CIV102 Matboard Bridge Design Project

Jessica Fu, Heidi Ma, Sara Parvaresh Rizi

1 Introduction

Our bridge is a small-scale box girder bridge made to resist Load Case 1 and as much of Load Case 2 as possible, as specified in the CIV course project PDF [5]. After multiple iterations and edits to Design 0, the predicted failure load of the bridge was calculated to be approximately 556 Newtons. It spans a total length of 1250 mm, requiring a total area of 609 x 10^3 mm^2 of matboard. Some key decisions that were made include: altering the dimensions of Design 0 to withstand each load case (such as flange width, height, and thickness of the bottom), increasing the amount of diaphragms all across the length, altering the cross-sections at each end of the bridge, adding equally spaced glue tabs to support the new cross-sections at the end, and adding splice connections.

2 Major Design Iterations

The final design of our bridge was decided through multiple iterations of Design 0 for Load Case 1. Starting from the initial hand calculations for Design 0's cross-section, the dimensions were changed to account for which sections needed improvement, depending on which forces were the largest at each section, such as maximum bending moments or shear forces. The factors of safety (FOS) of the results of each iteration were compared, and the components were changed to optimize the FOS for every fail case. Matlab was used for this process to decrease the amount of hand calculations. Note that in every Figure marked with an asterisk (*), the FOSs' are in the order of $FOS_{tension}$, $FOS_{compression}$, FOS_{shear}, FOS_{glue}, FOS_{flex_buck1}, FOS_{flex_buck2}, FOS_{flex_buck3}, and FOS_{shear_buck}.

2.1 Cross-section B Placed in the Middle

Cross-section B (see Figure 10) was originally built for the middle of the bridge, and it began by trying to optimize the dimensions of Design 0. Matlab was used to calculate the initial FOS, which was determined to be too small and would buckle due to shear buckling Case 1 under Load Case 1 (see Figure 1*). After iterating through multiple steps, we changed the bottom thickness (see Figure 2*), flange width (see Figure 3*), height (see Figure 4*), added diaphragms (see Figure 5*), and the cross-sections at the ends to help support more shear force at the end (see section 2.2). This gave a final minimum FOS of 1.5370 (see Figure 5*). These iterations are explained in more detail below. The glue tabs remained 5 mm for every bridge component, including diaphragms, webs, and diaphragm supports. As these FOS allowed the bridge to support much more than Load Case 1, the bridge was built based on these initial calculations.

The following Figures showcase the iterations we went through for each change in dimension, followed by an explanation of why those iterations were done.

```
All_FOS =

    4.2141    0.9973    1.5756    7.1851    0.6533    2.4990    4.7008    2.0706
```

Figure 1*: Factors of Safety for the original cross-section, based on Design 0.

```
All_FOS =

    5.3880    0.8522    2.1117    6.1196    0.5583    2.1354    2.6668    2.7751
```

Figure 2*: Factors of Safety after double thickness was applied to the bottom of the beam.

After the iteration in Figure 2*, the thickness at the bottom of the cross-section was doubled to ensure the different FOSs were more even, which would take unnecessary strength away from some parts of the bridge, as well as to increase y_{bot} for the ratio of y_{top}:y_{bottom} to be closer to 1:5. This is because the ratio that was given for the yield strengths for matboard in tension and compression was 30MPa and 6MPa respectively, which shows a compression to tension ratio of 1:5. Therefore, we chose to apply a double thickness to the bottom of the bridge.

```
All_FOS =

    4.2583    1.0607    1.5832    6.9502    0.6948    1.3560    5.2987    2.0806
```

Figure 3*: Factors of Safety after the top flange was changed to 110 mm.

After the iteration in Figure 3*, we noticed that increasing the width of the flange increases y_{top} because it increases the height of the centroidal axis from the base of the bridge, which was also done to bring the y_{top}:y_{bottom} closer to 1:5. As shown, though the FOS for some of the larger values decrease, the FOS's for the lowest values increase, which is what dictates the failure of the bridge. Therefore, we made the flange width to be 110 mm.

```
All_FOS =

    7.0087    1.5370    2.0716   10.0184    3.5399    1.9650    3.8405    1.5963
```

Figure 4*: Factors of Safety after the height was decreased to 60 mm.

The iteration in Figure 4* shows the FOSs after the height was 60 mm. The height of the bridge was decreased to 60 mm to conserve the matboard and glue, thus reducing the weight of the bridge, while still satisfying the requirement that the height be a multiple of 20 mm. As shown, though some of the values decrease, the lowest FOS, which is what dictates the failure of the bridge, increases. Therefore, we made the height of the bridge 60 mm.

```
All_FOS =

    7.0087    1.5370    2.0716   10.0184    3.5399    1.9650    3.8405    1.8647
```

Figure 5*: Factors of Safety after diaphragms were added at 100 mm, 220 mm, 420 mm, 620 mm, 780 mm, 980 mm, and 1140 mm along the bridge.

The iteration shown in Figure 5* shows the FOS after Design 0's diaphragm spacings of 400 mm were changed, where the maximum distance between diaphragms in our design was 200 mm.

This was done not only to increase the FOS for shear buckling as well as ensure the bridge remained rigid under loading as a rigid cross-section was assumed in the calculations, which will be discussed further in section 3.1.

At this stage, the iterations above were done with the idea that the calculations in Matlab were correct and that we were optimizing the bridge based on how large our minimum FOS value was. With this in mind, we finished building the bridge and had exhausted all our materials. However, after building, a mistake was found regarding the centroid calculation of a cross-section within the code (see Figure 6). The error happened because one of the areas wasn't correctly computed in the cross-section calculation, which gave a bigger moment of inertia than expected, which caused subsequent errors in other calculations. After correcting this mistake, as shown in Figure 7, it was found that the FOS for the bridge was much lower than the one we used to build the bridge and would not be able to support Load Case 1. As seen in Figure 8*, the lowest FOS was 0.5575 for Case 1 thin plate buckling, with another low FOS of 0.8511 for compression.

```
ybarB = (A1B*y1botB + 2*A2B*y2botB + 2*A3B*y3botB + A4B*y4botB)/(A1B+2*A2B+2*A3B+A4B);% ybar. location of centroidal axis from the bottom
```

Figure 6: The issue with the original Matlab code, regarding the centroidal axis location of cross-section B.

```
ybarB = (A1B*y1topB + 2*A2B*y2topB + 2*A3B*y3topB + A4B*y4topB + A5B*y5topB + A5B*y6topB)/(A1B+2*A2B+2*A3B+A4B+2*A5B)
```

Figure 7: The corrected version of the Matlab code from Figure 6.

	1	2	3	4	5	6	7	8
1	5.2005	0.8511	2.1319	4.8215	0.5575	1.0880	4.4736	5.9342

Figure 8*: Factors of Safety of cross-section B after the correction to the code, shown in Figure 7.

With these new FOS values, we realized that we had to increase the second moment of inertia (I) at the middle of the bridge to increase the FOS for compression, as stated by the formula:

$$FOS_{flexbuck1} = \frac{\sigma_{buck1}}{\sigma_{top}} \text{ where } \sigma_{buck1} = \frac{4\pi^2 E}{12(1-\upsilon^2)}\left(\frac{t}{b}\right)^2 \text{ and } \sigma_{top} = \frac{My_{top}}{I}.$$

It can be seen that σ_{buck1} depends on the thickness and width, which are difficult to change as our bridge has already been built and sealed. Thus, we decided to lower σ_{top}, by increasing the second moment of inertia (I) as the max moment and the y_{top} value were already set.

Since we had already optimized the materials for the bridge design using the previous code, we had no glue left, making it difficult to change the internal cross-section. Therefore, we decided to increase the second moment of inertia by adding a layer on the outside of our web. We decided on bending the top and bottom of leftover pieces of matboard and inserting them into gaps that we had on the top and bottom from the glue. See Figure 9 for a scaled-down version of the external piece. The height (labelled "b" in Figure 9) was made to be 57.46 mm. The bent sides (labelled "a" in Figure 9) of the external pieces were made to be 40 mm so that, when inserted, they served as a double layer for both the top and bottom of the bridge. This way, the second moment of inertia could be increased without using glue. Two pieces were inserted in the middle of both sides in between the diaphragms so that the cross-section of B was changed into the design shown in Figure 11. The implementation of these new pieces is shown on the real bridge in Figures 12 and 13.

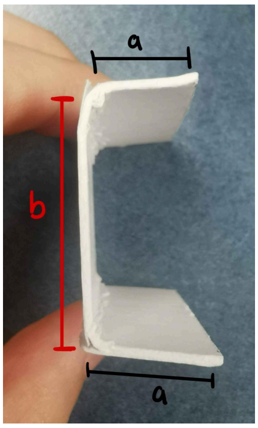

Figure 9: A prototype of the inserted piece for the web. The two bent pieces will be inserted into the bridge and will act as an additional layer for the web and the top and bottom flanges. The height (b) was made to be 57.46 mm and the length of the bent sides (a) was made to be 40 mm each.

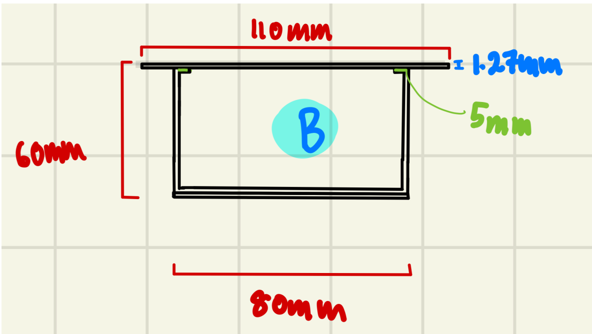

Figure 10: Cross-section B.

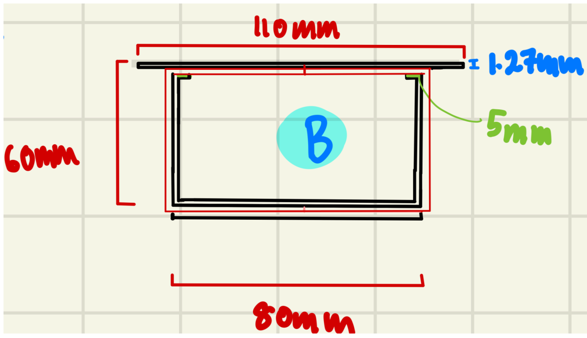

Figure 11: Cross-section of new design with the added pieces indicated in red.

Figure 12: Side view of the added piece onto the bridge.

Figure 13: Front view of the added piece onto the bridge

After making this change, our new FOSs' are much higher, especially for Case 1 thin plate buckling, which increased from 0.5575 to 1.2927, with the updated FOS values shown in Figure 14*.

```
All_FOSbridge = 1x8
       6.9973    1.3920    2.0516    2.0431    1.2927    2.4222    9.8886    5.7107
```

Figure 14*: New FOS for Load Case 1 after the additional pieces (shown in Figures 12 and 13) were added.

This allowed for the final failure load to be approximately 556 Newtons. We acknowledge that this is possibly lower than what we could have optimized the bridge for, however, we could have done much else with our remaining materials and the bridge that had already been built.

2.2 Cross-section A and Cross-section C Placed at the Ends

The cross-sections at the ends were modified by adding two additional webs to cross-section B's design ((see Figures 15 and 16). This was due to the shear being the highest at the end, meaning it had to be more reinforced to resist failing due to shear. The additional webs were implemented 225 mm from each end of the beam and spaced 75 mm from each other. The webs were implemented closer to the ends of the bridge, at up to 225 mm from each end of the bridge, because maximum shear forces occurred at the location of the supports. The dimensions of the web-spacing, 75 mm, are the same size as the train wheels, to prevent the train from sinking into the bridge, and for the bridge to be reinforced the most where the point loads are the heaviest. Furthermore, adding the extra vertical supports helped increase the second moment of inertia (I), which led to lower FOSs since this allowed both the compressive and tensile stress to be lower.

Glue tabs (77.5 mm x 10 mm from a bird's-eye-view of the bridge) were placed sparsely within the 225 mm range in which cross-sections A and C appeared, and they occurred at 75mm and 150mm from the edge of the bridge respectively. They are shown in the pink section drawn in Figure 15. These were placed to hold the webs securely in place and to ensure the webs do not slip.

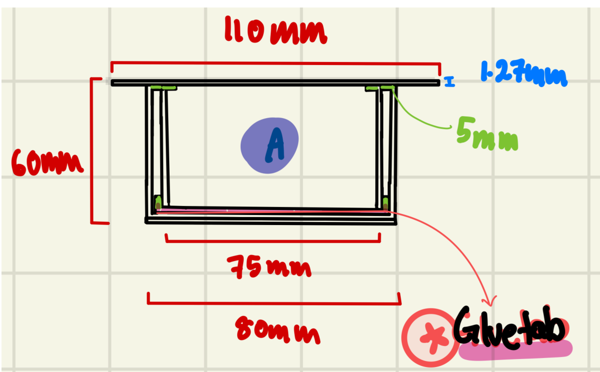

Figure 15: Diagram illustrating cross-section A made to resist high shear forces, placed 225 mm

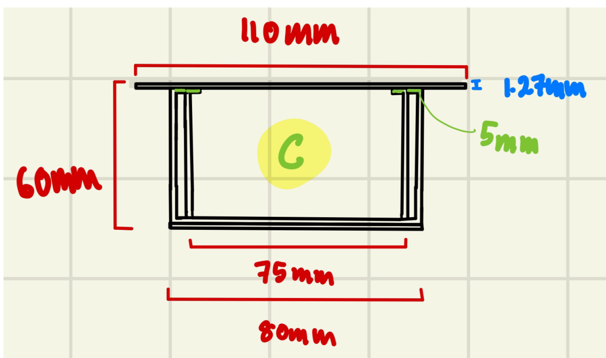

Figure 16: Diagram illustrating cross-section C used for the remaining sections of the beam in the

from either end of the bridge. A glue tab (pink) was placed between the interior webs to secure them.	225 mm section from the ends, wherever the glue tab was not present for these cross-sections.

The FOS values for cross-section A are shown in Figure 17* and for cross-section C in Figure 18*. These values show that the lowest FOS per cross-section is 2.0431 and 1.2927 respectively, for Load Case 1, meaning the bridge is able to withstand the loading well.

```
All_FOS = 1x8
     26.7521     3.2740     2.0516     2.0431     8.5791     4.1856    14.0002     5.7107
```

Figure 17*: The resulting FOSs' for a bridge made of cross-section A for Load Case 1.

```
All_FOS = 1x8
     13.3325     1.9733     3.7775     9.4600     1.2927     2.5228     9.8886    10.5149
```

Figure 18*: Figure 17: The resulting FOSs' for a bridge made of cross-section C for Load Case 1.

3 Additional Design Considerations

3.1 Diaphragms, Locations, and Types

For additional support, seven diaphragms were added at 100mm, 220mm, 420mm, 620mm, 780mm, 980mm, and 1140 mm along the bridge. Diaphragms were added near the ends of the bridge to account for placing the bridge on the supports, and the pressure that would be on the ends at those locations. To ensure the diaphragms stay at a 90-degree angle to the base of the bridge, and thus able to resist any vertical compressive forces, the sides of the diaphragms were glued to the webs of the bridge. Additionally, pieces of matboard were glued to the diaphragms in a triangle formation on either end of the diaphragms located in the middle of the bridge (see Figures 19a and 19b). Although normally, the glue would have been presumably enough, the triangle supports were still added in case the glue was not strong enough to resist the diaphragm slipping or in case the diaphragm buckles. This similar concept was used for vertical diaphragms throughout the rest of the bridge to ensure the bridge remains rigid under loading and that the surface does not buckle into the hollow cross-section of the bridge.

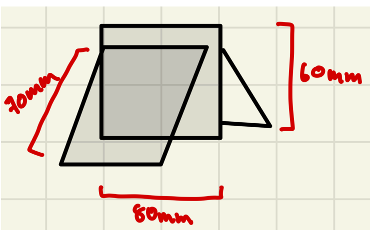	

Figure 19a: Diagram illustrating a model of the triangle supports on either side of the diaphragms.	Figure 19b: Photo of the bridge, showing the triangle supports on either end of each diaphragm (circled in red).

3.2 Splice Connections

Since the total length of the matboard was shorter than the minimum required length of the beam, a splice connection was needed to connect the pieces. We wanted to limit the number of splices across the bridge, as they cause weaker points. The bending moment is highest in the middle of the beam, at 600 mm, the shear force is the highest at the ends, and the cross-section at the ends continues until 225 mm from the ends of the beam. Therefore, we chose the ideal location to be 450 mm from one end of the beam, so it wasn't too close to the middle, or the ends. This meant we cut two pieces of 450 mm x 80 mm and 800 mm x 80 mm pieces for the bottom of the bridge. The pieces were overlapped, as shown in Figure 20, where the bottom length was cut into 80 mm x 800 mm and 80 mm x 450 mm pieces, so the longer bottom section was used to join the web splice because it could cover past the cut.

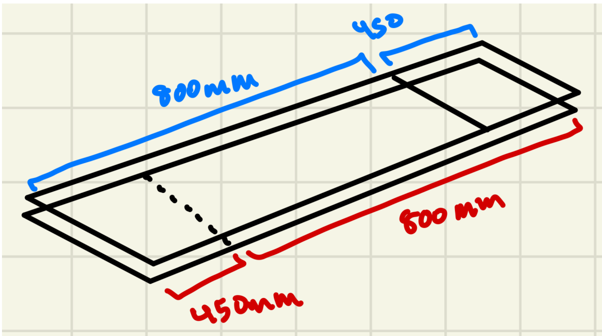

Figure 20: Diagram indicating how the cuts were made on the matboard with the blue indicating the cut location on the layer above and the red indicating the cut location on the bottom-most layer.

On the inside and outside of the web where the splices were connected, a piece of rectangular matboard was glued on both sides to hold it together. The rectangle on the outside aimed to cover most of the area around the splice to prevent slippage. Under the top flange, a rectangular, 55 mm x 107 mm matboard was used to join the two pieces, so the flange would not cave inward at that splice.

Since there is little to no research on splice connections with matboard, splice connections with steel were researched instead because steel and matboard have similar properties, like higher tensile and lower compressive capabilities, and are usable in the same way, unlike concrete, which is poured into a mold. Thus, the most commonly used splice connection design, the web-flange splice, was used (see Figure 21) [4]. As the bridge is a "small scale box girder bridge", the box girder splice design in the *Steel Bridge Design Handbook* was used, with the screw areas replaced with contact cement, and the steel replaced with matboard [2]. Since this design has been seen and proven to work in various box girder splice connections, it was chosen and used in our design. This design allows for the two sides of the bridge to be connected along the side and the bottom, with the bottom already accounted for by the double thickness.

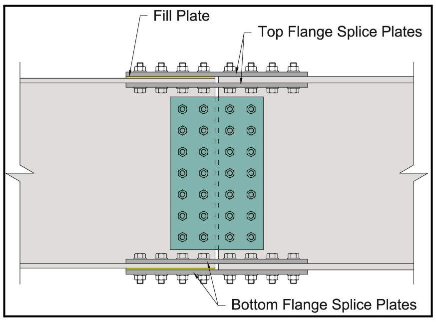

Figure 21: Diagram of a web-flange splice on a steel splice connection point [4].

4 Sources

[1] American Institute of Steel Construction. (n.d.). Steel Bridge Design Handbook. https://www.aisc.org/globalassets/nsba/design-resources/steel-bridge-design-handbook/b914_sbdh_chapter14.pdf

[2] Kulak, G., & Green, D. (n.d.). *Design of Connectors in Web-Flange Beam or Girder Splices*. View of design of connectors in web-flange beam or girder splices. https://ej.aisc.org/index.php/engj/article/view/549/548

[3] Michigan Department of Transportation. (n.d.). *Measuring the effect and value of intermediate diaphragms on ...* Research Administration. https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Programs/Research-Administration/Research-Spotlights/SPR-1702-Spotlight.pdf

[4] National Steel Bridge Alliance. (2024, March). https://www.aisc.org/nsba/design-resources/nsba-splice/

[5] Bentz, E. (2024). *CIV102 Matboard Bridge Design Project*