CIV102 Matboard Bridge Design Project

1. Project Introduction

In groups of three or four, you will apply the concepts taught in CIV102 to design and build a small-scale box girder bridge out of matboard that will be subjected to increasing loads until failure. You will be challenged in your ability to design a bridge that can handle the highest loading possible and to be accurate in your estimation of the final failure load.

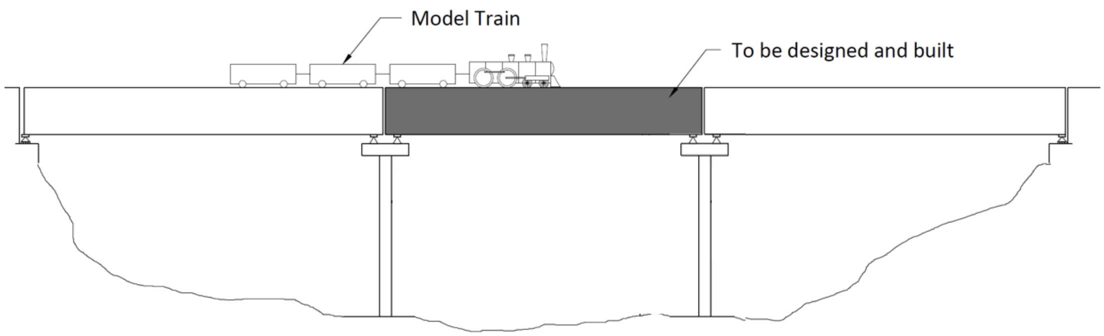


Figure 1. Three span bridge supporting the passage of a 400 N train. Teams must design the middle span.

1.1. Overview

The Matboard Bridge Design and Construction Project has four components:

- Report
  - Describes decisions made during design and construction and documents overall process
- Supporting Calculations
  - Calculations that describe the predicted performance of the Bridge while subjected to the specified loading conditions
- Engineering Drawings
  - Drawings showing both how the Bridge was built, and its final intended geometry
- Bridge built from specified materials
  - Bridge built by your team with the primary objective of permitting passage of the heaviest train.

1.2. Primary Objectives

- Design and build a bridge which can support a 400 N train across a span of 1200 mm
- Design and build the strongest bridge possible using the permitted construction materials
- Use concepts relating to engineering beam theory and thin-plate buckling theory to predict the maximum load the bridge can carry before failure

1.3. Secondary Objectives

- Articulate design decisions and document construction process in a design report.
- Demonstrate the ability to communicate design using engineering drawings.
- Demonstrate project planning and prototyping skills to successfully build the bridge as designed.

2. Project Design Details

2.1. Bridge Dimensions

Figure 2 provides the distance to be spanned by your bridge, and the maximum permitted dimensions of your bridge.

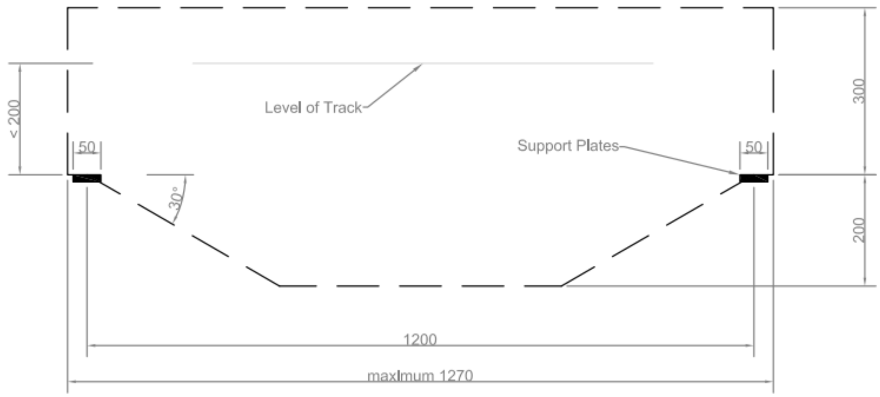


Figure 2. Dimensional constraints of the bridge in elevation.
The dotted line represents the maximum allowed dimensions.

In your analysis, you should assume the distance between the supports is 1200 mm. The actual supports have a width of 50 mm each, and 1200 mm will span the distance between the middle of these supports.

Your bridge must be at least 1250 mm long. If your bridge is less than 1250 mm long, it will not fit in the testing apparatus, meaning your bridge performance will not be able to be evaluated.

In addition to the dimensional constraints shown in Figure 2, the following dimensional requirements must be met:

- The total length of the bridge must be between 1250 and 1270 mm
- The level of the bridge deck (also referred to as the track) must be <200 mm above the level of the supports
- The distance between the level of the bridge deck and the level of the supports must be a multiple of 20 mm (In other words, values of 120 mm, 140 mm, 160 mm are examples of permitted distances, but a distance of 150 mm is not permitted)
- The bridge deck must be at least 100 mm wide
- The bridge deck must be horizontal and permit unhindered passage of the train. There can be no steps or grooves on the top surface for the train wheels to roll over
- There must be a 50 mm long flat portion on both ends of the bridge to allow your bridge to sit on the support plates

2.2. Bridge Loading

A train containing 3 cars will be pushed across your bridge. The dimensions of the train are shown in Figure 3, and a drawing showing the movement of the train is shown in Figure 4.

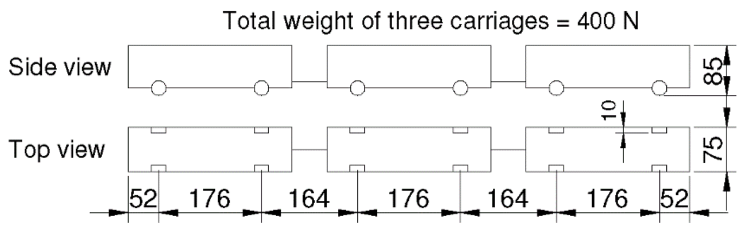


Figure 3. Train dimensions

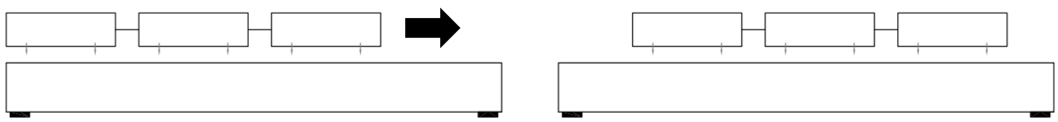


Figure 4. Loading schematic showing the movement of the train

Load Case 1

Initially, the train will not be loaded with any additional weight. This means the total train weight will be 400 N which will be evenly divided across the 6 sets of train wheels.

Load Case 2

If your bridge withstands the loads applied by the first train, the weight of the train will be progressively increased according to Load Case 2.

In Load Case 2, the first or last car is considered the "locomotive," and the other two cars are considered "freight cars." The locomotive weight will be 1.35 times heavier than the freight car weight. For example, if the freight car weight is $133.\overline{3}$ N, then the locomotive weight will be 180 N and the total train weight will be $446.\overline{6}$ N. This train with a total weight of $446.\overline{6}$ N will be considered the "base case" train loading for Load Case 2. Note that the locomotive may be at the front or end of the train, but will never be in the middle of the train.

2.3. Construction Materials

The following materials will be provided to each group:

- One sheet of matboard
  - 32” x 40” x 0.05” with a mass of ≈750 grams.
- Two tubes of contact cement
  - 30 ml, negligible mass when dry
  - **All students MUST review the attached technical data sheet in Appendix III outlining safe use of contact cement**
  - Full strength will only be attained if the contact cement is properly used and left to cure for at least 72 hours

The material properties of the matboard and contact cement are shown in Table 1. For both materials, you are allowed to use different values if obtained through testing.

Students are responsible for safely transporting their project materials/completed bridge to and from their practical. CIV102 teaching staff are not responsible for storage.

The use of any other materials or additional materials is strictly prohibited and will constitute a violation of academic integrity outlined by the University of Toronto.
Prior to testing, your bridge will be weighed. Any excessively large weight will cause your bridge to be inspected and potentially disqualified.

Table 1 – Specified Material Properties

Material	Material Property	Specified Value
Matboard	Specified Dimensions	32” x 40” x 0.05” (813 mm x 1016 mm x 1.27 mm)
	Tensile Strength, σ'_t	30 MPa
	Compressive Strength, σ'_c	6 MPa
	Shear Strength, τ'_m	4 MPa
	Young’s Modulus, E_m	4000 MPa
	Poisson’s Ratio, υ_m	0.2
Contact Cement	Shear Strength, τ'_g	Up to 2 MPa if properly cured**

*** Full strength will only be attained if contact cement is properly used and left to cure for at least 72 hours.*

2.4. Calculation Procedure

Consider the following procedure as a guide for calculations required to predict the failure load of the bridge based on the failure mechanisms discussed in CIV102.

1. Calculate internal **forces**, the Shear Force Diagram ($V(x)$), and the Bending Moment Diagram ($M(x)$), from a train at one fixed location that is loaded according to Load Case 1 or Load Case 2.
2. Consideration must be made to account for the train being at every location along the bridge (since the train will move across the bridge).
   Construct a Shear Force Envelope ($V_{env}(x)$), and a Bending Moment Envelope ($M_{env}(x)$), that reflects the maximum values of V and M at every bridge location considering all possible train locations.
3. Define bridge **geometry (Design Parameters)**:
   a. Define bridge cross-section shape, and parameterize dimensions: widths (b), height (h), thickness (t), ...
   b. Define changes (if any) to cross-sectional dimensions along the length of the bridge

$$Choose\ geometry\ \{b(x), h(x), t(x), \ldots\}$$

4. Calculate cross-sectional **geometric properties**

$$[\bar{y}(x), Q(x), I(x)] = f(geometry)$$

5. Calculate applied **stresses**

$$[\sigma_{top}(x), \sigma_{bot}(x), \tau_{cent}(x), \tau_{glue}(x)] = f\left(V_{env}(x), M_{env}(x), \bar{y}(x), Q(x), I(x)\right)$$

6. Calculate material/thin plate buckling **capacities**

$$\left[\sigma_{tens}(x), \sigma_{comp}(x), \sigma_{buck}(x)\ \tau_{max}(x), \tau_{glue}(x), \tau_{buck}(x)\right] = f(geometry, material\ properties)$$

7. Compare applied stresses vs capacities to determine **Factors of Safety *(FOS)*** against each failure mechanism

$$FOS_{tension}(x) = \sigma_{tens}(x)/\sigma_{bot}(x) \qquad FOS_{shear}(x) = \tau_{max}(x)/\tau_{cent}(x)$$

$$FOS_{compression}(x) = \sigma_{comp}(x)/\sigma_{top}(x) \qquad FOS_{glue}(x) = \tau_{glue}(x)/\tau_{glue}(x)$$

$$FOS_{flex.buck1,2,3}(x) = \sigma_{buck1,2,3}(x)/\sigma_{top}(x) \qquad FOS_{shear.buck}(x) = \tau_{buck}(x)/\tau_{cent}(x)$$

8. Find **minimum FOS**. This value represents "how many" trains would fail the current design
   a. If minimum FOS < 1, the current design will not support the given train
   b. If minimum FOS > 1, the current design will be able to carry a heavier train. Calculate maximum train weight the current design can hold.

9. For visualization, find the Shear Force Capacities, $V_{fail}(x)$, and Bending Moment Capacities, $M_{fail}(x)$

$$M_{fail\_tens}(x) = FOS_{tension}(x) \cdot M(x) \qquad V_{fail\_shear}(x) = FOS_{shear}(x) \cdot V(x)$$

$$M_{fail\_comp}(x) = FOS_{compression}(x) \cdot M(x) \qquad V_{fail\_glue}(x) = FOS_{glue}(x) \cdot V(x)$$

$$M_{fail\_buck1,2,3}(x) = FOS_{flex.buck1,2,3}(x) \cdot M(x) \qquad V_{fail\_buck}(x) = FOS_{shear.buck}(x) \cdot V(x)$$

10. **Repeat from step 2**, choose new geometry, to increase the minimum FOS and the maximum train weight (i.e., failure load)

2.5. Design Procedure

To start the process of iterative design, there must be an initial design chosen either arbitrarily or based on experience. For this project, the initial design (Design 0) has been chosen for you. Details of Design 0 are shown in Appendix II.

For Design 0, first calculate the FOS for Load Case 1 **by hand.** Choose the two locations of the 400 N train (loaded according to Load Case 1) that would generate the largest shear force and largest moment force. Produce the SFD and BMD for each and pick out the V_{max} and M_{max}. Use the V_{max} and M_{max} to calculate the applied stresses. Calculate the capacity of Design 0 in each of the failure mechanisms discussed in CIV102. Use the applied stresses and capacities to determine the FOS in each failure mode, and the overall FOS.

Once these calculations are complete, commence design of your own bridge by changing the geometric parameters (Step 10 in Section 2.4). For every major design iteration, record the:

- **Design decisions** you made
  - Changes to geometric parameters
- **Justification** for each decision made
  - Either from hypothesis or from calculation results
- Results to provide **evidence** for each justification
  - Important output parameters, including but not limited to, the failure load.

At the same time, you will have to balance:

- Material constraints: Available matboard area
- Feasibility constraints: Construction difficulty and how pieces will be cut from matboard areas.

Design decisions can and should be made based on constraints rather than solely based on the project objective.

2.6. Analysis Methods

Analysis of your own bridge design may be performed using one or all the following methods:

1. By Hand
2. Using Microsoft Excel Spreadsheets
   - If this method is selected, the accuracy of the spreadsheet's output must be validated
   - Groups must input the following case into the spreadsheet and submit the output:
     a. The geometry of Design 0
     b. Train loaded to 400 N according to Load Stage 1
   - The output of the spreadsheet should match the hand calculations (which must also be submitted)
3. Using code written in MATLAB or Python
   - If this method is selected, the accuracy of your code must be validated
   - Groups must input the following case into their script and submit the output:
     a. The geometry of Design 0
     b. Train loaded to 400 N according to Load Stage 1
   - The output of your script should match the hand calculations (which must also be submitted)
   - Appendix I contains pseudo-code which can be used as a starting place for developing a script
   - This method is recommended for groups considering using different cross sections at different locations along the length of the bridge.

2.7. Additional Design Considerations

Despite the wide scope of failure mechanisms covered in CIV102, there are other phenomena not discussed. To ensure the most accurate performance of your design, the following are some design considerations that must be addressed by your teams' engineering judgement.

- Splice connections.
  - The maximum dimension of the matboard provided is shorter than the required span. Therefore, a splice connection is required at some point. Failure across this location will not be represented in the set of calculations suggested in Section 2.4.
- Rigid Cross-Sections
  - The concepts discussed in CIV102 all assume that the cross-section remains rigid under loading. This may not remain true which could void the set of calculations in Section 2.4.
- Rigid Support Sections
  - Areas near supports will be subjected to direct vertical compression which is not considered in the calculations in Section 2.4.

To ensure your bridge's cross section remains rigid and your support zones can withstand the direct vertical compression, it is recommended that vertical diaphragms be installed at numerous locations throughout your bridge.

The above considerations (and perhaps others) can be the most difficult to design for due to the lack of evidence and justification for you to make design decisions. However, they are an inevitable part of real-life engineering problems and neglecting these considerations can cause failure at lower loads than predicted by your calculations.

2.8. Additional Construction Considerations

Care **MUST** be taken when determining the space you will use to build your bridge.

Discipline common rooms or residence common spaces are not recommend since they lack the ventilation necessary to keep you and other people safe while using contact cement. These spaces also contain easily damaged surfaces like tables that can be scratched by sharp knives, and couches which can be stained with contact cement.

<u>**The common spaces of Myhal are not permitted construction spaces.**</u> Groups that are found to have constructed their bridge in a common space of Myhal may be subject to mark penalties or disqualification.

Regardless of the location, you must not damage any space and clean up after yourselves. It is strongly recommended that you acquire and use a tarp and garbage bags.

3. Project Deliverable Details

Table 2 below shows the overall breakdown of marks. More details are discussed in subsequent sections.

Deliverables	Mark Allocation	Deadline
Design Report	**15%**	Nov. 26th (11:59 pm) on Quercus
Engineering Drawings	**5%**	Nov. 26th (11:59 pm) on Quercus
Design Calculations	**45%**	
Deliverable 1	*7%*	Nov. 13th (11:59 pm) on Quercus
Final Submission	*38%*	Nov. 26th (11:59 pm) on Quercus
Bridge Performance	**35%**	Nov. 28th – Dec. 1st in Tutorial

The project is worth 17% of your final CIV102 grade.

Your project submission on November 26th should consist of 4 or 5 separate pdf files as described in the following sections.

3.1. Deliverable 1

- Assume the train is centered on the bridge
- Assume the train is loaded according to the base case of Load Case 2
- Submit the shear force diagram *V(x)* and the bending moment diagram *M(x)*
- Calculate and submit the FOS against flexural tension failure and flexural compression failure of Design 0
- Peer evaluation survey on Quercus

3.2. Design Report

- Submit as a pdf titled "CIV102 Project Team xxx Design Report.pdf" replacing xxx with your team number
- Should include an Introduction section with a brief description of your bridge and a list of the key design decisions your team made
- Report your major design iterations in terms of which design parameters were changed, your reasoning to make those changes, and the results of your changes from your script
    - Ideally, the report should be generated as you are designing
    - The results of each iteration should be explained using CIV102 knowledge
    - Decisions can include non-calculation based considerations
    - It is expected that each group go through 3-10 major design iterations
- Detail the construction process
    - Provide timestamped photo evidence of work
    - You must include a picture showing all the precautions your group took to keep your building space clean. This can include tarps and garbage bags.
    - You must include a picture showing what your building space looked like when you finished a construction session. If you built your bridge over multiple sessions, you should include multiple photos showing the space as you left it. These photos should demonstrate that you cleaned up the space after using it.
    - Photos that show your group building your bridge in a common space in Myhal may be subject to mark penalties or disqualification.
    - You must submit your design report with or without this portion by Nov 26th at 11:59 PM
    - You may resubmit your design report including this portion by Dec 1st at 11:59 PM with no changes to any other portion of the report

3.3. Engineering Drawings

- Submit as a pdf titled "CIV102 Project Team xxx Engineering Drawings.pdf" replacing xxx with your team number
- The goal of the drawings is to convey your final bridge design and construction process to others. To accomplish so, consider the following components
  - Elevation view of your bridge
  - Top/Bottom views of your bridge
  - Cross-section views at important locations
  - Splice, connection details
  - Construction drawing showing how your piece of Matboard will be cut
- It is very likely that you will draw sketches of the above components throughout the project to convey details to your teammates. Think of the drawings that you submit as simply good drafts of your sketches.
- Drawings can be done by hand or digitally and can be spread across as many pages as necessary.

3.4. Design Calculations

- Submit a pdf titled "CIV102 Project Team xxx Hand Calculations.pdf" replacing xxx with your team number including the following:
  - Hand calculations to determine the FOS against failure and failure mode of Design 0 under a moving 400N train loaded according to Load Case 1
  - Any hand calculations done to determine the FOS against failure and failure mode of your final design under a train loaded according to the base case of Load Case 2. If you exclusively used Excel or code to perform these calculations, this portion may be empty.
- If you use Excel or code to assist with your calculations, submit a pdf titled "CIV102 Project Team xxx Additional Calculations.pdf" replacing xxx with your team number including the following:
  - Excel or code output for all intermediate calculations performed in the hand calculations of Design 0 under a moving 400N train loaded according to Load Case 1
  - Excel or code output of all FOS and a graphical presentation of all Shear Force Capacities and Bending Moment Capacities for Design 0 under a moving 400N train loaded according to Load Case 1
  - Excel or code output of all FOS and a graphical presentation of all Shear Force Capacities and Bending Moment Capacities for your final design under a train loaded according to the base case of Load Case 2
  - If you use Excel, include the spreadsheet with labels, comments and proper formatting
  - If you use code, include the entire script with comments and proper formatting.
  - Excel spreadsheets and code deemed illegible will receive mark deductions

3.5. Time Log

- Submit as a pdf titled "CIV102 Project Team xxx Time Log.pdf" replacing xxx with your team number
- Submit a detailed time log for all work on this project. The tasks and time spent on these tasks should be clearly recorded for each group member. Each group member is to sign this time log to signify they agree with the reported breakdown of project work.
- A template is available on Quercus

3.6. Bridge Performance

- Marks will be allotted for:
    - Construction quality
    - Bridge performance (the value of the test failure load)
    - The ratio between bridge weight and performance (meaning a strong, heavy bridge is not as good as an equally strong, light bridge)
    - Accuracy in estimation of test total failure weight
- Prior to testing, your bridge must be clearly marked with the following:
    - Your team number
    - Your team member names
    - Your bridge's name
    - Your TA's name
    - The predicted total failure weight

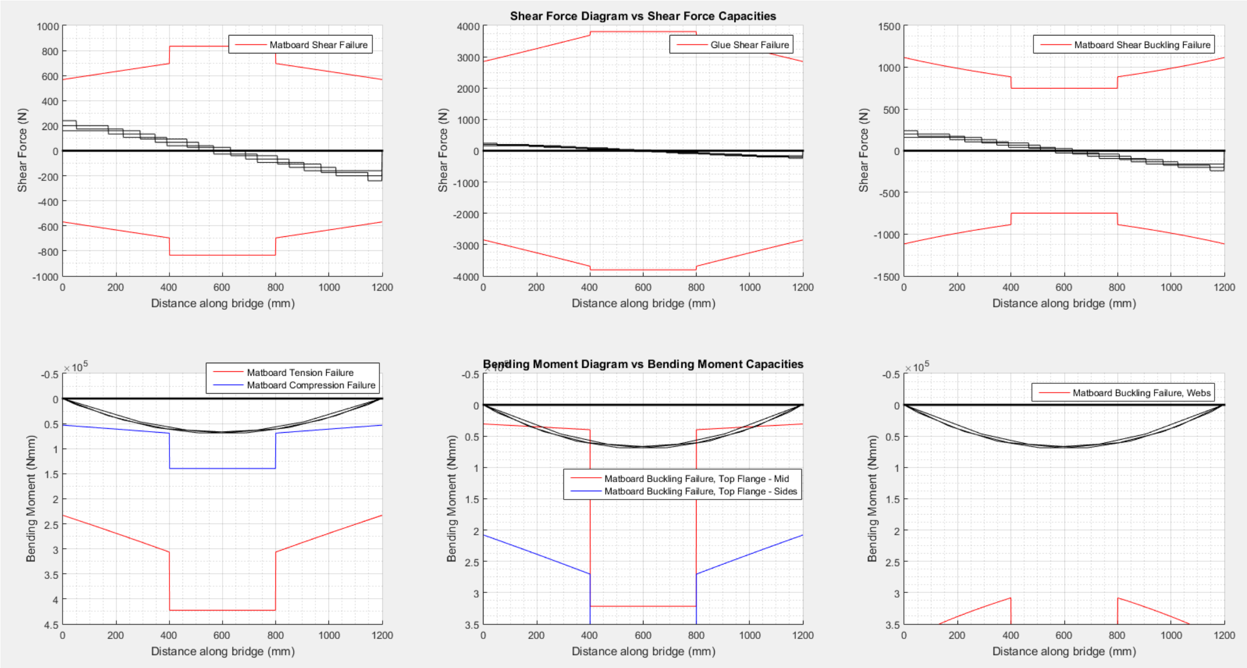
Appendix I – Pseudo Code and Sample Output from MATLAB Script

The following MATLAB code is meant as a guide only. You are not required to follow any of its given methods or format.

```
clear; close all;
%% 0. Initialize Parameters
L = 1200;                                               % Length of bridge
n = 1200;                                               % Discretize into 1 mm seg.
P = 400;                                                % Total weight of train [N]
x = linspace(0, L, n+1);                                % x-axis

%% 1. SFD, BMD under train loading
x_train = [52 228 392 568 732 908];                     % Train Load Locations
P_train = [1  1   1   1   1   1] * P/6;

n_train = 3;                                            % num of train locations
SFDi = zeros(n_train, n+1);                             % 1 SFD for each train loc.
BMDi = zeros(n_train, n+1);                             % 1 BMD for each train loc.

% Solve for SFD and BMD with the train at different locations
for i = 1:n train
                                                        % start location of train

                                                        % sum of moments at A eqn
                                                        % sum of Fy eqn

                                                        % construct applied loads
                                                        % w(x)

                                                        % SFD = num. integral(w)
                                                        % BMD = num. integral(SFD)
end

SFD = max(abs(SFDi));                                   % SFD envelope
BMD = max(BMDi);                                        % BMD envelope

%% 2. Define Bridge Parameters
%       = xc,   bft,  tft,
param   = [0,   100, 1.27,                                      ...
           400, 100, 1.27,                                      ...
           800, 100, 1.27,                                      ...
           L,   100, 1.27,
%x_c     Location, x, of cross-section change
%bft     Top Flange Width
%tft     Top Flange Thickness




% Extracting user input assuming linear relationship
bft     = interp1(param(:,1), param(:,2), x);
tft     = interp1(param(:,1), param(:,3), x);





%% 3. Calculate Sectional Properties
% ybar. location of centroidal axis from the bottom
```

```
ybar =

ybot =
ytop =

% I
I =



% Q at centroidal axes
Qcent =


% Q at glue location
Qglue =

%% 4. Calculate Applied Stress
S_top  =
S_bot  =
T_cent =
T_glue =

%% 5. Material and Thin Plate Buckling Capacities
E  = 4000;
mu = 0.2;
S_tens  =
S_comp  =
T_max   =
T_gmax  =
S_buck1 =
S_buck2 =
S_buck3 =
T_buck  =

%% 6. FOS
FOS_tens    =
FOS_comp    =
FOS_shear   =
FOS_glue    =
FOS_buck1   =
FOS_buck2   =
FOS_buck3   =
FOS_buckV   =

%% 7. Min FOS and the failure load Pfail
minFOS      =
Pf          =

%% 8. Vfail and Mfail
Mf_tens  =
Mf_comp  =
Vf_shear =
Vf_glue  =
Mf_buck1 =
Mf_buck2 =
Mf_buck3 =
Vf_buckV =

%% 9. Output plots of Vfail and Mfail
subplot(2,3,1)
hold on; grid on; grid minor;
plot(x, Vf_shear, 'r')
plot(x, -Vf_shear.* SFD, 'r')
plot(x, SFDi, 'k');
plot([0, L], [0, 0], 'k', 'LineWidth', 2)
legend('Matboard Shear Failure')
xlabel('Distance along bridge (mm)')
ylabel('Shear Force (N)')
```

Sample Output

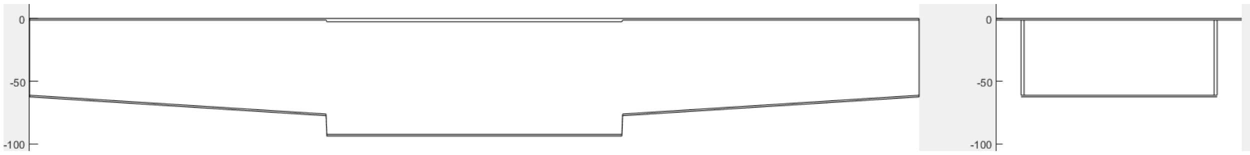


In the above analysis, the proposed bridge is:

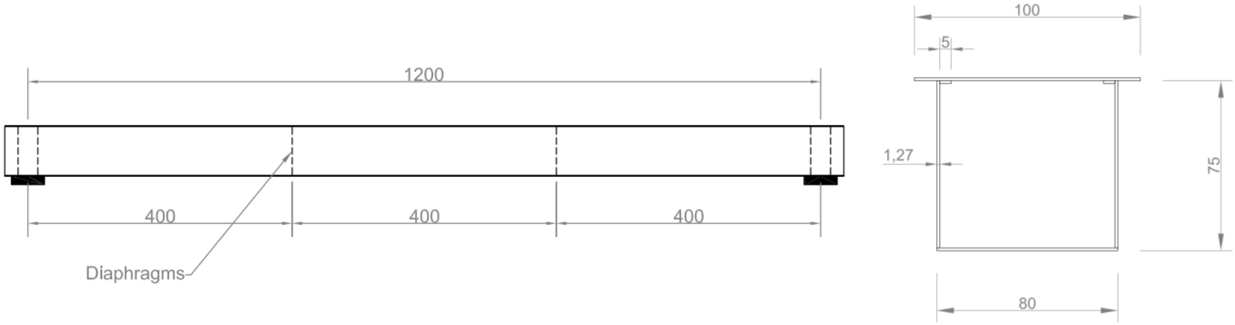
- Far from failing due to glue failure (FOS = 11.87)
- Far from failing due to buckling in the webs (FOS = 5.03)
- Far from failing due to tension (FOS = 5.00)
- Far from failing due to shear buckling (4.49)
- Far from failing due to buckling in the side flanges (4.42)
- Close to failing due to shear (2.37)
- Very close to failing due to compression (1.127)
- Going to fail due to buckling in the middle flange (0.649)

The maximum train this bridge can support weighs 260N

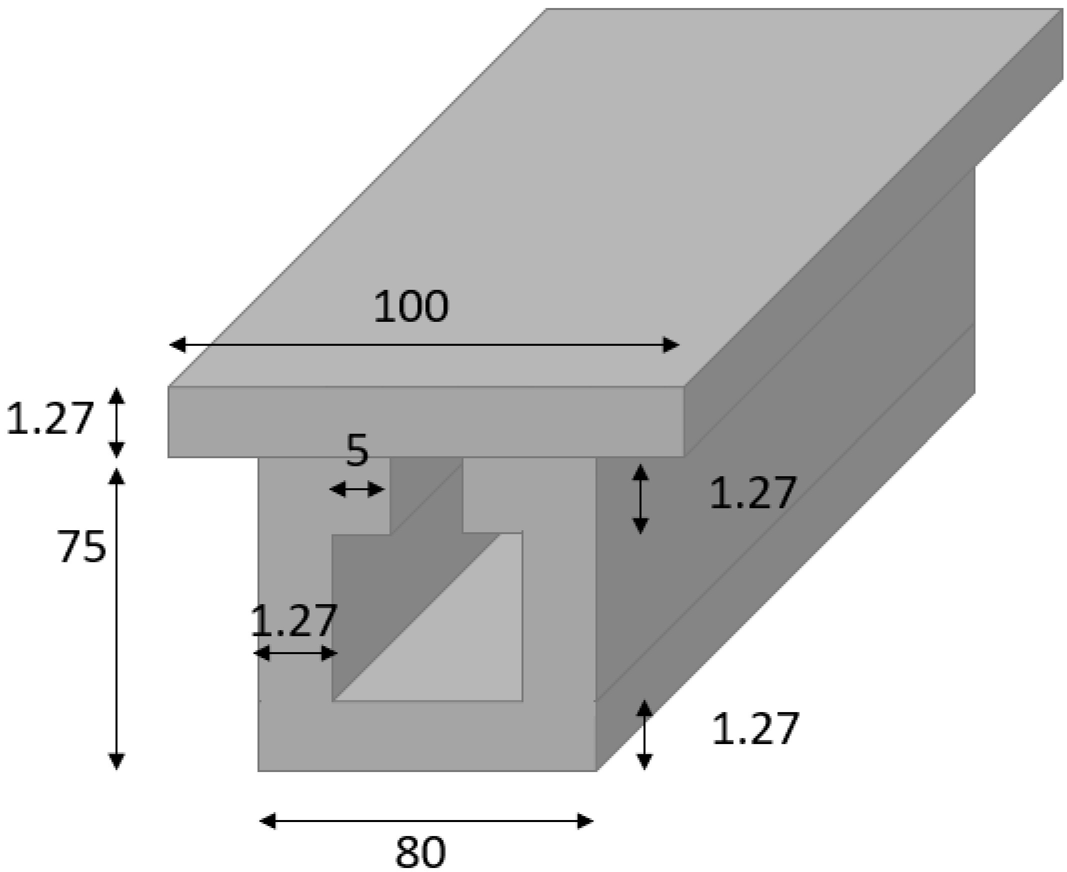
The bridge had the following geometry. This output is not required.



Appendix II – Design 0 Details



Elevation view and cross-section view of Design 0 (same cross-section view along the entire span)



Not to scale sketch showing cross-sectional shape and dimensions. The 5 mm wide piece is a surface for which glue on be applied to in order to attach the bottom "U" piece to the top. There are other ways to glue your bridge together, this is only showing one example

Appendix III – Contact Cement Technical Data Sheet

Please note that the ***contact cement is volatile*** and prolonged exposure to its smells is ***not*** healthy. ***Take breaks while working.***

Make sure you work in a ***well-ventilated*** environment.

Contact cement is difficult to clean so do not get it everywhere.