Matboard Bridge Design and Construction Project

The Matboard Design and Construction Project is the final project in CIV102. This project tests groups of students to both design and build a bridge which will be tested to failure. This document describes the scope of work of the project, and necessary parameters to carry out the design.

Overview

The Matboard Bridge Design and Construction 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 a 400N train. If the Bridge successfully supports the train, it will then be loaded to failure. The top teams with the highest strength/weight ratio will be eligible for a prize.

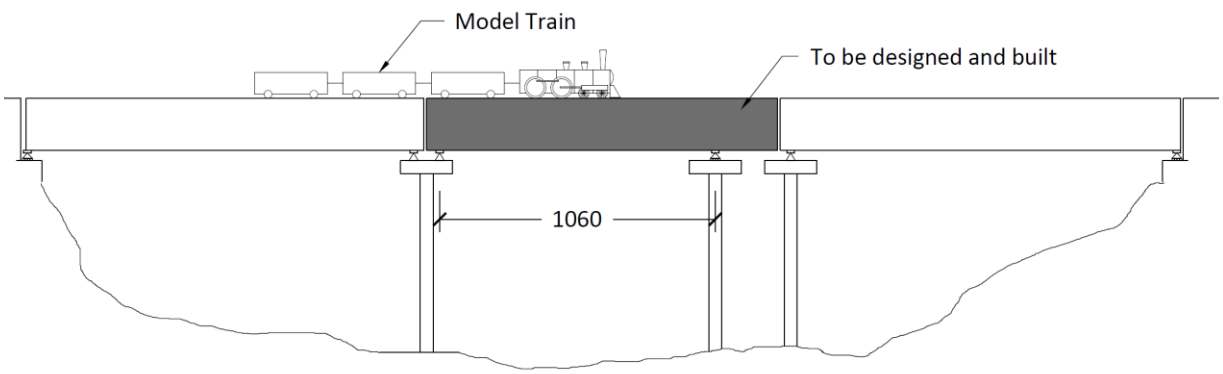


Figure 1. Three span bridge supporting the passage of a 400 N train. Teams must design the middle span.

Primary Objectives

1. Design and build a bridge which can support a 400 N train across a span of 1060 mm.
2. Design and build the strongest bridge possible using the permitted construction materials.
3. Use concepts relating to engineering beam theory and thin-plate buckling theory to predict the maximum load the bridge can carry before failure.

Secondary Objectives

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

Construction Materials

1. One sheet of mat-board 32” x 40” x 0.05”, with a mass of ≈750 grams will be provided to each team. A summary of material properties can be found in Table 1.
2. Two tubes of contact cement (30 ml each weighing roughly nothing when dry) will be provided.

Notes:

- Additional contact cement may be purchased at external retailors if required at the expense of the team.

- For all materials, you are allowed to use different values if obtained through testing. **The use of any other materials or additional materials is prohibited** and your bridge will be disqualified Further, any such act will constitute a violation of academic integrity outlined by the University.
- **!!! All students MUST review the attached technical sheet which outlines safe use of the contact cement. Students must work in well-ventilated areas when using the contact cement and take appropriate precautions when cutting matboard.**
- Students are responsible for safely transporting their project materials/completed bridge to and from tutorial. CIV102 teaching staff are not responsible for storage.

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.*

Bridge Loading

1. Load Case 1, Train Loading: (Figure 2)
   a. The train will contact, and apply loading to, the bridge via the 6 set of train wheels
   b. Since the train is moving across the bridge, the forces and stresses within the bridge will change depending on the location of the train.
2. Load Case 2, Point Loading: (Figure 3)
   a. Two equivalent point loads (P) applied at the locations specified in Figure 3. The magnitudes of these loads (P) will be increased until the bridge fails.

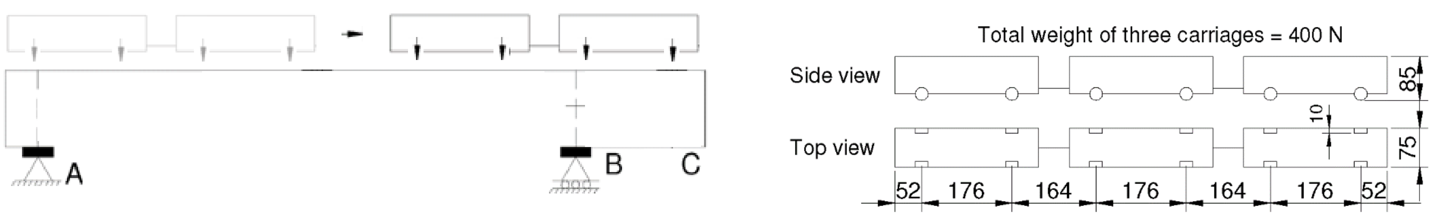


Figure 2. a) Load Case 1: Train Loading diagram (2 carriages shown for clarity). b) Train dimensions

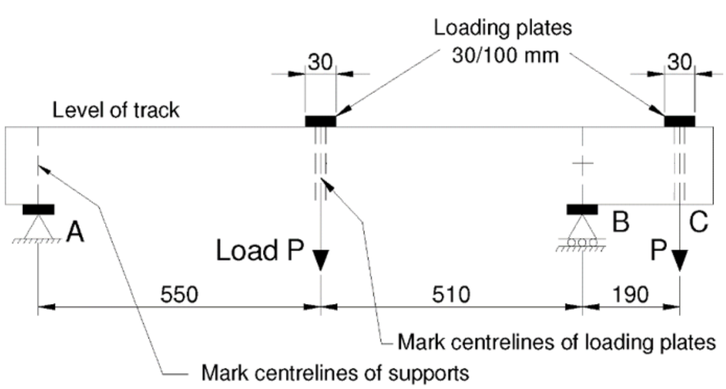


Figure 3. Load Case 2: Point Loading diagram

Bridge Dimensions and Constraints

- The full length of the bridge must be at least 1280 mm (1060+190+30/2+30/2) in order to fit the loading setup as seen in Figure 4. Additional tolerances should be given for construction error; however, the full length must be less than 1325 mm (1060+190+25+50).
- The height of the bridge at the two support points must be less than 200 mm.
- The deck of the bridge must be horizontal, be at least 100 mm wide and permit unhindered passage of the train. There can be no steps on the top surface for the train wheels to climb over.
- The support plates and loading plates used to apply point loads in Load Case 2 are 30 mm x 100 mm. These locations must be marked and flat in order to fit the loading setup.

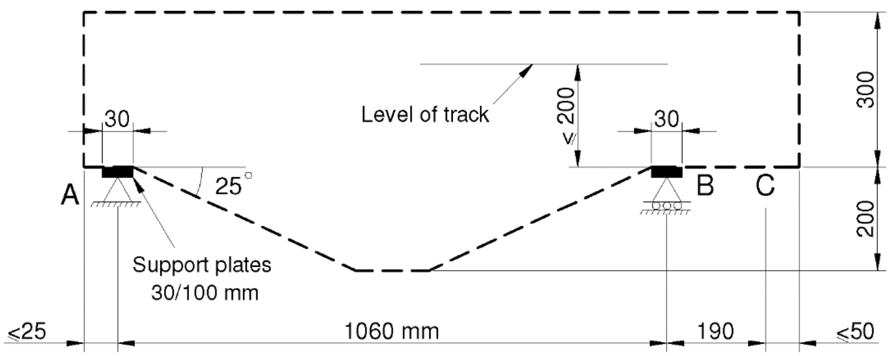


Figure 4. Dimensional constraints outlining the maximum allowed dimensions of the bridge in elevation

Calculation Procedure

In order to design a bridge that can withstand the applied loading or predict the failure load by considering all failure mechanisms, the following calculations must be conducted and presented.

1. Calculate internal forces within the bridge from applied loading (shear force and bending moment)
   a. Under train loading, multiple instances of the application of train loads must be considered at different locations on the bridge to determine the largest internal forces
2. Define cross-section inputs (geometric inputs) and calculate cross-section properties ($\bar{y}$, I, Q, etc.)
   a. These properties are dependent on the dimensions of the cross-sections and will vary along the bridge if the cross-section varies along the bridge
3. Define material properties (material inputs)
4. Determine the capacity of the bridge:
   4.1 Calculate the shear force (V_{fail}) that would cause a matboard shear failure
   4.2 Calculate the shear force (V_{fail}) that would cause a glue shear failure
   4.3 Calculate the shear force (V_{fail}) that would cause a matboard shear buckling failure
   4.4 Calculate the bending moment (M_{fail}) that would cause a matboard tension failure
   4.5 Calculate the bending moment (M_{fail}) that would cause a matboard compression failure
   4.6 Calculate the bending moment (M_{fail}) that would cause a matboard flexural buckling failure
   4.7 Check for failure / Calculate failure load
   a. Load Case 1 (train loading): calculate the FOS between the internal shear force and bending moment vs the failure shear forces and failure bending moments
   b. Load Case 2 (point loading): calculate the value of the applied loads P that causes the internal shear force and bending moment to reach the failure shear forces and failure bending moments
5. Calculate the mid-span deflection under applied points loads (2) of P = 200 N.

All calculations shall be written as Python or MATLAB (or others) functions with a main script calling the required functions. Each function must be accompanied by a handwritten example for verification. A sample pseudocode has been provided in Appendix I.

Bridge Design Procedure

The script written by your team will be executed multiple times in the design process in order to produce stronger bridges (higher failure loads) under Load Case 2.

1. Begin with Design0, a constant depth, uniform cross-section design as seen in Figure 5. The details of Design0 can be found in Appendix II. Input the geometric properties of Design0 into your script and see its performance. Note the failure load P that would cause Design0 to fail and state whether Design0 will pass the train loading. Provide plots of the SFD and BMD together with the various V_{fail} and M_{fail} similar to the plots shown in Appendix I.

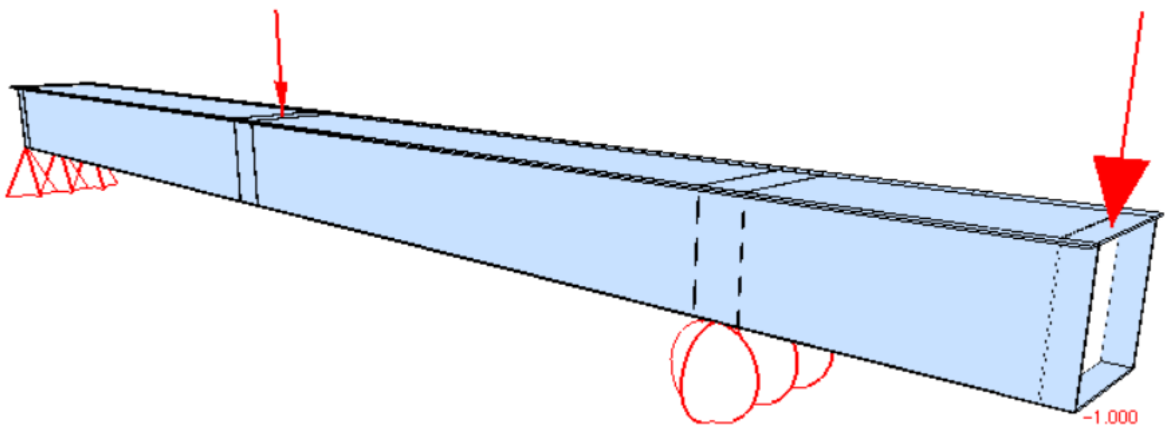


Figure 5. 3D view of Design0

2. Design your own bridge by iterating through different bridge geometries and cross-sectional dimensions (Calculation step 2). Doing so will lead to different results in calculation step 4. You are also allowed and encouraged to introduce more drastic design changes (such as removing cross-section components altogether) to produce the strongest bridge you can. However, it is your teams' responsibility to ensure that your script is robust enough to handle such changes. Describe these design decisions in the report with reference to the failure mechanism and using relevant equations as evidence for your decisions.
   For your final design, note the failure load P that would cause failure and state the FOS under the train loading. Provide plots of the SFD and BMD together with the various V_{fail} and M_{fail} similar to the plots shown in Appendix II.

Additional Design Considerations

Despite the wide scope of failure mechanisms covered in CIV102, there are other phenomena not discussed. In order to ensure the best performance, the following are some considerations that must be considered.

- Area of Matboard Used: At each design iteration it is important to note the amount of Matboard used. In addition, how the Matboard is cut into components must be planned to reduce the amount of "wasted" Matboard.
- Connections: Consider and describe how your connections will be located and built to ensure no connection failure occurs. Use schematics, calculations or other explanations as necessary.
- Rigid Cross-Sections: The calculations discussed all assume that the cross-section remains rigid under loading. It will be up to your teams' engineering judgement to design for this rigidity.
- Rigid Supports: Zones near supports will be subjected to vertical compression which are not considered in the calculations. These areas should be additionally reinforced.

Design Report Requirements

1. For both Design0 and your final bridge design, present:
    a. FOS against failure under Load Case 1 (train loading)
    b. Failure load P under Load Case 2 (point loading) and expected cause of failure
    c. Plots of SFD, BMD against various failure loads V_{fail} and M_{fail}.
2. Compare and list the improvements made between Design0 and your final design. For each design improvement, indicate the justification behind the design decision using equations of failure mechanisms as evidence.
3. Include a section in the report where the construction process is documented in detail. Provide photo evidence of work and include annotations which describe how you built the bridge.

Supporting Calculations Requirements

1. All code including the main script and all functions must be compiled into one PDF
    a. For each function, a sample call must be produced, clearly showing all inputs and outputs. Plot inputs/outputs if required.
    b. For each function, a handwritten sample calculation must be provided that can replicate the outputs for the same inputs. If inputs/outputs are in the form of arrays, show one sample value.
2. All code must be commented.

Engineering Drawing Requirements

1. Three drawings showing the following views of your bridge must be developed:
    a. All views of the bridge including views from above, below, and from the side. (Drawing 1)
    b. Include a cross section view which is cut along the length of the bridge to show components which are inside the bridge, such as diaphragms, connections, etc. (Drawing 1)
    c. Draw as many cross-section views as necessary to sufficiently to describe your bridge and indicate where along the length of the bridge the section views correspond to. (Drawing 2)
    d. Include construction drawings which describes how the sheet of Matboard shall be cut to create your bridge. Indicate the purpose of each piece. (Drawing 3)
2. Drawings must include annotations, dimensions, a border and a completed title block. Research typical engineering drawing conventions when preparing your drawings.
3. Drawings may be prepared by hand or digitally. Straight lines must be drawn with a ruler if done by hand. Drawings prepared by hand should be done on 11 x 17 paper and may be submitted as paper copies instead of a digital file.

Bridge Requirements (For Test Day)

1. The following information must be clearly printed in large font on the front of your bridge so that it is visible in a group photo:
    a. Your names, your bridge's name, your TA's name, your classroom (GB117 or GB217) and group number,
    b. The predicted total load applied to your bridge in Load Case 2 that will cause failure.
    c. The predicted midspan deflection under a total load of 400 N (P = 200 N) in Load Case 2.
2. Markings indicating the centrelines of the supports and loading plates on each side of the bridge must be provided

Deliverables and Deadlines

Due date: Tuesday November 30 at 11:59pm Toronto time

a. Submit the project Design Report. The total length of this report including both text and images must not exceed 5 pages. Text shall be written in 11-point font and single spaced.
b. Submit the Supporting Calculations.
c. Submit a set of Engineering Drawings which completely describe your bridge and satisfies all of the requirements outlined in the Engineering Drawing Requirements section. Three pages of drawings shall be submitted and be organized as follows:
    i. Views of top, bottom, side and cross section along length
    ii. Cross-section views
    iii. Construction drawing showing matboard cuts
d. 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. Indicate the date and times that each task was performed. This time log is not included in the page limit for the report. Each group member is to sign this time log. Use quarter hour precision.

Submissions shall be uploaded to Quercus in the form of four pdf files. Only one submission is required for each group, and all of the files must be submitted by one member of each team. These files must have the following naming convention, where xx is your group number. Each file must contain the names of each group member and your classroom TA on the first page.

a.	Report:	CIV102-Project-Report-Group-xx.pdf
b.	Calculations:	CIV102-Project-Calculations-Group-xx.pdf
c.	Drawings:	CIV102-Project-Drawings-Group-xx.pdf
d.	Time log:	CIV102-Project-Timelog-Group-xx.pdf

Drawings prepared by hand may be submitted in person instead of as a digital file. Please include a placeholder file in your Quercus submission if your team is submitting your drawings this way. Details of how/when the drawings will be submitted will provided at a later date

During the tutorial two weeks from distribution (December 1 and December 3):

a. Bring the completed bridge to GB117. All group members must be present to take a team photo with their bridge.

Grading Scheme and Project Weight

Approximate Grading Scheme

The overall project grade will consist of the report (10%), drawings (20%), bridge construction quality (10%), bridge performance (15%) and calculations (45%).

Project Weight

This project is worth 10% of the course grade. The same grade will be assigned to all members of each team except in the condition of a serious dispute. If your team is experiencing serious challenges, please email your classroom TA and cc Allan Kuan and Raymond Ma.

Appendix I – Pseudo Code and Sample Output from Design Script

The following MATLAB code is meant as a guide only. You are not required to follow any of its given methods or format as long as you can meet all the steps given in the calculation procedure.

Design Script for Load Case 2 only

```
%% 0. Initialize Parameters
n = 1000;                  % Number of locations to evaluate bridge failure
L = 1250;                  % Length of bridge

x = linspace(0, L, n);     % Define x coordinate
SFD_PL = zeros(1, n);      % Initialize SFD(x)

%% 1. Point Loading Analysis (SFD, BMD)
P = 318;
[SFD_PL, BMD_PL] = ApplyPL(550, P, x, SFD_PL);      % Construct SFD, BMD
[SFD_PL, BMD_PL] = ApplyPL(L, P, x, SFD_PL);        % Construct SFD, BMD

%% 2. Define cross-sections
% There are many (more elegant ways) to construct cross-section objects
xc = [0 550 L];            % Location, x, of cross-section change
bft = [100 100 100];       % Top Flange Width
tft = [2.54 2.54 2.54];    % Top Flange Thickness
hw = [100 120 100];        % Web Height
tw = [1.27 1.27 1.27];     % Web Thickness (Assuming 2 separate webs)
bfb = [80 80 80];          % Bottom Flange Width
tfb = [1.27 1.27 1.27];    % Bottom Flange Thickness
a = [400 400 400];         % Diaphragm Spacing

% Optional but you need to ensure that your geometric inputs are correctly implemented
VisualizeBridge( {CrossSectionInputs} );

%% 3. Define Material Properties
SigT = 30;
SigC = 6;
E    = 4000;
TauU = 4;
TauG = 2;
mu   = 0.2;

%% 4. Calculate Failure Moments and Shear Forces
V_Mat = Vfail({CrossSectionInputs}, TauU);
V_Glue = VfailGlue({CrossSectionInputs}, TauU);
V_Buck = VfailBuck({CrossSectionInputs}, E, mu );

M_MatT = MfailMatT({CrossSectionInputs}, SigT);
M_MatC = MfailMatC({CrossSectionInputs}, SigC);
M_Buck1 = MfailBuck({CrossSectionInputs}, E, mu, 1 );
M_Buck2 = MfailBuck({CrossSectionInputs}, E, mu, 2 );
M_Buck3 = MfailBuck({CrossSectionInputs}, E, mu, 3 );

%% 4.7 Calculate Failure Load
Pf = FailLoad(P, SFD_PL, BMD_PL, V_Mat, V_Glue, V_Buck, M_MatT, M_MatC, M_Buck1, M_Buck2, M_Buck3);

%% Visualization
VisualizePL(x, P, SFD_PL, BMD_PL, V_Mat, V_Glue, V_Buck, M_MatT, M_MatC, M_Buck1, M_Buck2, M_Buck3,
Pf);

%% 5. Curvature, Slope, Deflections
Defls = Deflections(x, BMD_PL, I, E);
```

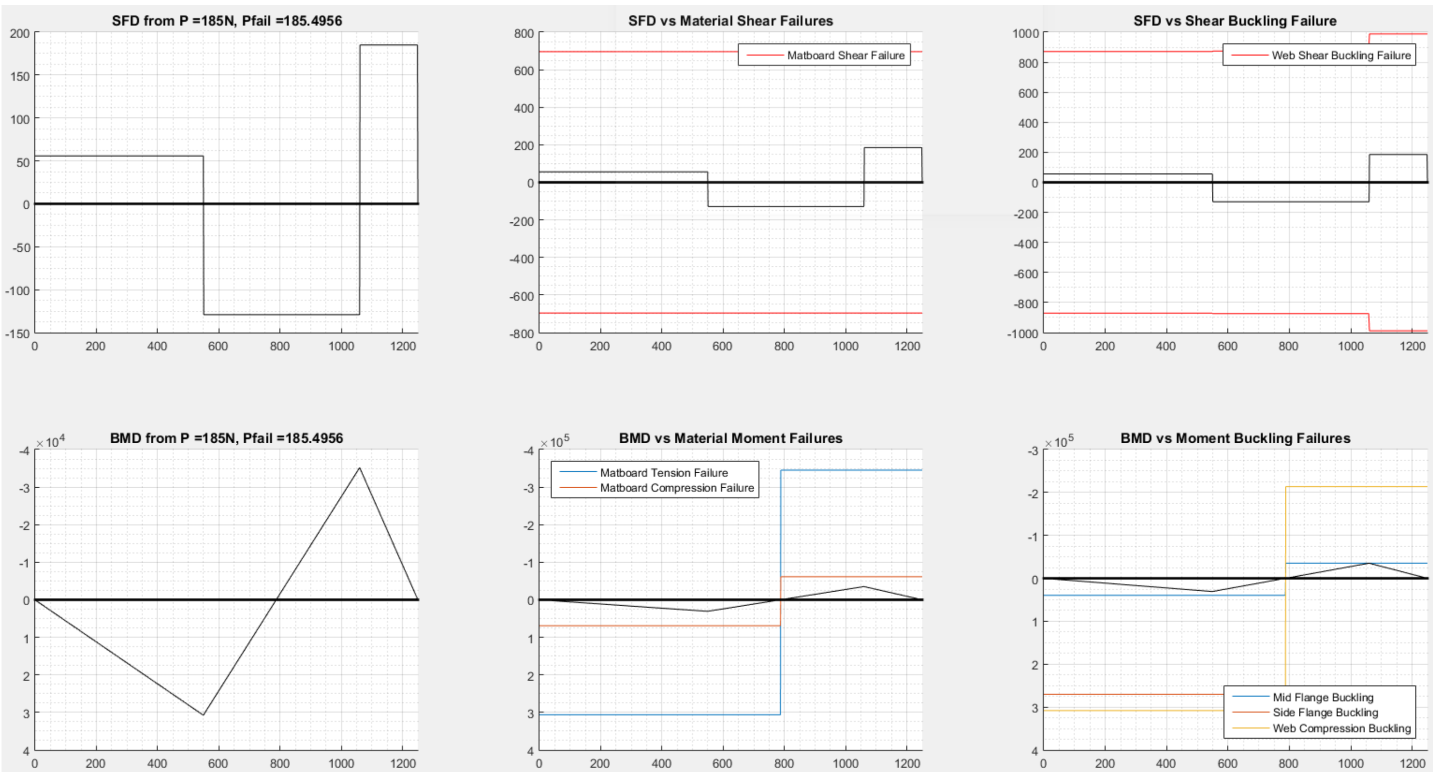
Function Definitions

```
function [ SFD, BMD ] = ApplyPL( xP, P, x, SFD )
% Constructs SFD and BMD from application of 1 Point Load. Assumes fixed location of supports
%      Input: location and magnitude of point load. The previous SFD can be entered as input to
%             construct SFD of multiple point loads
%      Output: SFD, BMD both 1-D arrays of length n

function [  ] = VisualizeBridge( {Geometric Inputs} )
% Optional. Provides a graphical interpretation of user geometric inputs

function [ {Sectional Properties} ] = SectionProperties( {Geometric Inputs} )
% Calculates important sectional properties. Including but not limited to ybar, I, Q, etc.
%      Input: Geometric Inputs. Format will depend on user
%      Output: Sectional Properties at every value of x. Each property is a 1-D array of length n

function [ V_fail ] = Vfail( {Sectional Properties}, TauU )
% Calculates shear forces at every value of x that would cause a matboard shear failure
%      Input: Sectional Properties (list of 1-D arrays), TauU (scalar material property)
%      Output: V_fail a 1-D array of length n
    I = {Sectional Properties};
    b = {Sectional Properties};
    Qcent = {Sectional Properties};

    V_fail = TauU .* I .* b ./ Qcent;
end

function [ V_Buck ] = VfailBuck( {Sectional Properties}, E, mu )
% Calculates shear forces at every value of x that would cause a shear buckling failure in the web
%      Input: Sectional Properties (list of 1-D arrays), E, mu (material property)
%      Output: V_Buck a 1-D array of length n

function [ M_MatT ] = MfailMatT( {Sectional Properties}, SigT, BMD )
% Calculates bending moments at every value of x that would cause a matboard tension failure
%      Input: Sectional Properties (list of 1-D arrays), SigT (material property), BMD (1-D array)
%      Output: M_MatT a 1-D array of length n
    [I, ybot, ytop] = {Sectional Properties};

    for i = 1 : length(x)
        if BMD(i) > 0 % If the moment is positive, the tension failure will be at the bottom
            M_MatT(i) = SigT * I(i) / ybot(i);
        elseif BMD(i) < 0 % If the moment is negative, the tension failure will be at the top
            M_MatT(i) = -SigT * I(i) / ytop(i);
        end
    end
end

function [ M_MatT ] = MfailMatC( {Sectional Properties}, SigC, BMD ) % Similar to MfailMatT

function [ M_Buck ] = MfailBuck( {Sectional Properties}, E, mu, BMD )
% Calculates bending moments at every value of x that would cause a buckling failure
%      Input: Sectional Properties (list of 1-D arrays), E, mu (material property), BMD (1-D array)
%      Output: M_MatBuck a 1-D array of length n

function [ Pf ] = FailLoad( P, SFD, BMD, V_Mat, V_Buck, M_MatT, M_MatC, M_Buck1, M_Buck2, M_Buck3 )
% Calculates the magnitude of the load P that will cause one of the failure mechanisms to occur
%      Input: SFD, BMD under the currently applied points loads (P) (each 1-D array of length n)
%             {V_Mat, V_Glue, … M_MatT, M_MatC, … } (each 1-D array of length n)
%      Output: Failure Load value Pf

function [] = VisualizePL(x, SFD, BMD, V_Mat, V_Buck, M_MatT, M_MatC, M_Buck1, M_Buck2,…, Pf)
% Plots all outputs of design process

function [ Defls ] = Deflections( x, BMD, I, E )
% Calculates deflections
%      Input: I(1-D arrays), E (material property), BMD (1-D array)
%      Output: Deflection for every value of x (1-D array) or for the midspan only
```

Sample output plots.

In this case, the bridge is:

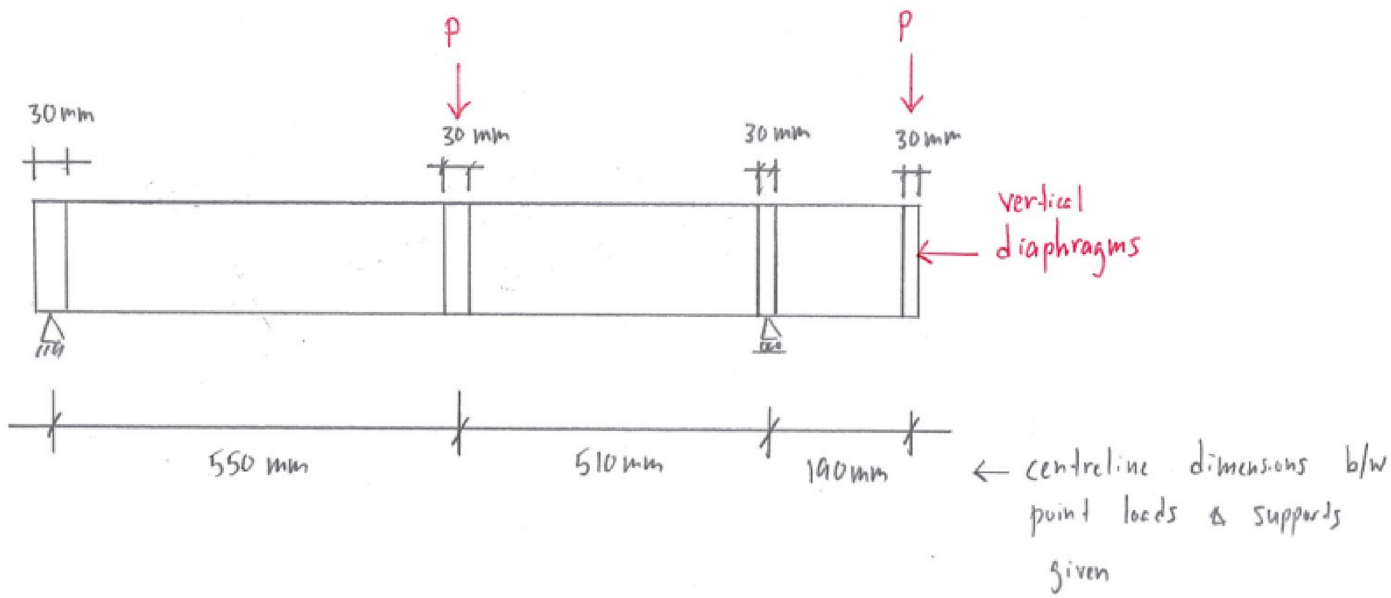
- far from failure due to shear
- far from failure due to shear buckling
- far from failure due to flexural tension
- far from failure due to flexural buckling of the web.
- far from failure due to flexural buckling of the side flange.
- close to failure due to flexural compression
- but before that can occur, it will fail due to flexural buckling in the mid flange.
    - this will occur on the bottom of the bridge at x = 1060 mm which is at the right support.



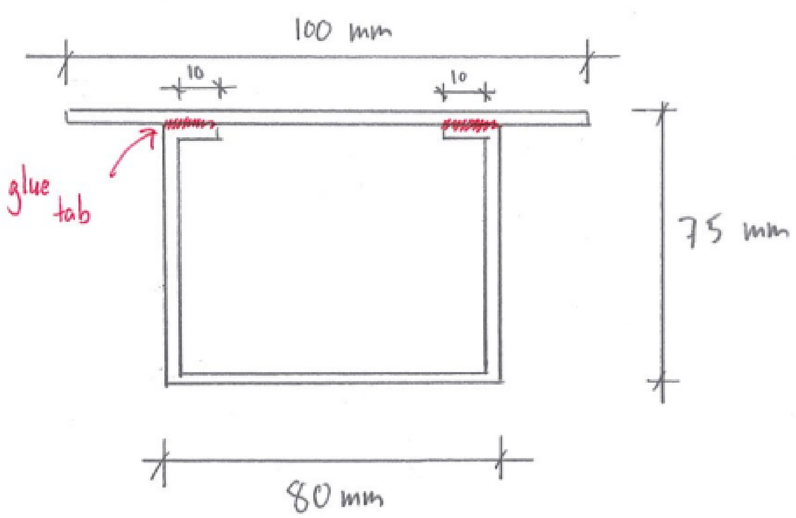
(In this example, the glue shear failure was not checked).

Appendix II – Design0 Details

Design0 - elevation view



Cross-Section View



recall: matboard is 1.27 mm thick.

- cross section is constant over entire bridge

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.

If you purchase an extra can of contact cement, ***ensure that its lid is covered when not in use to avoid spreading fumes in your work environment.***