CIV102 Bridge Project

Introduction

The report aims to describe the iterations that led to our final design of the box girder bridge. Our major iterations included changing web height, glue tab width, diaphragm spacing and optimising location of cross sections A and B. We also experimented with diverging from the Design 0 outline to removing the bottom flange. The final design had a non-uniform cross-section with cross-section A spanning from 380 mm to 820 mm of the bridge, and cross section B spanning from 0.00mm to 380 mm and from 820 mm to 1260 mm. The cross section dimensions are specified in Figure 1. The theoretical minimum FoS was 3.32, where the bridge would fail due to compression with a load of 1328 N.

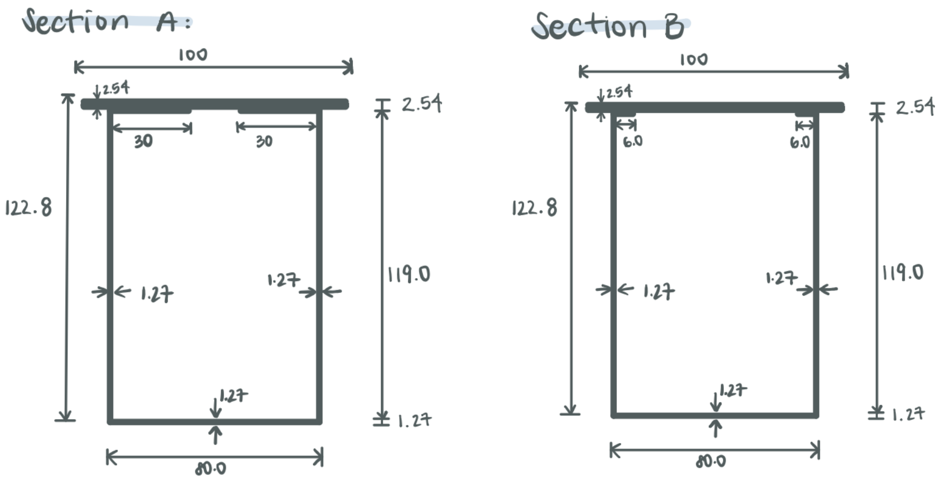

Figure 1: Cross-section dimensions for Section A and Section B

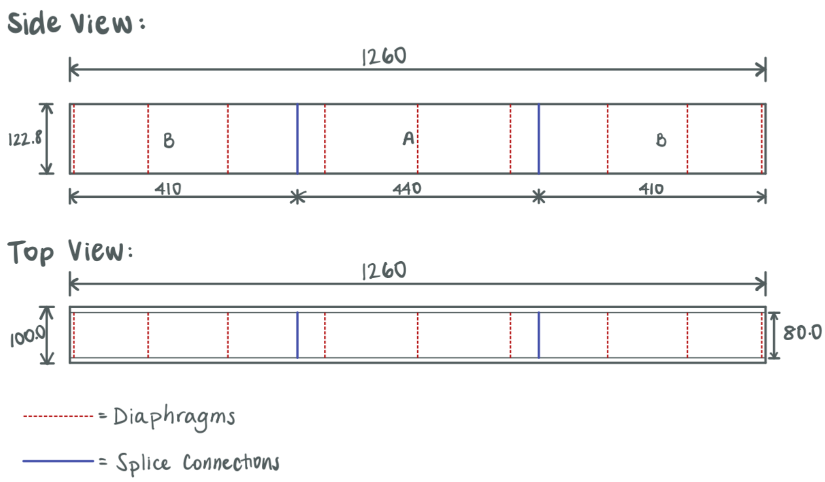

Figure 2: Side view and top view of the bridge, indicating locations of Section A and Section B, splice connections and diaphragm spacing

Major Design Iterations

Our iterations started with altering the cross-sectional properties of the given Design 0 to find a compromise between increasing Factor of Safety (FoS) and minimising area of the Matboard used. While iterating, our major design changes included changing the height of the box-girder, increasing the length of the glue tabs, altering diaphragm spacing, experimenting with a bottomless cross section and non-uniform cross-sections. The main FoS failures were associated with tensile failure, compressive failure and shear buckling.

1. **Altering height**

Design 0 had a minimum FoS of 0.617, which led to bucking failure in case 1. (add equation) To increase the FoS in this case, the thickness of the top flange was doubled from 1.270 mm to 2.54 mm to increase the value of t, resulting in an increased buckling stress. This creates a greater stress and subsequently a greater FoS of 3.97, making the minimum FoS to be compressive stress at 1.671 (see screenshot from code below).

Section	Width	Height
Bottom flange	80.0	1.270
Side webs	1.270	73.7
glue tabs	5.00	1.270
Top flange	100.0	2.54

```
Min_FOS = 1.6714
Max_load = 668.5497
y = 49.5402
I = 5.4165e+05
min_FOS_tens = 4.7233
min_FOS_comp = 1.6714
min_FOS_shear = 2.7010
min_FOS_glue = 6.2085
min_FOS_buck1 = 3.9744
min_FOS_buck2 = 23.1425
min_FOS_buck3 = 12.9299
min_FOS_buckV = 4.2143
```

Iteration 1: Increasing thickness of the top flange

The next iteration focuses on decreasing the compressive stress. σ_{top} = My / I, so decreasing this would mean decreasing y_{top} (i.e increasing y-bar) and increasing the second moment of inertia, I. After iterating through different thicknesses of the top flange, we noticed how increasing the thickness of the top flange increased the minimum FoS compression from 1.038 (Design 0) to 1.671 (iteration 1). This supported our intuition to raise the y-bar, and led us to conclude that continuing to make the cross section taller would improve the FoS of compression. We increased the height of the webs from 73.7 mm to 85.0 mm, leading to a higher FoS of compression at 1.950.

Section	Width	Height
Bottom flange	80.0	1.270
Side webs	1.270	85.0
glue tabs	5.00	1.270
Top flange	100.0	2.54

```
percent_used = 78.0602
Min_FOS = 1.9549
Max_load = 781.9792
y = 56.2088
I = 7.3767e+05
min_FOS_tens = 5.6694
min_FOS_comp = 1.9549
min_FOS_shear = 3.0763
min_FOS_glue = 7.2135
min_FOS_buck1 = 4.6488
min_FOS_buck2 = 27.0690
min_FOS_buck3 = 11.0077
min_FOS_buckV = 2.9471
```

Iteration 2: Increasing height of webs

Considering that only 78.1% of the total matboard area was used, we decided to increase the web height further to 120.0 mm for a higher y-bar value, thus lowering y_{top} and compressive stress. This led to a higher FoS compression of 2.89, with 92.0% of the area used.

Section	Width	Height
Bottom flange	80	1.270
Side webs	1.270	120.0
glue tabs	5.00	1.270
Top flange	100.0	2.54

```
percent_used = 91.9830
Min_FOS = 2.1427
Max_load = 857.0755
y = 76.3584
I = 1.5845e+06
min_FOS_tens = 8.9642
min_FOS_comp = 2.8850
min_FOS_shear = 4.2170
min_FOS_glue = 10.5120
min_FOS_buck1 = 6.8604
min_FOS_buck2 = 39.9471
min_FOS_buck3 = 7.4770
min_FOS_buckV = 2.1427
```

Iteration 3: Further increasing height of webs to 120.0 mm

Increasing the height further would compromise the matboard area, so we decided to find other ways to improve FoS compression rather than continuing the increase of web height.

2. Bottomless-cross section

Compressive stress was our most significant problem throughout the design process. Therefore, we tried to optimise the y-bar to the point where the compressive stress on the top was proportional to the tensile stress on the bottom. Matboard has a 5:1 ratio of tensile stress capacity to compressive stress capacity, so the optimal y-bar for pure flexural stress would theoretically be ⅚ of the height.

After maximising the web heights, we experimented taking out the bottom piece from the box girder, aiming to shift the area distribution upwards. This bottom piece that was taken out could be attached to the top flange, allowing a higher top flange thickness than before without a significant compromise in matboard area usage.

The next iteration removed the bottom flange and increased the thickness of the top flange from 2.54 mm to 3.81 mm. The results reflected more efficient area usage and a higher FoS compression at 3.07.

Section	Width	Height
Bottom flange	0	0
Side webs	1.27	120.0
glue tabs	5	1.270
Top flange	100	2.54

```
percentage_used = 83.9181
y_bar = 95.5615
Tot_I = 1.0502e+06
Min_FOS = 3.0738
Max_load = 1.2295e+03
FOS_tens = 4.7474
FOS_comp = 3.0738
FOS_shear = 3.5798
FOS_glue = 7.7681
FOS_buck1 = 16.4461
FOS_buck2 = 95.7629
FOS_buck3 = 22.2818
```

Iteration 4: Removing bottom flange, increasing height of the top flange

While this seemed like an optimal design in theory, we decided to first continue iterating on Design 0 to match this level of minimum FoS due to concerns about the bridge standing on its own. Additionally, it was difficult to account for case 4 shear buckling due to a free edge at the bottom of the web, which was not covered by the k = 5 case.

3. Altering glue-tab length

Next, we experimented with increasing the length of the glue tabs. This would improve glue failure and also increase the y-bar value, increasing the FoS compression. While iterating, we were conscious of the construction process, we knew the glue tabs would be difficult to bend and glue on if they were only 5.00 mm short. Increasing the glue tab widths would be less area intensive than adding another layer to the top flange, while still providing additional support against glue failure. Therefore, we increased the glue tab width from 5.00 mm to 10.00 mm, which increased the FoS compression from 2.89 (iteration 3) to 2.98 (iteration 5).

Section	Width	Height
Bottom flange	80.0	1.270
Side webs	1.270	120.0
glue tabs	10.00	1.270
Top flange	100.0	2.54

```
percent_used = 93.5088
Min_FOS = 2.1411
Max_load = 856.4257
y = 77.1783
I = 1.6089e+06
min_FOS_tens = 9.0058
min_FOS_comp = 2.9810
min_FOS_shear = 4.2138
min_FOS_glue = 21.7341
min_FOS_buck1 = 7.0887
min_FOS_buck2 = 41.2764
min_FOS_buck3 = 8.0076
min_FOS_buckV = 2.1411
```

Iteration 5: Increasing glue tab width

With 93.5% of the area used, we decided to continue iterating in this direction by increasing the glue tab lengths to 20.0 mm, which successfully increased the FoS compression to 3.17.

Section	Width	Height
Bottom flange	80.0	1.270
Side webs	1.270	120.0
glue tabs	20.0	1.270
Top flange	100.0	2.54

```
percent_used = 94.5744
Min_FOS = 2.1411
Max_load = 856.4257
y = 78.7304
I = 1.6552e+06
min_FOS_tens = 9.0820
min_FOS_comp = 3.1723
min_FOS_shear = 4.2138
min_FOS_glue = 21.7341
min_FOS_buck1 = 7.5436
min_FOS_buck2 = 43.9251
min_FOS_buck3 = 9.1359
min_FOS_buckV = 2.1411
```

Iteration 6: Further increasing glue tab width

However, in this case the bridge would fail due to shear buckling in case 4, with a minimum FoS of 2.14, indicating that we needed to decrease diaphragm spacing and increase the number of diaphragms.

4. Diaphragm spacing

The next iteration decreased diaphragm spacing from 400 mm to 140.0 mm. This increased the number of diaphragms to 9 diaphragms. We came up with this number by trying out different diameter spacing values like 210, 200, 160, etc., and we chose the final number such that the number of diaphragms would be a whole number, to give us a realistic value for FoS shear buckling. This successfully increased the FoS shear buckling to 3.44, making the FoS compression to be our minimum FoS at 3.17.

Section	**Width**	**Height**
Bottom flange	80.0	1.270
Side webs	1.270	120.0
glue tabs	20.0	1.270
Top flange	100.0	2.54

```
percent_used = 94.5744
Min_FOS = 3.1723
Max_load = 1.2689e+03
y = 78.7304
I = 1.6552e+06
min_FOS_tens = 9.0820
min_FOS_comp = 3.1723
min_FOS_shear = 4.2138
min_FOS_glue = 21.7341
min_FOS_buck1 = 7.5436
min_FOS_buck2 = 43.9251
min_FOS_buck3 = 9.1359
min_FOS_buckV = 3.4445
```

Iteration 7: Increasing diaphragm spacing from 400 mm to 140.0 mm

The increase in area using 9 diaphragms was accounted for in the code previously. We decided to space the diaphragm starting from the end of the bridge, as maximum shear occurs when the train is at the -52.0 mm location at the end of the bridge. Our focus continued on increasing FoS compression.

5. Non-uniform cross sections

Increasing the width of the glue tabs would continue to increase the FoS compression. However, it would compromise the area of the matboard used. To optimise this, we analysed the maximum moment locations and created a non-uniform cross-section. Section A refers to the section in the middle, while Section B refers to the two sections on the sides (see Figure 2).

The maximum bending moment occurred near the middle (at 644 mm from the edge of the bridge), therefore, we decided to increase the compressive capacity of Section A, while compromising the strength of Section B. We found that the shear force was not governing in any of the iterations with this method, and therefore focused on the compressive stress. The strategy we used to optimise was setting the load in Matlab to the current design maximum load, and attempting to trace the compressive stress capacity lines optimally around the bending envelope on the graph, updating the max load every time. We lengthened and shortened glue tabs to optimise compressive strength as described earlier. We aimed to stay below 95% of the matboard used in the design to allow for splice connections and fitting the designed pieces on the board. Below (iteration 8) demonstrates the product of this process.

<table>
<tr><th>Bridge Section</th><th>Section</th><th>Width</th><th>Height</th><th>Length</th><td rowspan="3"><pre>percent_used = 94.8457
Min_FOS = 3.3530
Max_load = 1.3412e+03
y = 80.1753
I = 1.6983e+06
min_FOS_tens = 9.1504
min_FOS_comp = 3.3530
min_FOS_shear = 4.2164
min_FOS_glue = 12.6996
min_FOS_buck1 = 7.9733
min_FOS_buck2 = 46.4274
min_FOS_buck3 = 8.7529
min_FOS_buckV = 3.4466</pre></td></tr>
<tr><td>A</td><td>Glue tabs</td><td>30.0</td><td>1.270</td><td>440</td></tr>
<tr><td>B</td><td>Glue tabs</td><td>6.00</td><td>1.270</td><td>380</td></tr>
</table>

Iteration 8: Modifying glue tabs with other sections constant from Iteration 7.

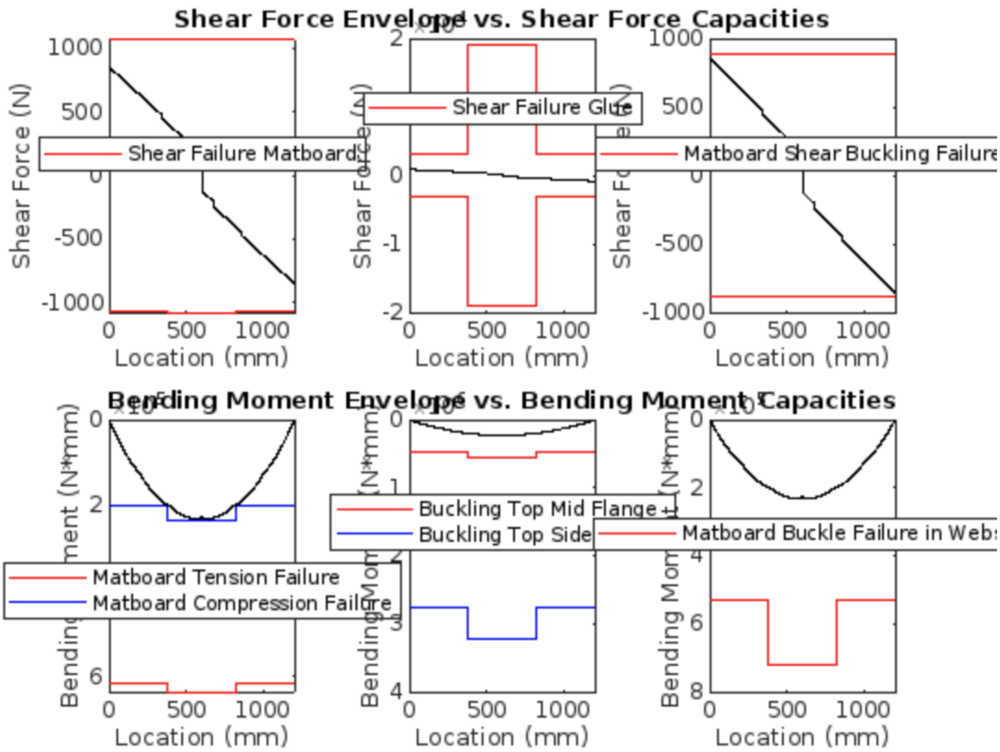

Figure 3: Bending Moment and Shear Force Diagrams with Variable Cross Sections and Maximum Load (1341 N)

The bridge still fails due compressive stress, however, the Matboard Compression Failure line hugs the bending moment envelope, as opposed to being a straight line, reallocating material to where it is needed.

6. Final design

Finally, the two layers of the top flange were constructed by attaching three separate pieces of matboard together. We decided against having splices at locations of the highest bending moment near the middle to avoid failure. To avoid having all the three splice connections (two top layers and the Sections A and B) at the same location, the lengths of the top pieces were chosen to not align with the change in the three cross-sections. We offset the splicing of the two top layers to avoid buckling at one splice location. The lengths in the top layer of the top flange were cut to be 390mm, 390mm, 480mm and the final lengths in the bottom layer of the top flange are 405mm, 405mm, and 450mm.

The web length of both cross-sections was decreased by 1 mm to fit the pieces on the matboard and account for sufficiently large pieces to be used for splices (Figure 5). This slightly decreased the minimum FoS to 3.21. Below are the final dimensions and data shown in Iteration 9, the final graphs shown in Figure 4 and the matboard cut out in Figure 5.

<table>
<tr><th>Bridge Section</th><th>Section</th><th>Width</th><th>Height</th><th>Length</th><td rowspan="9">percent_used = 94.4479
Min_FOS = 3.3209
Max_load = 1.3284e+03
y = 79.5851
I = 1.6665e+06
min_FOS_tens = 9.0457
min_FOS_comp = 3.3209
min_FOS_shear = 4.1843
min_FOS_glue = 12.5812
min_FOS_buck1 = 7.8970
min_FOS_buck2 = 45.9827
min_FOS_buck3 = 8.8345
min_FOS_buckV = 3.4527</td></tr>
<tr><td rowspan="4">A</td><td>Bottom flange</td><td>80.0</td><td>1.270</td><td rowspan="4">440</td></tr>
<tr><td>Side webs</td><td>1.270</td><td>119.0</td></tr>
<tr><td>Glue tabs</td><td>30.0</td><td>1.270</td></tr>
<tr><td>Top flange</td><td>100.0</td><td>2.54</td></tr>
<tr><td rowspan="4">B</td><td>Glue tabs</td><td>6.00</td><td>1.270</td><td rowspan="4">820 (split into two parts)</td></tr>
<tr><td>Side webs</td><td>1.270</td><td>119.0</td></tr>
<tr><td>Glue tabs</td><td>6.0</td><td>1.270</td></tr>
<tr><td>Top flange</td><td>100.0</td><td>2.54</td></tr>
</table>

Iteration 9: Final parameters of bridge with decreased web length

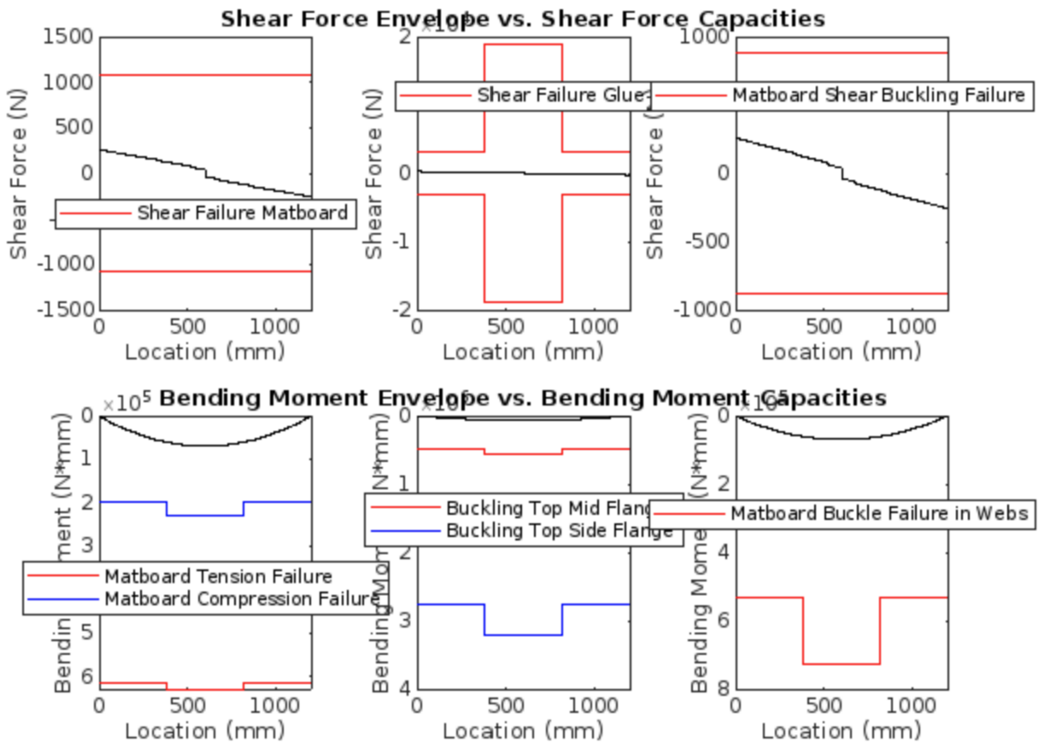

Figure 4: Final Graphs with updated web length (119 mm) and 400 N applied

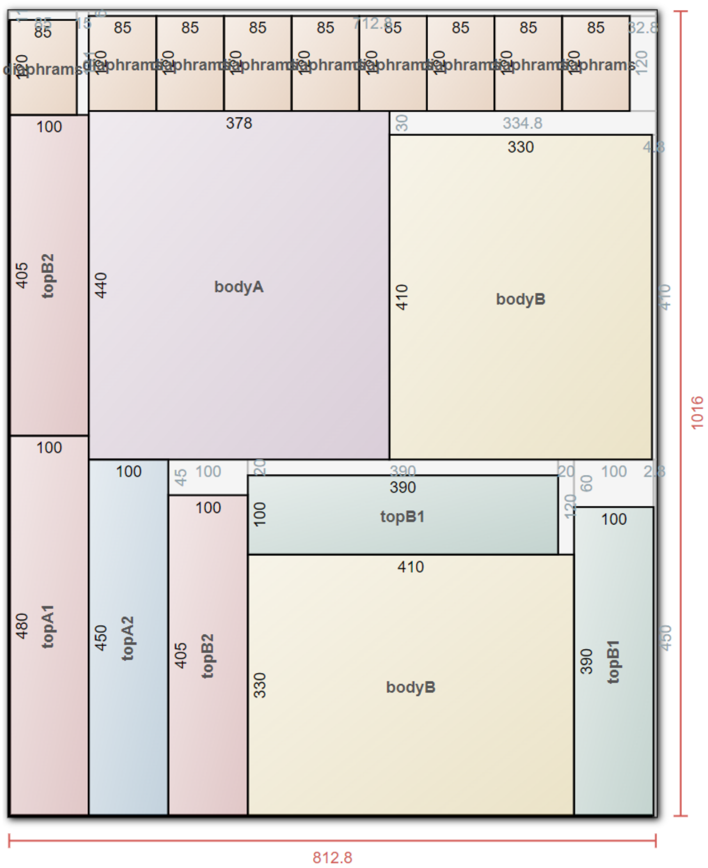

Figure 5: Final cutout plan for matboard