac{1}{24cm}\left(W(1cm) + W(2cm) + W(3cm)\right) = \boxed{\frac{1}{4}W \quad (= F_{Ey})}$

(3) => $F_{Ay} = \frac{W}{2} - F_{Ey} = \boxed{\frac{1}{4}W \quad (= F_{Ay})}$

sys: Pin A



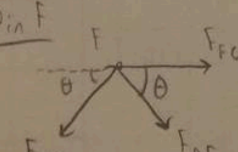
$\Sigma F_x = F_{AB} + F_{AF}\cos\theta + F_{Ax} = 0$ (1)

$\Sigma F_y = F_{Ay} + F_{AF}\sin\theta = 0$ (2)

(2) => $F_{AF} = \frac{-F_{Ay}}{\sin\theta} = \boxed{-\frac{W}{4\sin\theta} \quad (= F_{AF})}$

(1) => $F_{AB} = -F_{AF}\cos\theta - F_{Ax} = \frac{W}{2\sin\theta}\cos\theta - 0 = \boxed{\frac{W}{4\tan\theta} \quad (= F_{AB})}$

sys: Pin F



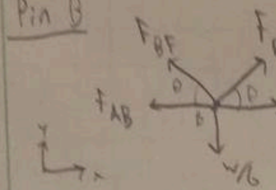
$\Sigma F_x = F_{FG} + F_{BF}\cos\theta - F_{AF}\cos\theta = 0$ (1)

$\Sigma F_y = -F_{BF}\sin\theta - F_{AF}\sin\theta = 0$ (2)

(2) => $F_{BF} = -F_{AF} = \boxed{\frac{W}{4\sin\theta} \quad (= F_{BF})}$

(1) => $F_{FG} = (F_{AF} - F_{BF})\cos\theta = \boxed{-\frac{W}{2\tan\theta} \quad (= F_{FG})}$

Sys: Pin B



$$\Sigma F_x = F_{BC} + F_{BG}\cos\theta - F_{BF}\cos\theta - F_{AB} = 0 \quad (1)$$

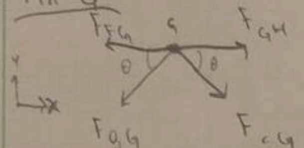
$$\Sigma F_y = F_{BG}\sin\theta + F_{BF}\sin\theta - \frac{W}{6} = 0 \quad (2)$$

$$(2) \Rightarrow F_{BG} = \frac{W}{6\sin\theta} - F_{BF} = \boxed{-\frac{W}{12\sin\theta} \quad (= F_{BG})}$$

$$(1) \Rightarrow F_{BC} = F_{AB} + (F_{BF} - F_{BG})\cos\theta = \frac{W}{4\tan\theta} + \left(\frac{W}{4\sin\theta} + \frac{W}{12\sin\theta}\right)\cos\theta$$

$$\Rightarrow \boxed{F_{BC} = \frac{7W}{12\tan\theta}}$$

Sys: Pin G



$$\Sigma F_x = F_{GH} + F_{CG}\cos\theta - F_{BG}\cos\theta - F_{FG} = 0 \quad (1)$$

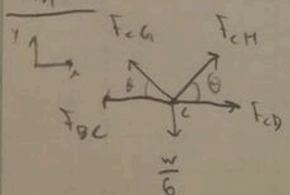
$$\Sigma F_y = F_{CG}\sin\theta + F_{BG}\sin\theta = 0 \quad (2)$$

$$(2) \Rightarrow F_{CG} = -F_{BG} = \boxed{\frac{W}{12\sin\theta} \quad (= F_{CG})}$$

$$(1) \Rightarrow F_{GH} = F_{FG} + (F_{BG} - F_{CG})\cos\theta = -\frac{W}{2\tan\theta} + \left(-\frac{W}{12\sin\theta} - \frac{W}{12\sin\theta}\right)\cos\theta = \boxed{-\frac{2W}{3\tan\theta} \quad (= F_{GH})}$$

Since the external loads on the frame and its geometry are both symmetric about C, the loads in the members are also symmetric about C. That is, $F_{AB} = F_{DE}$, $F_{AF} = F_{EI}$ and so on. With this in mind, we use pins C & H as a check:

Sys: Pin C



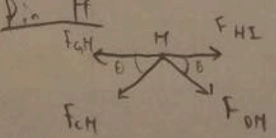
$$\Sigma F_x = F_{CD} + F_{CH}\cos\theta - F_{CG}\cos\theta - F_{BC} = 0 \quad (1)$$

$$\Sigma F_y = F_{CH}\sin\theta + F_{CG}\sin\theta - \frac{W}{6} = 0 \quad (2)$$

$$(2) \Rightarrow F_{CH} = \frac{W}{6\sin\theta} - F_{CG} = \frac{W}{12\sin\theta} = F_{CG} \quad ✓$$

$$(1) \Rightarrow F_{CD} = F_{BC} + (F_{CG} - F_{CH})\cos\theta = F_{BC} \quad ✓$$

Pin H



$$\Sigma F_x = F_{HI} + F_{DH}\cos\theta - F_{CH}\cos\theta - F_{GH} = 0 \quad (1)$$

$$\Sigma F_y = -F_{DH}\sin\theta - F_{CH}\sin\theta = 0 \quad (2)$$

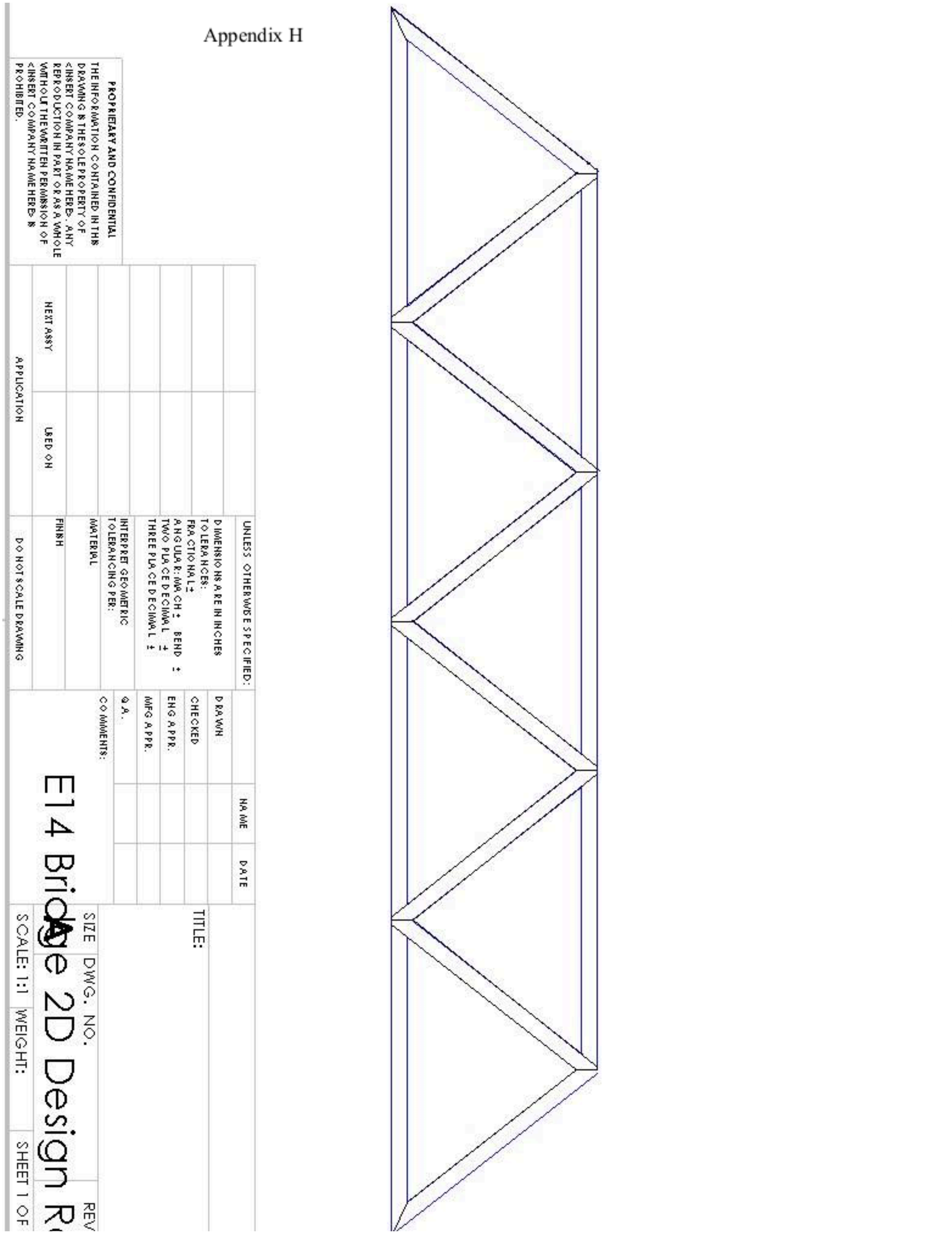
$$(2) \Rightarrow F_{DH} = -F_{CH} = -F_{CG} = -\frac{W}{12\sin\theta} = F_{BG} \quad ✓$$

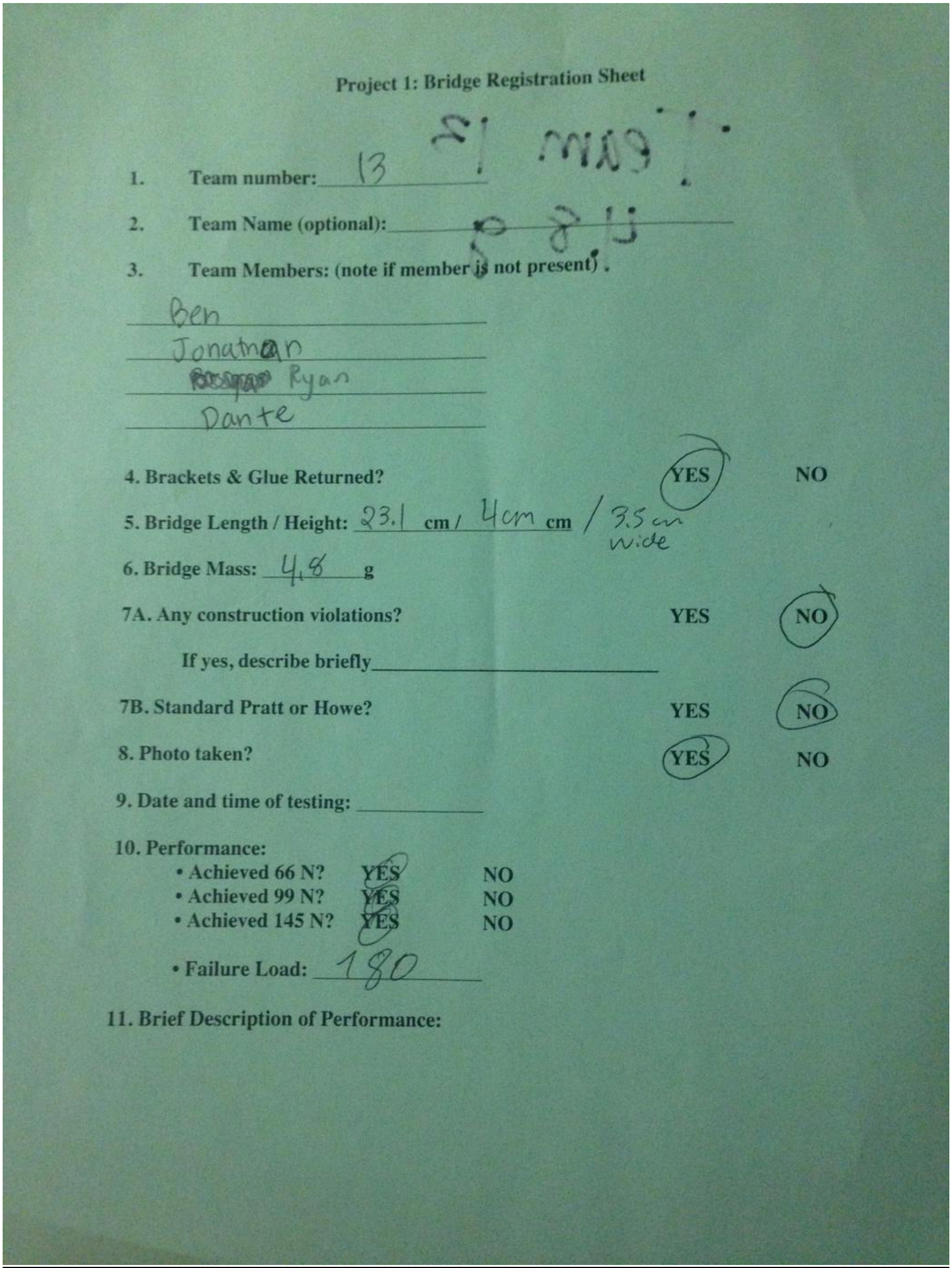
$$(1) \Rightarrow F_{HI} = F_{GH} + (F_{CH} - F_{DH})\cos\theta = -\frac{2W}{3\tan\theta} + \left(\frac{W}{12\sin\theta} + \frac{W}{12\sin\theta}\right)$$

$$\Rightarrow F_{HI} = -\frac{W}{2\tan\theta} = F_{FG} \quad ✓$$

Symmetry then gives us the remaining member forces.

Appendix H


PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
FINISH
MATERIAL
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
A
DWG. NO.
REV
E14 Bridge 2D Design
SCALE: 1:1
WEIGHT:
SHEET 1 OF



Project 1: Bridge Registration Sheet

1. Team number: 13
2. Team Name (optional): ______
3. Team Members: (note if member is not present)

Ben
Jonathan
Ryan
Dante

4. Brackets & Glue Returned? **(YES)** NO

5. Bridge Length / Height: 23.1 cm / 4cm cm / 3.5 cm wide

6. Bridge Mass: 4.8 g

7A. Any construction violations? YES **(NO)**

If yes, describe briefly ______

7B. Standard Pratt or Howe? YES **(NO)**

8. Photo taken? **(YES)** NO

9. Date and time of testing: ______

10. Performance:
- Achieved 66 N? **(YES)** NO
- Achieved 99 N? **(YES)** NO
- Achieved 145 N? **(YES)** NO
- Failure Load: 180

11. Brief Description of Performance: