CIV102 Bridge Design Report

Introduction:

The purpose of this design report is to propose an optimum design for a box girder bridge that maximizes the failure load. After assessing and analyzing the governing failures for a preliminary Design (Design 0), 3 different design iterations were considered to select the optimum design for the bridge construction. These design iterations were proposed by varying the geometric parameters and the cross-sectional properties while adhering to the material and feasibility constraints. FOS outputs from the python script for each design iterations are attached in the Appendix of this report. Eight different failing mechanisms were considered which include Matboard tension and compression, mid-flange, side-flange and web buckling, Matboard shear at the centroidal axis, at the webs and the glue shear. The optimum design was selected based on the highest factor of safety (FOS) across the eight failing mechanisms.

Initial Design Consideration: Design 0

Initially Design 0 was assessed to examine the different failure mechanisms. Using the hand calculations and calculations made using the python script 8 different failure mechanisms were determined (refer to calculations package). This helped us to make necessary amendments and modifications to geometric parameters to conclude our final design choice.

Table 1 Failure Mechanisms and FOS for Design 0 (in Project Handout)

Failure Mechanism	**FOS** (Quoted according to slide-rule precision)
Matboard tension	4.36
Matboard compression	1.038
Matboard mid-flange buckling	0.617
Matboard side-flange buckling	3.59
Matboard web buckling	5.29
Matboard shear at the centroidal axis	2.86
Matboard shear buckling at the webs	3.76
Glue shear	10.06
Governing failure: Matboard mid-flange bucking	0.617
Failure load: 239 N	

Evaluation of the Failure Mechanisms for Design 0:

As shown in the chart above (Table 1.1), the governing failure of Design 0 is the Matboard Mid-flange Buckling Failure. The highest FOS's are associated with Matboard shear buckling at the webs and matboard shear failure in the centroidal axis. Additionally the top flange of the design is also very close to failing due to Matboard compression, having an FOS of 1.038. As such, bridge dimensions should be optimized such that the FOS against mid-flange buckling and Matboard compression is larger.

Potential Geometric Parameter Modification(s):

- Number of top flanges
- Variation of the number of top flanges with the distance along the bridge
- Number of web members
- Height of the web members

Zone consideration(s):

- The maximum bending moment occurs in the center of the bridge. This creates larger flexural stresses, requiring a higher second moment of area (I) to decrease the failure load.
- The shear force is the greatest at the ends of the bridge, which causes higher shear stresses. As such, more diaphragms should be added near the ends to prevent shear thin plate buckling.

Parameters to Optimize: Height of web members, *h*, Number of top flanges, *n*, Number of layers of web members, *w*.

Design Iterations:

2.1 Design 1:

Failure Load: 648 N

Modification(s): Design 1 was adapted from Design 0 by adding two additional top flanges to increase the FOS for the Matboard compression occurring in the Top flange. This will mitigate the failure caused by Matboard compression and mid-flange buckling observed in Design 0.

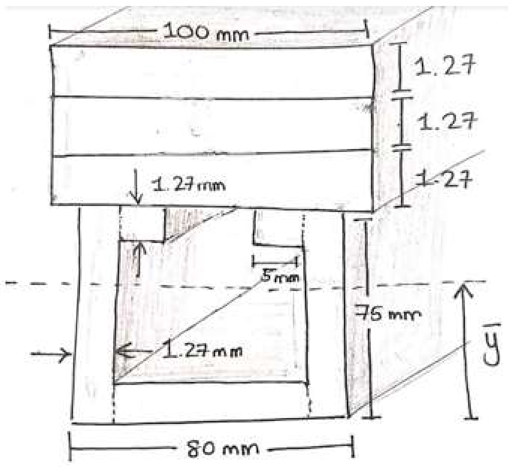


Figure 2.1.1 Design 1 Cross-sectional view with dimensions (Not drawn to scale)

Justification:
To increase the FOS against matboard compression failure, $\frac{y_{top}}{I}$ needs to be decreased. Therefore, y_{top} needs to decrease and I need to increase. To increase I, the height of the web members can be increased. However, this will decrease the FOS against web member buckling.

To increase the FOS against mid flange buckling, either the thickness of the top flange can be increased or the base of the flange can be reduced. Decreasing the base of the flange decreases the second moment of area of the cross section, which increases the flexural stress.

Increasing the thickness of the top flange increases both FOS's, as it increases I and raises the centroidal axis. Therefore, more top flanges will be used in our final design if material constraints permit.

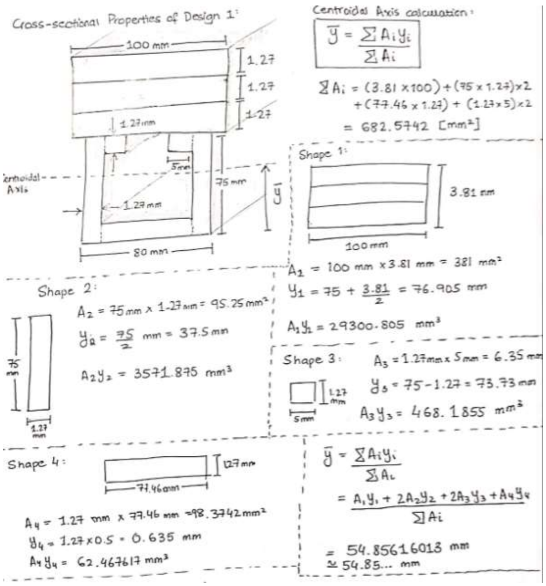
FOS (see appendix)

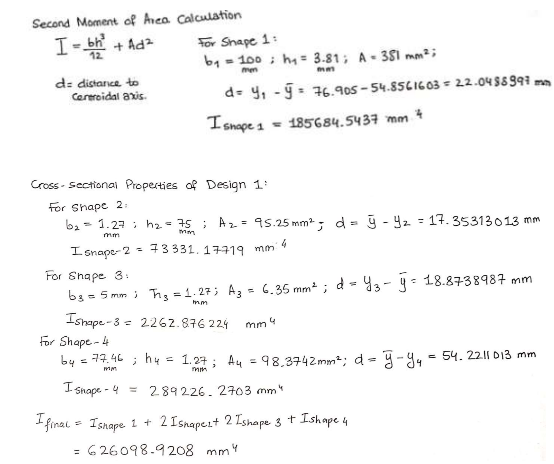
As shown in the code output attached in the appendix, the minimum FOS of this design is 1.62 and the governing failure is buckling due to compression. The highest FOS, which is against side-flange buckling, is 50.5- 31.2 times the minimum FOS. This demonstrates that material used in the side flange is a waste of material and should be used in other sections.

Figure 2.1.2: Optimizing the FOS due to tension/compression by varying the Top Flanges using the Python Script

```python
def tens_comp_FOS(n, h, start, end):
    ''' Take in n, the number of top flanges and h, the height of web members,
    and computes the tensile and compressive FOS
    Designs where the tensile and compressive FOS's are similar are preferred
    '''
    M = max(create_V_M_envelopes()[1][start:end + 1])
    print(M)
    for i in range(1, n):
        print(n)
        dim = [[100, 1.27*i, h+1.27*(1+i/2)], [2.54, h, 1.27+h/2], [10, 1.27, h+1.27/2],\
        [80, 1.27, 1.27/2]]
        yb = centroidal(dim)
        y_tot = 1.27 * (i + 1) + 75
        I = I_calculator(dim, yb)
        print(I)
        tens_stress = flexural(M, (yb), I)
        FOS = FOS_calculator(tens_stress, 30)
        print("tensile FOS:", FOS)
        comp_stress = flexural(M, (y_tot - yb), I)
        FOS = FOS_calculator(comp_stress, 6)
        print("compressive FOS:", FOS)
```

Figure 2.1.3: Hand Calculations for Centroidal Axis and Second Moment of Area (Design 1)





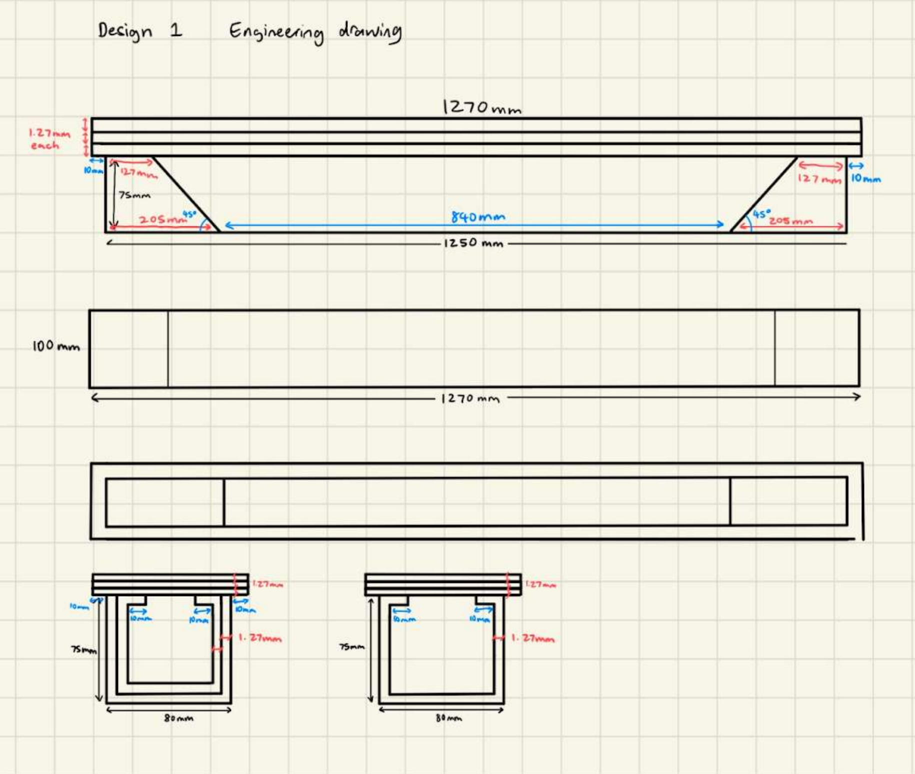
ȳ = 54. 85 mm y_top = 23.96 mm

I = 626096.9208 mm^4

As clearly observed in the calculations above the new y_top has decreased to 23.96 mm from being 34.84 in Design 0 while increasing I to 626096 mm^4.

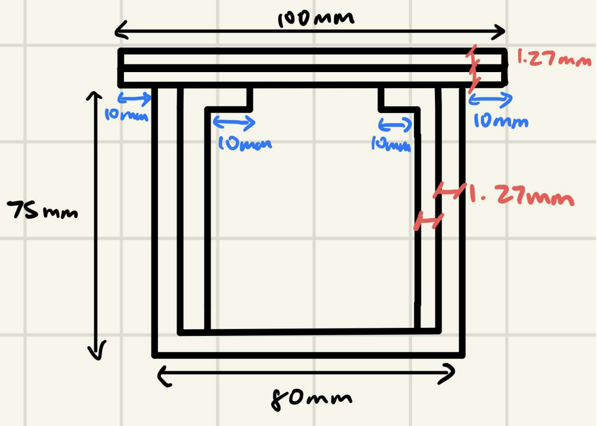
Disadvantage of this Design: This design does not effectively utilize the full matboard material, essentially the height of the cross section of the area can be increased even more with the given material constraint which can effectively increase the second moment of area.

<u>Figure 2.1.4:</u> Engineering Drawing of Design 1



<u>2.2 Design 2</u>

<u>Figure 2.2.1:</u> Cross section of Design 2 (Elevation View Same as Design 0)

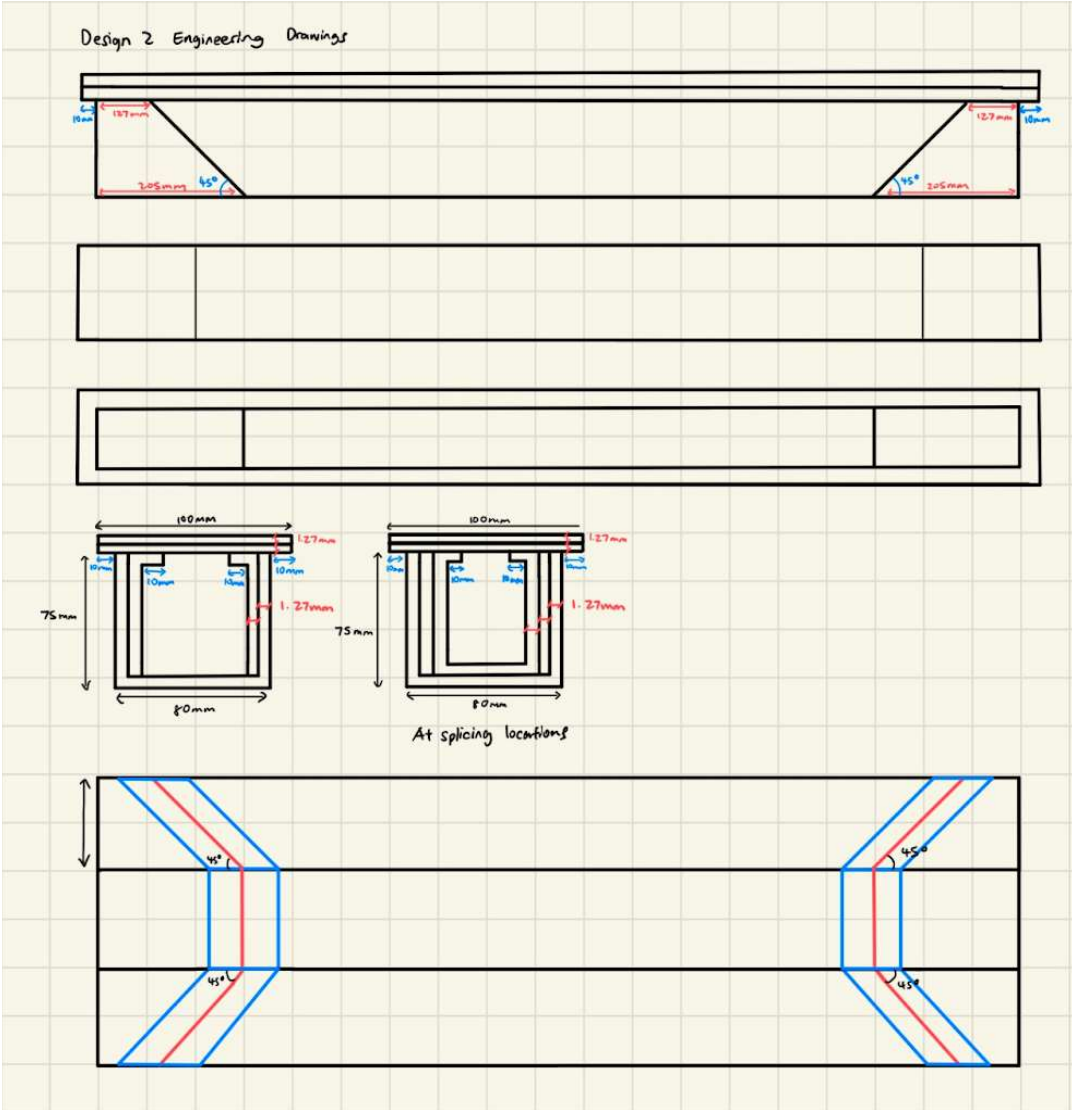


<u>Failure Load: 800 N</u>

<u>Modification(s)</u>: Design 2 is an adaptation of design 0, by adding an additional layer to top flange and an additional layer to both side web members. The additional layer of top flange will raise the centroidal axis higher and also increase the second moment of area(I). The height of the web members is kept the same as increasing the layer of web members would take up a significant amount of matboard. Additionally, in order to maintain a bridge length of at least 1250 mm, only three diaphragms can be added.

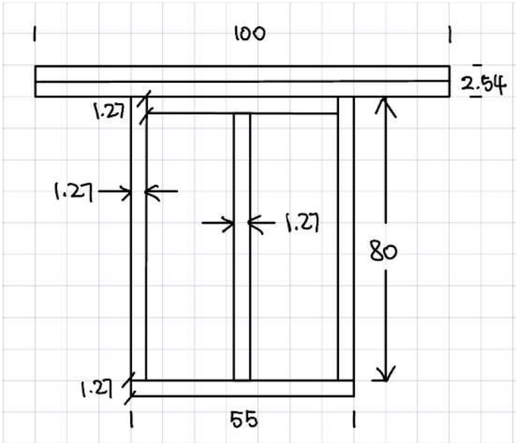
FOS and Disadvantage: The minimum FOS (refer to appendix) of this design is 2.00 and the governing failure is matboard shear failure. This is due to the large *b* value caused by the double walls. Therefore, in subsequent designs, only one layer of web members will be used on each side.

Figure 2.2.2: Engineering Drawings of Design 2



2.3 Design 3

Figure 2.3.1: Cross section of Design 3 (the elevation view is the same as that of designs 1 and 2)



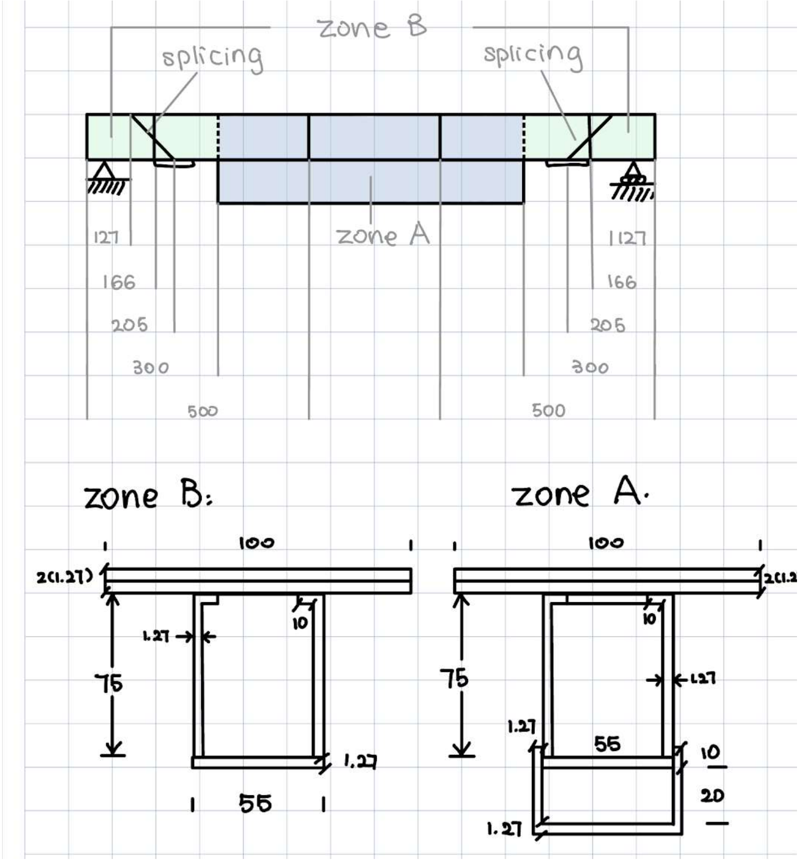
Failure load: 868 N

Modification(s): This design has a bottom flange narrower than the one presented in design 0 with a center support. The width of the bottom flange is equivalent to the wheel spacing (55 mm) of the train to allow direct support to the weight of the live load (i.e. train). The elevation view is identical to that of designs 1 and 2, with taller web members.

Disadvantages and FOS of Design 2.3 (refer to Appendix for Code Outputs): While the train is moving along the box girder bridge, it may not necessarily be aligned with the center of the bridge which means that there will be a greater shear stress on the side flanges if the wheels are not directly at web members. Since side members already have a small *k* value, this design would not be as effective because it would cause the side flange to buckle. Moreover, the minimum FOS of this design is 2.17 (see Appendix), which is not significantly greater than the other designs. However, the existence of the vertical support in the center presents a construction challenge when installing the diaphragms, potentially lowering the shear buckling FOS (which is the third lowest in this design). Therefore, it is not an ideal design due to the feasibility constraint for construction.

Design 2.4

Figure 2.4.1: Engineering drawings of Design 4



Modification(s):

Design 4 is an adaptation of design 0, where there is an additional cross section portion added to the bottom of the middle zone (zone A) of the bridge. This additional partition would increase the FOS against buckling due to compression, as the cross section is taller. The width of the bottom flange is also narrower, and there is an added layer of top flange.

Disadvantages

This design was not a good potential design because it consumed too much matboard area and did not adhere to the material constraints. As such, this design was immediately eliminated because it was not feasible to construct a box girder with insufficient material. Hence, we didn't calculate the FOS for this design as we knew it wasn't feasible. The additional set of web members and bottom flange were added to increase the height of the cross section and increase the second moment of area of the cross-section. However, this also lowered the centroidal axis and increased y_{top} which means that the matboard failure due to compression is high.

Final Design Choice (in reference to our design iterations)

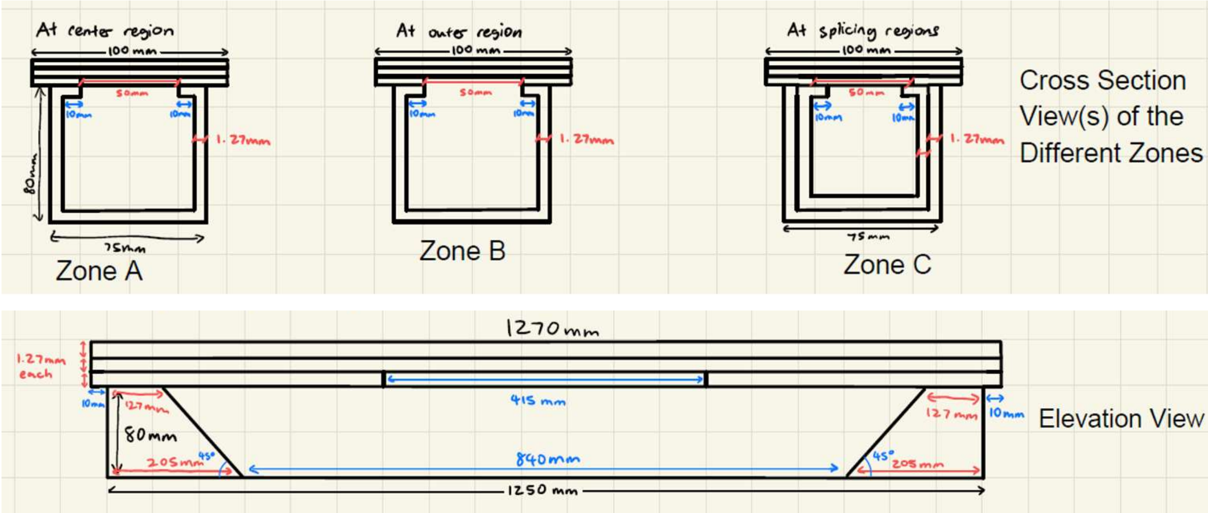


Figure 3(a) and (b) Final Design Cross-Section and Elevation View

Building off design 0 as an adaptation into our final design choice iteration, we made several main changes. The first change is that we decided to add more layers to the top flange in order to reduce mid-flange buckling, because the governing failure of design 0 is buckling in the top flange. Second, due to limited matboard material, we only added a full third layer to the center portion of the top flange. The center portion was chosen because the bending moment, and thus compressive stress, is the greatest in that region. Third, we increased the height of the web members while keeping material constraints and the effects on shear and web member buckling in mind. This increases the second moment of area (I). Finally, we added more diaphragms in order to increase the FOS against shear thin plate buckling. We also optimized the placement and spacing of the diaphragms to increase the minimum FOS. We did this by first looking at the shear force diagram and inputting test values for the spacing, then adjusting the input spacing to improve the minimum FOS.

Design 1 was also our next most feasible design. However, assuming that we use the same number of diaphragms, our final design performs better than design 1 in terms of buckling due to compression because it has a greater I value. Although design 1 would have a higher FOS for mid flange buckling due to a thicker mid flange, the FOS for mid flange buckling is 14.1 for our final design, which is still far from the governing failure.

Table 2 - Minimum FOS for Final Design

Minimum FOS (Quoted according to Slide-rule)	**Zone A**	**Zone B**
Matboard Failure Due to Compression	2.31	2.26
Matboard Failure Due to Tension	5.14	5.76
Glue Shear Failure	38.9	16.15
Matboard Shear Failure	6.33	3.08
Mid-flange Buckling	14.10	6.12
Side-flange Buckling	19.09	18.64
Web-Buckling	24.9	19.73
Shear Buckling	7.40	3.78

** Exact values with more significant figures can be found in the Python Script Code Output attached in the appendices

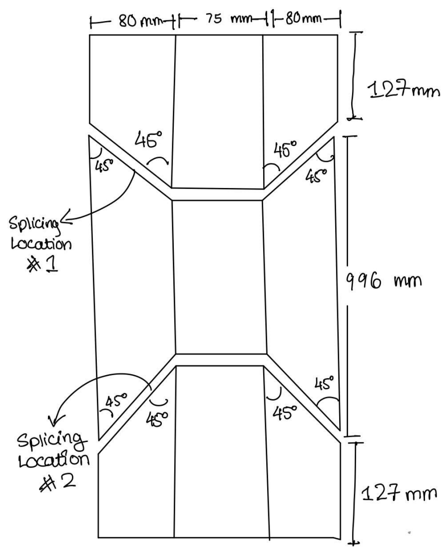
<u>Minimum FOS:</u> 2.26
<u>Governing Failure:</u> Matboard Failure due to Compression in Zone B
<u>Predicted Failure Load:</u> 904 N

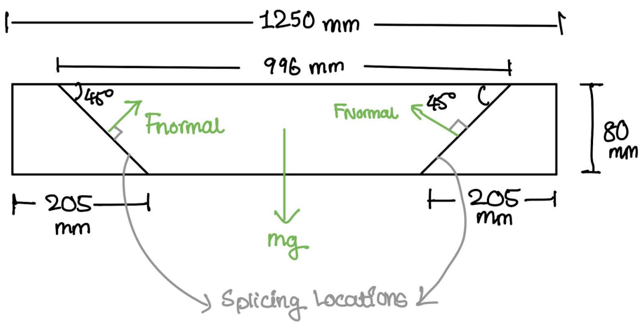
<u>Reflection on the Predicted Failure Load for our final design:</u>

According to our calculations the predicted failure load for this box girder bridge is 900 N. However we expect that this bridge will have a failure load around 688 N. This difference in our personal prediction and calculated value is because there were many assumptions that were neglected within the calculations. Firstly the assumption that the cross-section remains rigid during loading does not hold true and there may be out-of-plane deformations and warping of the cross-section throughout the duration of the loading. Secondly, glue was not uniformly applied at all locations and there might have been sections that were missed during the gluing process and this may decrease the value b in $\tau_{xy} = \frac{VQ}{Ib}$ and increase the shear stress. Furthermore, at the splicing locations the shear and flexural stresses are only resisted by the glue. Since glue has a shear stress capacity of 2 MPa (half of that of matboard), the predicted FOS against shear failure at the splice locations is expected to be 1.721 at the splicing location (see calculations at the end of source code). This allows us to estimate the real failure load will be around 688 N. Additionally since the areas near the support are subjected to vertical compression, the calculated FOS for areas near the support is not precise. Ultimately these calculations will not accurately reflect the actual failure load and hence our estimated failure load is lower than this calculated failure load.

<u>Additional Design Decisions/Considerations:</u>

- <u>Splicing:</u>
  Two diagonal splicing were added at each end of the bridge to reach the required minimum length of 1250 mm. The diagonals were configured at an angle of 45 degrees (refer to figure 4.1). Diagonal splicings were chosen because they would be able to better support and resist gravity (refer to figure 4.2). Essentially at the spliced location, the diagonal splicing will exert an equal and opposite force (according Newton's third law) to resist the self-weight and the weight of the live load (i.e. train).

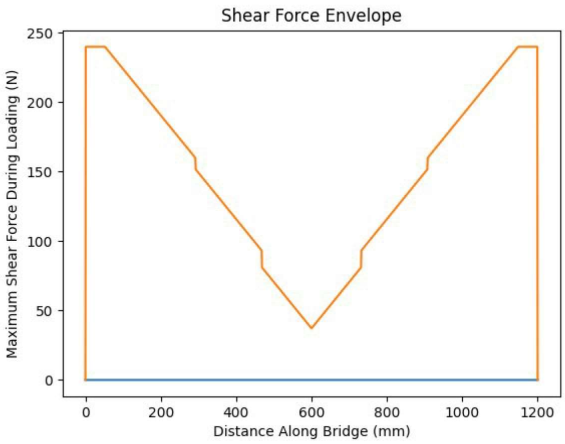




<u>Figure 4.2</u> Free Body Diagram of the forces acting on the spliced locations (Elevation View of the Bridge)

- <u>Diaphragm locations:</u>

By looking at the shear force diagram below, we see that the graph on average linearly decreases on both sides as it goes towards the middle of the bridge. The first pair of diaphragms go on the very ends of the bridge, because we see that the shear forces are greatest at the end locations. The second pair of diaphragms are placed at 205mm in from both ends of the bridge, which is where the splicing occurs. This location is chosen in order to further support the splicing locations. The third pair of diaphragms is decided from repeated calculations of the minimum FOS against shear buckling on the bridge. This was done by obtaining the maximum shear forces between the diaphragms using the shear force envelope, calculating the shear buckling capacity with the determined spacings, and adjusting the spacings by small increments until they are optimized.



<u>Figure 4.3:</u> Shear Force Envelope Diagram of Final Design

Construction Procedure

This section is the documentation that outlines our construction process of our box girder bridge. All figures have been annotated.

First, we started off by mapping out and finding an efficient way to draw the dimensions of the pieces that need to be cut out on the matboard, in order to maximize efficient use of the material given. We used our pre calculated dimensions and a ruler. In the figures below, you can see us measuring our dimensions and drawing with a pencil.

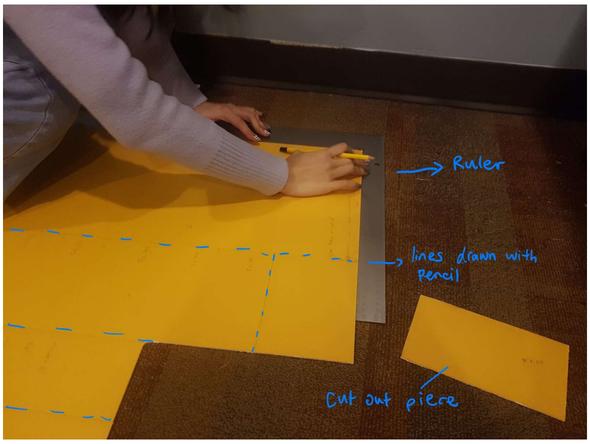


Figure C.1: Drawing out where to cut

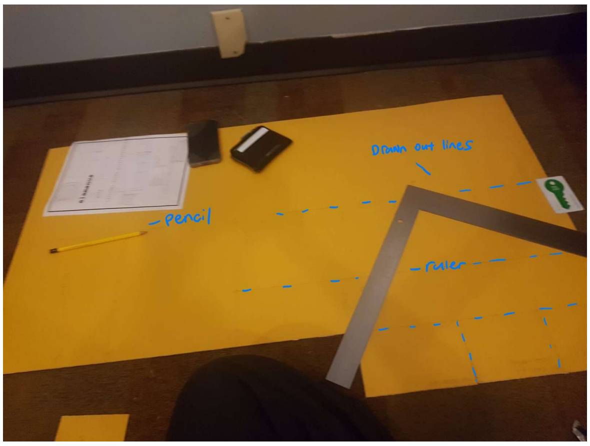


Figure C.2: Matboard with completed cutting guidelines

Next, we used a ruler and an exacto knife to cut out the pieces along the lines we drew. In the figure below are some of the pieces right after we cut them out.

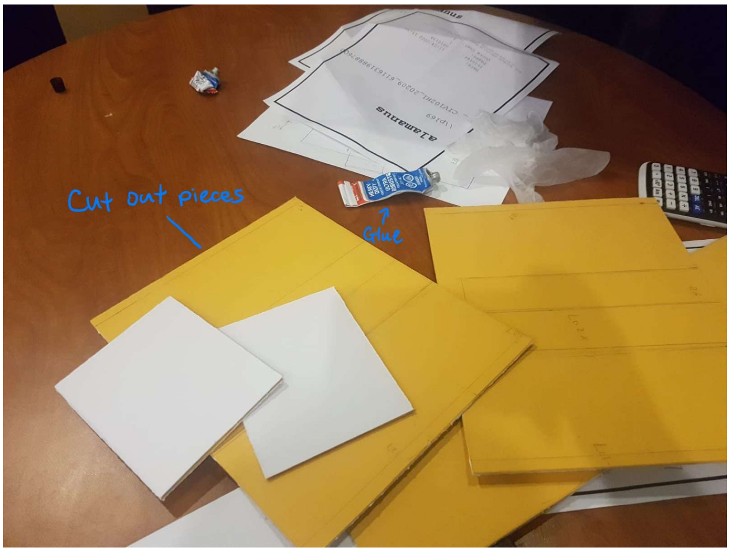


Figure C.3: Cut mat board pieces

Then, we folded some pieces along measured lines that we drew. This included the bottom flange and web members which are a connected piece of matboard that we folded into 3 sections. The outer section of the splicing, diaphragms, and all glue tabs were also folded along drawn lines. We used the straight edge of the ruler to help us fold each section. In the figure below, we are folding the bottom flange and web members piece, and folding the diaphragm glue tabs.

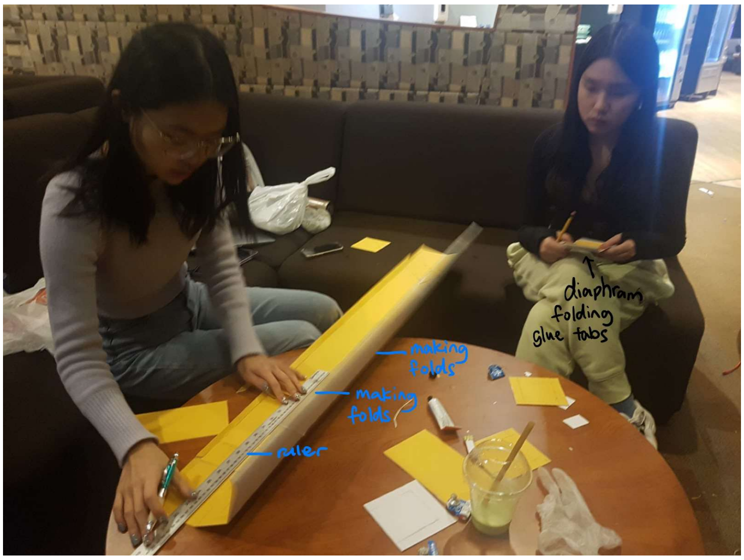


Figure C.4: Folding mat board pieces

Next we began to apply the cement glue to pieces that were confirmed to be the correct dimensions, and that we knew belonged together. We applied glue to several pieces at once to decrease the waiting time of 15 mins that each piece needs. Here in the figure below, we glued on the third center layer of the top flange, and some layers on the sides.

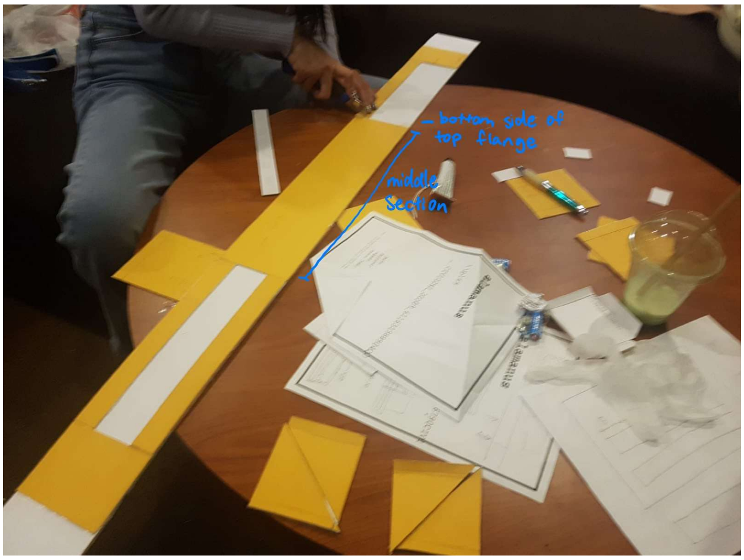


Figure C.5: Gluing layer of the top flange together

Before gluing the other pieces together, we had to modify some of the pieces to better fit together. There was some misalignment due to human cutting and precision errors. We recut some pieces slightly with the exacto knife so that they would correctly align with other pieces.

Before gluing on our outer splicing pieces, we had to recut some of the diagonals. After this was done, we applied glue to all the pieces involved in the splicing and splicing reinforcement at the same time. After 15 mins, we glued together the splicing cut.

For most of our 6 diaphragms, we had to recut and modify each piece and their glue tabs, to properly fit where they would be glued to the flanges and web members, once again due to some human errors.

After this was done, we applied due to the top glue tab of the diaphragm, and glued the diaphragm directly to the top flange along the locations of where we calculated the diaphragms should go in order to maximize FOS.

After the cement glue dried, we began attaching the top flange with the diaphragm to the bottom flange and web members matboard piece. This matboard piece was connected and folded into 3 parts, with glue tabs on the sides. We applied glue to the first side glue tab, and the corresponding side web member, and glued those together. Then we proceeded to do the same with the bottom glue tab, and bottom flange. Finally, we glued together the remaining side glue tabs, and side web member. As seen in the figure below, we are gluing the flanges and web members to the inner diaphragm glue tabs.

Figure C.6: Diaphragms are glued to the top flange

Figure C.7: Gluing the diaphragms, flanges, and web members together

Finally, with all the parts and pieces glued together, we use some of the remaining scrap pieces of matboard to further reinforce the bridge at the splicing locations where there is a cut. We glued scrap pieces to the outer seams of the splicing. Then to allow the bridge to cure properly, we used clamps at locations of diaphragms to insure the pisces were tightly bound together. In the figure below is our final bridge construction curing with the clamps in place.

Figure C.8: Gluing all the final web flanges, members, and reinforcements together.

Figure C.9: Completed bridge with clamps to allow the glue to cure properly

Appendix (Code Outputs for Design 1, 2, 3 and Final)

Design 1 FOS

```
compressive stress capacity: 6
maximum compressive stress: 3.7007027000043253
minimum FOS against compression failure: 1.621313703473934

tensile stress capacity: 30
maximum tensile stress: 6.6013501676725435
minimum FOS against tension failure: 4.544524868096367

glue shear stress capacity: 2
maximum shear stress at glue location: 0.16280415737964463
minimum FOS against glue shear failure: 12.284698573981622

matboard shear stress capacity: 4
maximum shear stress in matboard: 0.7869427516873547
minimum FOS against matboard shear failure: 5.08296186911086
```

```
mid-flange buckling capacity: 32.102340541312245
maximum shear stress in the mid-flange: 0.7869427516873547
minimum FOS against mid flange buckling: 8.67466077220273

mid-flange buckling capacity: 186.9266188825997
maximum shear stress in the mid-flange: 0.7869427516873547
minimum FOS against side flange buckling: 50.51111478973473

mid-flange buckling capacity: 41.37923424591888
maximum shear stress in the mid-flange: 0.7869427516873547
minimum FOS against web buckling: 11.181453253694364

shear buckling capacity: 5.256619850378164
maximum shear stress: 0.7869427516873547
minimum FOS against shear buckling: 6.67979956497086
```

Design 2 FOS

```
compressive stress capacity: 6
maximum compressive stress: 2.011725728753402
minimum FOS against compression failure: 2.9825139253540276

tensile stress capacity: 30
maximum tensile stress: 6.013268113964851
minimum FOS against tension failure: 4.988967634809066

glue shear stress capacity: 2
maximum shear stress at glue location: 0.1464549341345452
minimum FOS against glue shear failure: 13.65607797250887

matboard shear stress capacity: 4
maximum shear stress in matboard: 2.0035222671759976
minimum FOS against matboard shear failure: 1.996483925101604
```

```
mid-flange buckling capacity: 14.73939633241101
maximum shear stress in the mid-flange: 2.0035222671759976
minimum FOS against mid flange buckling: 7.3267424687879865

mid-flange buckling capacity: 73.98024901921309
maximum shear stress in the mid-flange: 2.0035222671759976
minimum FOS against side flange buckling: 36.77452048349361

mid-flange buckling capacity: 401.89756640336043
maximum shear stress in the mid-flange: 2.0035222671759976
minimum FOS against web buckling: 199.77751472731958

shear buckling capacity: 5.256619850378164
maximum shear stress: 2.0035222671759976
minimum FOS against shear buckling: 2.623689257912501
```

Design 3 FOS

```
compressive stress capacity: 6
maximum compressive stress: 2.7664252207443334
minimum FOS against compression failure: 2.168863974709442

tensile stress capacity: 30
maximum tensile stress: 5.353991906350539
minimum FOS against tension failure: 5.6032957323704675

glue shear stress capacity: 2
maximum shear stress at glue location: 0.3732080237971905
minimum FOS against glue shear failure: 5.358941588798327

matboard shear stress capacity: 4
maximum shear stress in matboard: 1.2698250843077286
minimum FOS against matboard shear failure: 3.1500401507509066
```

```
mid-flange buckling capacity: 68.92607038177799
maximum shear stress in the mid-flange: 1.2698250843077286
minimum FOS against mid flange buckling: 24.915211828220958

mid-flange buckling capacity: 17.555961236260305
maximum shear stress in the mid-flange: 1.2698250843077286
minimum FOS against side flange buckling: 6.346081977786736

mid-flange buckling capacity: 49.013833747152226
maximum shear stress in the mid-flange: 1.2698250843077286
minimum FOS against web buckling: 17.71738971276606

shear buckling capacity: 4.560325097592219
maximum shear stress: 1.2698250843077286
minimum FOS against shear buckling: 3.5913017894731345
```

Final Design (Minimum FOS)

Zone A FOS

```
minimum FOS against compression failure: 2.311011590535187
minimum FOS against tension failure: 5.144043861603292
minimum FOS against glue shear failure: 38.98903408157252
minimum FOS against matboard shear failure: 6.333651899405308
minimum FOS against mid flange buckling: 14.098717409130842
minimum FOS against side flange buckling: 19.087392918252025
minimum FOS against web buckling: 24.916300794908594
minimum FOS against shear buckling: 7.397553131559167
```

Zone B FOS

```
minimum FOS against compression failure: 2.2563694325073067
minimum FOS against tension failure: 5.7571337130824976
minimum FOS against glue shear failure: 16.149708700110235
minimum FOS against matboard shear failure: 3.0837848442928477
minimum FOS against mid flange buckling: 6.117939410854254
minimum FOS against side flange buckling: 18.63608564465335
minimum FOS against web buckling: 19.728760810404186
minimum FOS against shear buckling: 3.7782871909208633
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