CIV 102 bridge project

Group 106
Neil Karkhanis, Jan Kazimierczak, Adi Prasad
TA: Christian Pavlidis

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Contents

1 Introduction

1.1 Background

The CIV 102 bridge project presents an opportunity for EngSci students to develop their skills in every engineering domain. The goal is to design a bridge using given materials that will sustain a moving train of varying weight. The goal is to sustain as much weight as possible without the bridge breaking apart. [1]

1.2 Our design

"The Bee-am" bridge was designed with the intentions of supporting the requirements of Load Case 1 and 2 while using the least amount of material possible. Load Case 1 requires the bridge to support a 400N three-car train in crossing a 1200mm gap [1]. Load Case 2 requires a three-car train with a combined load of 452N to cross the 1200mm gap [1]. If the bridge supports the first pass, the loading of the train will increase for subsequent passes, as shown in the image to the right. For subsequent passes, the "locomotive" car, which will be at the front or back of the train will have a loading of 1.38x the middle freight car. The freight car on the opposite end of the locomotive will have a loading of 1.10x the middle freight car. Although supporting the highest Load Case 2 capacity was a major goal, when designing the bridge strong considerations were also given to the material being used. The bridge had to be manufactured from the following materials: a matboard with dimensions 32" × 40" × 0.05" (813 mm × 1,016 mm × 1.27 mm) and two 30mL tubes of LePage Heavy Duty Contact Cement. The constraints imposed by the given materials required an analysis of load capacity vs material used for every proposed iteration. All iterations that were considered for the final design are listed with greater explanation in the Design Process of the report.

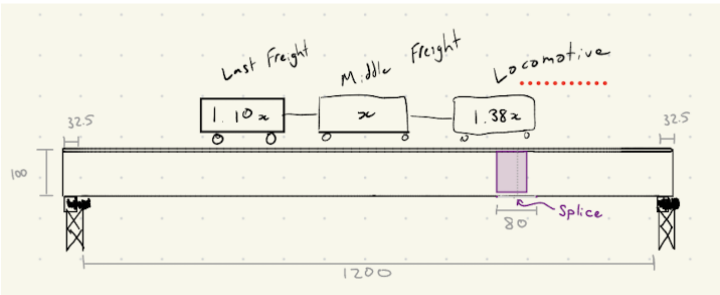

Figure 1: Load Case 2

The bridge has a total length of 1265mm, so that it can span the 1200mm gap and has 32.5mm on either end to rest upon the 50mm supports. The length of 1265mm was chosen to avoid being too close to the limits of 1250mm and 1270mm, ensuring the bridge was not over or under the length requirements. However, the max dimension of the given matboard is 1016mm. This required two sections of different length to be produced and later adjoined together at a splice. The longer of the two sections was 900mm, while the shorter cross section was 365mm. The bridge deck (AKA track) has a constant width of 100mm. This was the minimum requirement to allow the train to pass, and since enlarging its width did little to help increase the loading capacity of the bridge, it was kept at minimum to reduce the total amount of material used. The bottom flange of the bridge had no requirements imposed upon it and was chosen to have a width of 80mm. The height of the bridge was required to be a multiple of 20 less than 200mm. After selecting a desirable cross-section, and iterating through multiple heights, a constant bridge height of 100mm was chosen for the final design. Based on calculations, this bridge height was found to support a larger load capacity while also limiting the material used, ensuring that the bridge did not require more matboard than given.

For "The Bee-am" cross-section, Design 0 was iterated upon several times. Design 0, which was given in CIV102 Matboard Design Project and is shown below, was deemed as impractical design since it could not support the weight imposed by Load Case 2. As shown through the calculations, Design 0's Factor of Safety for Flexural Compression is 0.930. However, Design 0 was not completely a write-off and just needed some improvements in order to survive Load Case 2. The improvements made to use Design 0 inspired geometry in “The Bee-am” are described as following.

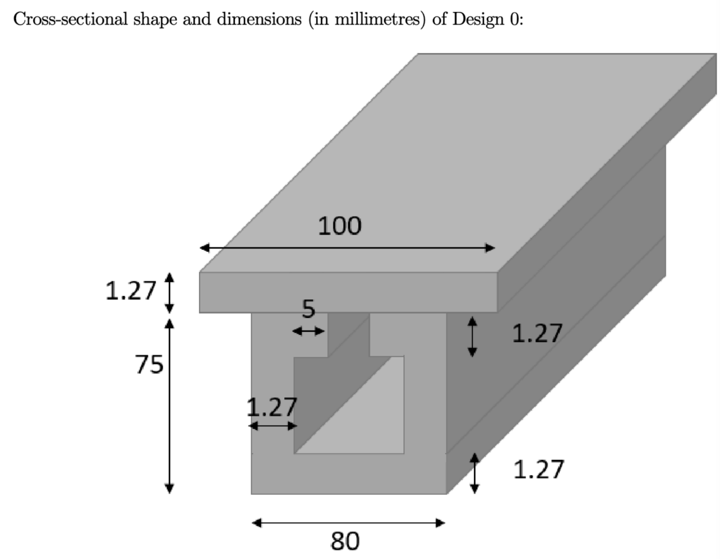

Figure 2: Cross Section of Design 0 [1]

The top flange of the Design 0 cross section had only one layer with dimensions 100mm x 1.27mm. After iteration, it was decided to add an extra 100mm x 1.27 layer to the top flange, making the bridge cross section capable of carrying larger loads. Adding an extra layer to the top flange helped increase the cross section’s I, second moment of area, which is inversely proportional to the flexural compression. In other words, increasing I helped decrease flexural compression and increase the factor of safety. The other significant change made to Design 0 was increasing the height of the cross section. Design 0s original height of 76.27mm was updated to 100mm, changing the centroid height and the height of the webs significantly. These modifications once again increased the I and helped increase the factor of safety. Overall, a higher factor of safety means a greater minimum failure load. Thus, the Design 0 failure load of 240 N is outshone by the improvements on “The Bee-am” cross section, which has a failure load of 869.5 N.

Another critical feature of “The Bee-am” is its diaphragms. The bridge has 12 evenly spaced diaphragm positions, starting 32.5mm from each end and with 109.1mm of spacing between individual diaphragms. At 11 out of 12 of these diaphragm positions are matboard diaphragms with dimensions 80.0mm x 96.19mm. One of the diaphragm positions is at the location of the splice, that connects the larger section of the bridge to the smaller section. At this location, it was not possible to use a singular diaphragm piece so instead a different connection was made (further discussed below). Each internal diaphragm was additionally fastened to the interior bridge walls by adding an L-shaped piece of matboard, 30mm x 18 mm on either side. The outer two diaphragms were fixed with two L-shaped pieces on the same side, so that they were on the interior. These L-shapes were implemented with hopes of strengthening the connection between the bridge walls and diaphragms, which beforehand were only held together by strips of contact cement.

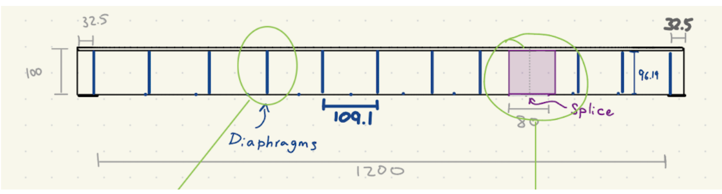

Figure 3: The uniform spacing of diaphragms

The last important bridge feature to talk about is the splice between the longer and shorter section. On both the interior and exterior of the bridge, there are three pieces each adjoining the two parts together. The internal and external connecting pieces that run along the bottom flange of the bridge are identical and have dimensions, 80mm x 80mm. The four pieces that connect the respective webs together have dimensions of 80mm x 96.19mm. These extra pieces assisted in connecting the two different sections of the bridge, making it one complete entity. The above description of the bridge can be simplified into the table below, which briefly summarizes all the major features.

The above description of the bridge can be simplified into the table below, which briefly summarizes all the major features.

"The Bee-am"	Description
Dimensions	Length: 1265mm (900mm + 365 mm sections) Top Deck/Track Width: 100mm Height: 100mm Bottom Flange Width: 80mm
Cross section	Top Flange: 100 mm x 2.54mm Glue Tabs: 5 mm x 1.27 mm Webs: 2x (1.27 mm x 96.19mm) Bottom Flange: 80mm x 1.27mm Minimum Failure Load: 869.5 N
Diaphragms	First Diaphragm: 32.5 mm Last Diaphragm: 1232.5mm Diaphragm Spacing: 109 mm Diaphragm Dimensions: 80mm x 96.19mm L-Shape Connections: 2x (30mm x 18mm), one on either side
Splice	Bottom Connection: 2x (80mm x 80mm) (Interior and Exterior) Web Connections: 4x (80mm x 97.46mm) (Interior and Exterior)

Table 1: Summary of major bridge features

2 Design process

2.1 Bridge Description

The final design, The Bee-am is a two web box girder design. This cross section is a modified version of the design 0 cross section (also a two web box girder). As such, this cross section is known to be both reliable and simple to build. The total height of the cross section is roughly 100 mm, an amount that finds the perfect balance between material consumption and the different failure cases. The additional thickness in the top flange from design 0 (1.27 mm $\rightarrow$ 2.54 mm) helps reduce bending, the increased amount of diaphragms and web height reduced shear and improved bending stiffness.

The aesthetics of the design were accomplished using black sharpie and the already yellow colour of the matboard.

2.2 Key Design Choices

Cross section: A double layer top flange (2.54 mm thickness) was utilized to reduce local buckling due to compression and increase the factor of safety (FOS) for this failure case. The total height was increased to 100 mm to reduce the stress on the top flange and improve the overall bending stiffness of the design.

Webs, glue tabs and bottom flange: A piece of matboard was folded to create the webs, glue tabs and bottom flange to avoid human error. As all these components were the same thickness, it was possible to create them out of folding one piece of matboard and this was found to be more beneficial than gluing separate pieces together because improper gluing with the contact cement could have led to premature failure (i.e. the webs separate from the bottom flange).

Splicing: The top flange as well as the web-glue tab-bottom flange pieces were spliced as the minimum length of the bridge (1250 mm) exceeded the length of the given matboard piece. The top flange had two splices (to attach the two layers of the top flange more effectively) while the web-glue-tab-bottom flange had one splice. The splices were also positioned away from the mid-span of the bridge (location of the highest bending moment). The splices were also designed in a way so as to not overlap (i.e. the top flange splices was located away from the web-glue tab-bottom flange splice).

Diaphragms: As previously mentioned, 11 normal (wall), full sized (spanned the width of the bottom flange and the height of the webs) diaphragms and 1 box diaphragm were used in the final design. Of the 11 normal diaphragms, two were placed in close proximity to the support (the area with the maximum shear forces). A box diaphragm was placed at the location of the web-glue tab-bottom flange splice. The box diaphragm was essentially a hollow box that was placed inside the bridge at the location of the splice, replacing a traditional diaphragm to provide more support to an area where past bridges have often failed. The primary goal of these diaphragms was to strengthen critical failure areas (the supports and splice) and to provide additional protection against shear forces.

Contact cement: The contact cement was applied onto one piece and left to rest for 15 minutes before being attached to another piece. After the two pieces were attached, some weight would be applied to increase the pressure and help the contact cement stick. The glue was also applied in uniform layers to increase bond strength. Finally, the full 72 hour period for curing was utilized to ensure maximum bond strength and to reduce stresses.

2.3 Design 0 calculations

Below are the properties of design 0, calculated using a python program:

- Centroid: 41.4 mm
- $I \approx 418 \times 10^3$ mm^4
- $Q \approx 6.50 \times 10^3$ mm^3
- $Q_{\text{glue}} \approx 4.45 \times 10^3$ mm^3

Factors of Safety:

- Tension: 4.33
- Compression: 0.993
- Buckling 1 (top): 0.610
- Shear 2 (web): 12.57
- Glue: 72.3
- Shear web buckling: 15.99

2.4 Code

For the purpose of efficient and rapid iteration, code was developed to help with the calculations. Code was written in visual studio code using python. Imported libraries included matplotlib, numpy and math. The entire script can be found using this link Link to access script. To ensure the code works without error, 3 different bridge iterations were used to ensure that the values the code outputs are correct, thus 3 hand calculations for different geometries and test cases were made. The graphs were made using matplotlib and the documentation was used to make a correct use of the library [2]

2.5 Iterations:

5 major iterations were performed throughout the design process for this bridge. Each iteration was checked for predicted failure load and FOS for each failure case using a python code.

2.5.1 Iteration 1 (increasing top flange thickness):

In the first iteration, the top flange thickness was doubled, becoming 2.54 mm (original: 1.27 mm), The rest of the bridge components (bottom flange, web, etc.) remained completely unchanged. Material use considerations had to be further considered as the amount of matboard and contact cement used would increase.

Section Properties: The neutral axis shifted to 49.5 mm, which also shifted the second moment of area to 530 x 10^3 mm^4. Based on these changes and the formula for flexural stresses ($\sigma = \frac{My}{I}$), the compressive stresses at the top of the bridge were reduced in comparison to design 0. The first moment of area also became 8730 x 10^3 mm^3, which increased the shear stress according to the formula for shear stress ($\tau = \frac{VQ}{Ib}$), however, the pro of this change (reducing buckling at the top) outweighed this con.

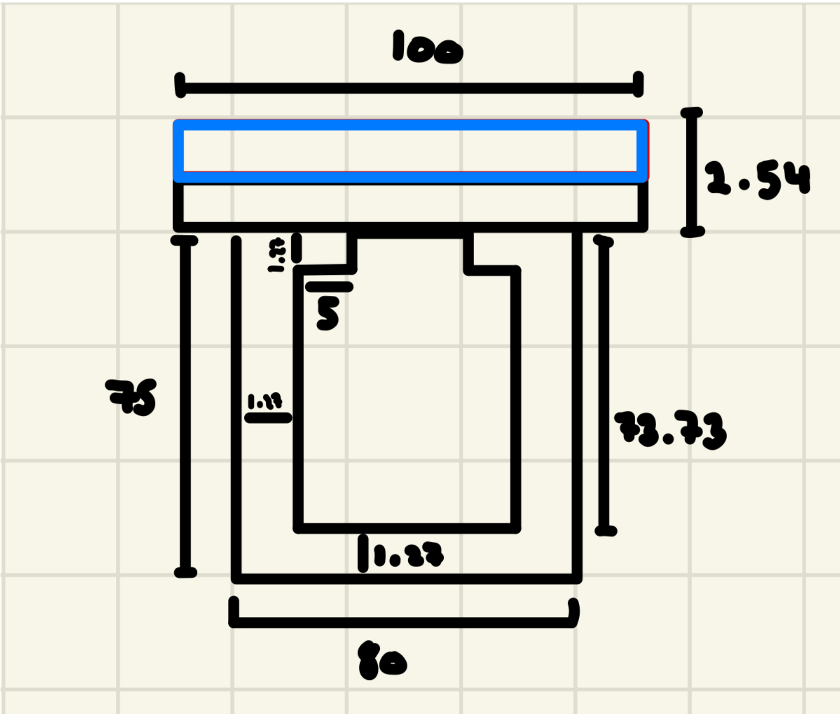

Figure 4: A drawing of iteration 1. The blue part represents the change of increasing the thickness of the top flange to 2.54 mm from 1.27 mm.

Factors of Safety:

- Tension: 4.62
- Compression: 1.565
- Buckling 1 (top): 3.84
- Buckling 2 (web): 11.95
- Glue: 71.2
- Shear web buckling: 15.20

Because of this change, the predicted failure load more than doubled, becoming 626 N. The failure mode was flexural compression. The main goal for the next iteration was to increase the factor of safety for flexural compression as that was the current failure mode.

2.5.2 Iteration 2 (increasing web height):

In the second iteration, the height of the webs was increased to 96.19 mm (original: 73.73 mm) with the overall height becoming 100 mm. The changes made in iteration 1 as well as everything else remained the same.

Section Properties: The neutral axis shifted to 62.7 mm, which also shifted the second moment of area to 946 x 10^3 mm^4. Based on these changes and the flexural stress equation ($\sigma = \frac{My}{I}$), the flexural compression stresses were reduced. The first moment of area also became 12060 mm^3. However, the increase in height also led to higher shear web buckling (diagonal shear) according to the following formula: ($\tau_{\mathrm{Cr}} \propto \left(\frac{t}{h}\right)^2$). The reason for this is the taller the web, the more slender the plate.

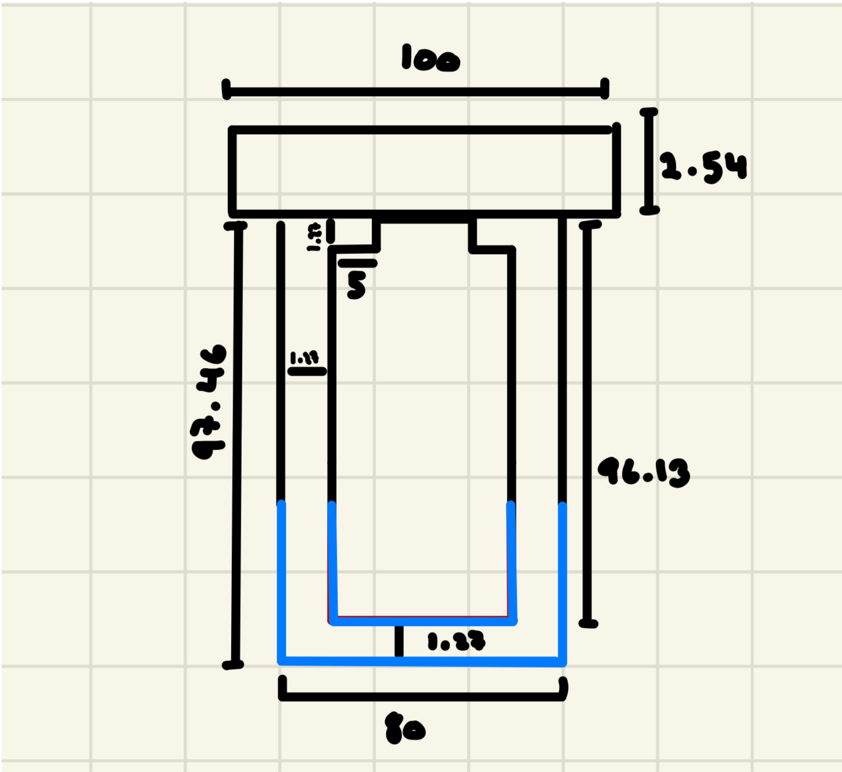

Figure 5: A drawing of iteration 2. The blue part represents the change of increasing the web height from 73.73 mm to 96.19 mm (overall height becomes 100 mm).

Factors of Safety:

- Tension: 6.52
- Compression: 2.12
- Buckling 1 (top): 5.21
- Buckling 2 (web): 15.45
- Glue: 101.0
- Shear web buckling: 11.91

The predicted failure load for this iteration was 848.8 N and the failure mode remained flexural compression. The main goal for the next iteration was to increase the factor of safety for shear web buckling as upper years and TAs have noted that bridges have often failed to shear web buckling before reaching their predicted failure load.

2.5.3 Iteration 3 (increasing the amount of diaphragms):

For this iteration, the number of diaphragms was increased from 2 to 12 (11 normal, 1 box diaphragm). These diaphragms were spaced 109 mm apart with the first one positioned at the first support and the last one positioned at the last support. The changes made in iterations 1 and 2 as well as everything else remained the same.

Section Properties: The neutral axis, first moment of area and second moment of area all remained the same. However, the addition of more diaphragms led to lower shear web buckling, increasing its factor of safety. The reason for this is that diaphragms provide the cross section, particularly the webs with more support. This creates a more rigid structure and braces the webs against displacement and shear web buckling.

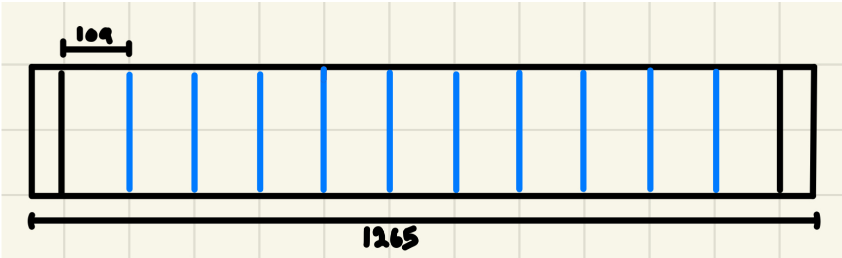

Figure 6: A drawing of iteration 3. The blue part represents the change of increasing the number of diaphragms from 2 to 12.

Factors of Safety:

- Tension: 6.52
- Compression: 2.12
- Buckling 1 (top): 5.21
- Buckling 2 (web): 15.45
- Glue: 101.0
- Shear web buckling: 23.8

The predicted failure load for this iteration remained 848.8 N and the failure mode remained flexural compression. However, upper years and TAs have noted that bridges often fail to shear web buckling rather than their predicted failure mode, so this change likely made the predicted failure load more accurate to what would happen in reality. The main goal for the next iteration was to improve ease of construction (making the bridge easier to build) while increasing the predicted failure load.

2.5.4 Iteration 4 (increasing glue tab width):

This was the final iteration made and for this iteration, the width of the glue tabs that connect that webs to the top flange was increased from 5 mm to 10 mm. The changes made in all previous iterations as well as everything else remained the same.

Section Properties: This change shifted the second moment of area to 952 x 10^3 mm^4 and changed the first moment of area for the glue 6890 mm^3. As a result of this change, the shear stress for glue decreased according to the equation: ($\tau = \frac{VQ}{Ib}$). This is because the b doubled.

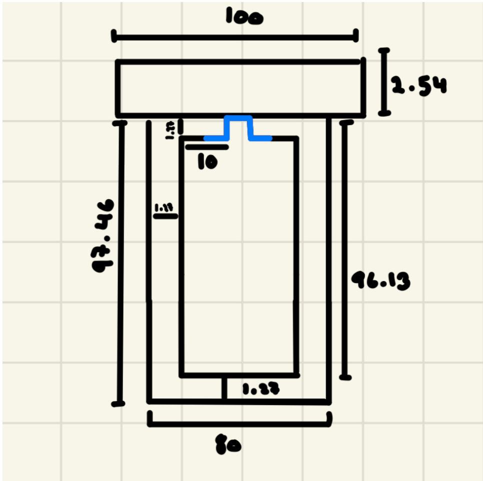

Figure 7: A drawing of iteration 4. The blue part represents the change of increasing the width of the glue tabs from 5 mm to 10 mm.

Factors of Safety:

- Tension: 6.49
- Compression: 2.17
- Flange buckling: 5.34
- Shear: 15.88
- Glue: 107.0
- Shear buckling: 24.4

Changing the width of the glue tabs also modified some of the other factors of safety and as a result, the predicted failure load increased to 869.5 N and the predicted failure mode remained flexural compression. There were further ways to increase the predicted failure loads, however, there was not enough material to implement said changes. Therefore, the design after iteration 4 was the final design chosen for The Bee-am.

3 Construction process

3.1 Day 1

The first day of construction was the 20th of November after classes. It was decided to construct the bridge in the Chestnut residence as most of the team resided there. After classes on the 20th the team gathered in the Chestnut common room to prepare the layout for the cuts. This process was done using a computer software. First it was neccessary to calculate all the measurments and plan out how all the pieces are going to be attached before inputing this information into the software. After the computer outputed the layout all shapes were drawn on the matboard as per figure 8. Before cutting it was essential to verify that all lines were perfectly alligned and that the measurments were correct. This process took around 2 hours. Materials such as pencils, rulers, meter sticks and measurment tapes were used for this step.

Figure 8: Matboard with all the drawings done ready to be cut, Nov 20, 2025 10:11 PM

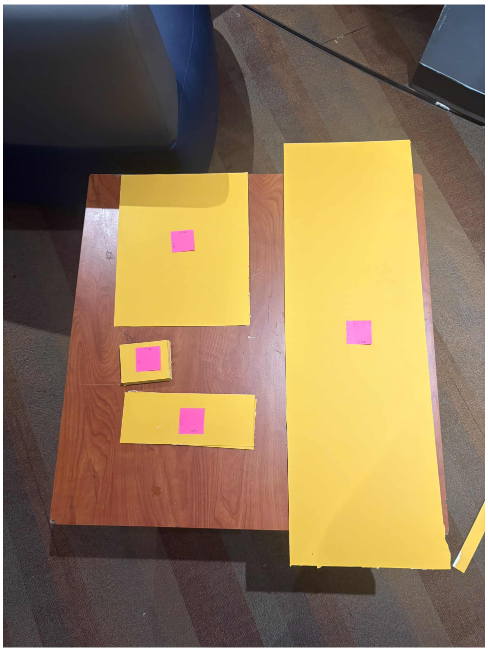

Figure 9: Matboard cut and labeled into pieces later used for construction, Nov 20, 2025 10:59 PM

When all the drawing were ready the process of cutting began. To ensure that nothin will be damaged we placed a plastic bag under the matboard. Two Xacto knives were used for this process. To ensure clean cuts, each pass of the blade was made with light force so the cut is clean, and for each cut the blade was passed around 10 times. After all the pieces were cut as is shown in figure 9 they were labeled and ready for glueing. The first pieces that were glued together were the top flanges. As the chosen design has two upper flanges, two rectangular pieces of matboard had to be glued together. As it was getting late on the first day this is all the team did. The two flanges glued together can be seen being pressed together to ensure proper connection in figure

3.2 Day 2

On the second day, November 21st construction started much earlier and lasted much longer. The team was constructiong together most of the time. The first thing that had to be done is to fold the main body of the bridge. As the chosen design has a bottom flange with two webs the team decided to have

Figure 10: Top flanges being pressed to ensure proper connection, Nov 20, 2025 11:31PM

the two webs and the bottom flange as one piece and just fold it. This way the use of glue was avoided, knowing that it is hard to glue correctly.

For the process of folding small incisions were made with the help of a Xacto knife. After the fold the pieces were squished between two tables to ensure the fold stays.

After the folding process the diapraghms were attached with the help of an L-shaped connector. After attaching all the diaphramgs the structure was again squished between two tables to ensure that the glue sticks securely. A picure of this final piece is shown in figure 11

Figure 11: Bridge piece with all diaphgrams securely attached Nov 22,2025 12:54 AM

After the diaphragms were securely attached to the main body, the process of attaching the top flange started. The design has 10mm wide glue tabs to ensure a secure connection. Glue was applied on both the glue tabs as well as the bottom of the flange to ensure a proper connection and after waiting the 15 required minutes the team proceeded with attaching the top flange. As it is shown in figure 12 after the flange was attached, weight was put on it to ensure a proper connection between the glue tabs and the top flange.

Figure 12: Weight on beam to ensure secure connection, Nov 22, 2025 1:08AM

This was the last step of the bridge construction, only waiting fot the glue to settle was left. The team waiting for the top flange to connect securely is shown in figure 13

Figure 13: Picture of the beam with the group in the background, Nov 22, 2025 1:27AM

After waiting for around 30 minutes the beam was moved to a member's room and left there with weight on top to ensure proper curation for the next 72 hours. Figure 14.

Figure 14: Picture of the beam in group member's room

4 Conclusion

Designing The Bee-am brought together many different aspects of CIV102. Rather than just doing calculations, the theories learnt in the course were actually used in a real-life application. The design process of this bridge implemented material properties, material constraints, structural analysis, programming and construction skills to create one unified project, mimicing the work of real professional engineers. The iterations and calculations performed were especially helpful in deciding on a final design and taught valuable engineering skills. One valuable lesson was that parts of the design could not be altered without effecting other parts. For example, increasing the factor of safety for flexural compression could have resulted in a decrease in the factor of safety for shear buckling in the webs. Another valuable lesson was that there may be some designs that are theoretically better than others, but in a real-life build, material constraints, cost and safety have to be considered. Although the theories and calculations were correct in principle, this project introduced a whole new dimension, that being construction. Any mistake in the building process could result in premature failure and as such, drawings, cuts, folds and attatchements had to be performed with extreme care. As well, this assignment helped introduce the team to keeping workspaces safe, clean and efficient. All in all, this project went beyond theory and introduced the team to the more practical and uncertain side of engineering. This assignment also furthered the team's knowledge of CIV102 concepts.

References

[1] CIV102. *CIV102-2025F-BDP-Handout-v2*. EN. (Visited on 11/23/2025).

[2] *Pyplot tutorial — Matplotlib 3.10.7 documentation*. URL: https://matplotlib.org/stable/tutorials/pyplot.html (visited on 11/23/2025).