CIV102 Matboard Bridge Design Project

Fall 2025, Revision 2: October 30, 2025

University of Toronto

Engineering Science (NΨ) Program

An example of a very aesthetically pleasing bridge! (November 2024.)

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1. Project Introduction

In teams of three (3) or four (4), you will apply the concepts taught in CIV102 to design and build a small-scale box girder bridge out of matboard. An example of such a bridge is shown in Figure 1. Your bridge will be subjected to increasing loads until failure. Throughout this project, 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.

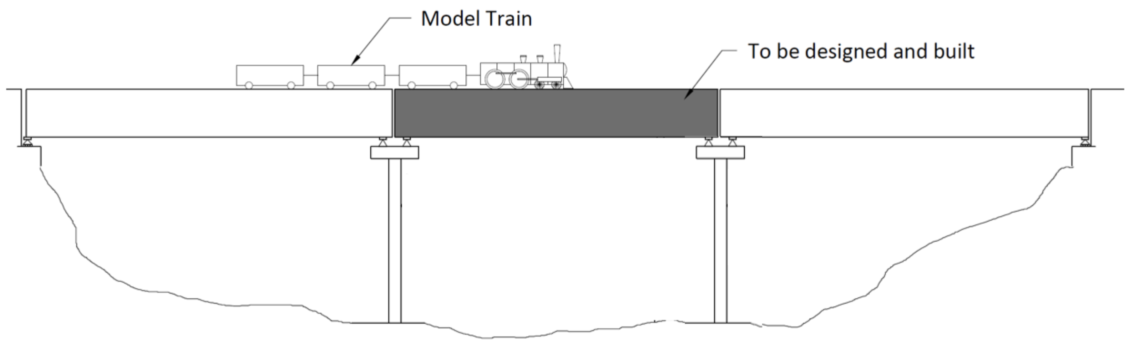


Figure 1. This is a three-span bridge supporting the passage of a 400 N train. Teams must design the left, right, or middle spans.

1.1. Overview

This Bridge Design Project is worth **17%** of your final CIV102 grade and consists of the **five (5) components** as shown in Table 1. Deadlines for each component are specified in Section 2.

Table 1: The breakdown of weights and marks for this Bridge Design Project.

Category	Component	Weight	Marks
Structural Calculations (45%)	Deliverable 1	7%	7
	Design Calculations	38%	38
Writing Components (20%)	Design Report	12%	12
	Engineering Drawings, Construction Process, and Time Log	8%	8
Bridge Performance (35%)	Physical Build	35%	35

Some comments about each component are presented below.

1. **Deliverable 1 (7 marks).**
    - Deliverable 1 is an exercise that asks your team to compute the factor of safety (FOS) against flexural failure for a given cross-section and bridge loading. It is intended to help your team get started with the design process.
2. **Design Report (12 marks).**
    - The design report describes and documents the decisions your team made during the design and construction processes.
3. **Supporting Calculations (38 marks).**
    - These are numerical calculations and/or computer code that describe the predicted performance of the bridge when subjected to the specified loading conditions.
4. **Engineering Drawings and Construction Process (8 marks).**
    - These are drawings showing how the bridge was built and its final intended geometry.
5. **Bridge Built from Specified Materials (35 marks).**
    - This is the physical bridge built by your team!

1.2. Primary Objectives

1. Design and build a bridge to support large gravity loads across a 1,200-mm span using only the permitted construction materials (see Section 1.7).
2. Use engineering beam theory and thin plate buckling theory to predict the maximum load your bridge can carry prior to failure.
3. **Have fun!**

1.3. Secondary Objectives

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

1.4. Photography During Testing Day

As per CIV102 tradition, all teams will have a **photograph** 📷 taken with their constructed matboard bridge prior to train loading. Top-performing teams will have their team photograph displayed outside office GB213D, in a glass-encased bulletin board shown below in Figure 2. **If you do not wish to have your photograph taken, then the teaching staff will respect your request—just let us know!**

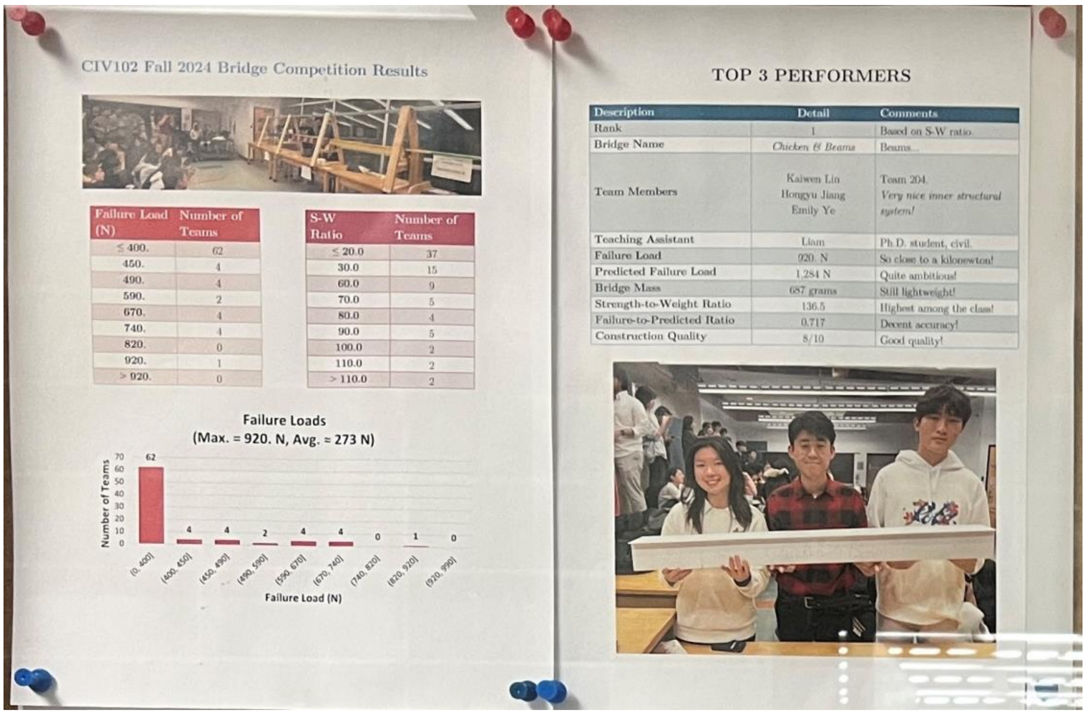


Figure 2. Photograph of a portion of the CIV102 bulletin board.

1.5. Bridge Dimensions

Figure 3 illustrates the distance to be spanned by your bridge and indicates the maximum permitted dimensions of your bridge.

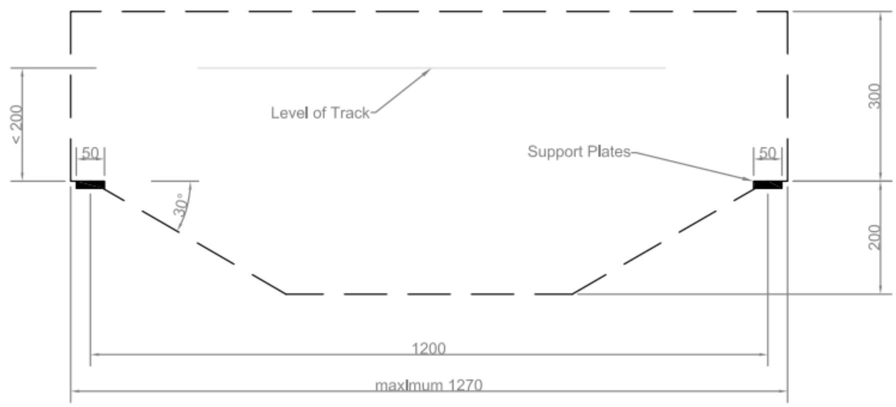


Figure 3. Dimensional constraints of the bridge shown in an elevation view.
The dashed line represents the maximum allowable dimensions for your entire bridge.

1. In your analysis, you should assume the **distance between the supports is 1,200 mm.**

2. The actual supports have a width of approximately 50 mm each, and 1,200 mm will span the distance between the middle of these supports (i.e., the centre-to-centre distance).

3. When you construct your bridge, it **must be at least 1,250 mm long.**

4. If your bridge length is less than 1,250 mm, it **will not fit** in the testing apparatus, and your bridge performance will be severely compromised.

In addition to the dimensional constraints previously specified in Figure 3, the teaching staff request your team abides by the following requirements.

1. The total length of your built bridge must be **between 1,250 and 1,270 mm.**

2. The level of the bridge deck (also referred to as the **track**) must be **less than 200 mm** above the level of the supports.

3. The distance between the track and the level of the supports must be a **multiple of 20 mm.**
    a. Examples of permissible values: 120 mm, 140 mm, 160 mm, etc., up to 180 mm.
    b. Examples of non-permissible values: 30 mm, 50 mm, 70 mm, 150 mm, etc.

4. The bridge deck must be **at least 100 mm wide at any point along the bridge's length.**

5. The bridge deck must be **horizontal** and **permit unhindered passage** of the train at any point along the deck's length. There can be **no steps, no grooves, nor bumps** on the top surface for the train wheels to roll over.

    a. The word "horizontal" in the context of this bridge design project means visually horizontal or visually determined via a levelling device such as a small bubble level (or spirit level).
    b. The phrase "unhindered passage" refers to the condition where the bridge deck does not have any obstacles or protrusions standing in the way of the train.

6. There must be a **60-mm long flat portion on the bottom of both ends** of the bridge to allow your bridge to rest upon the support plates without falling down.

1.6. Bridge Loading

A train comprised of three (3) cars will be pushed across your bridge. The dimensions of this train (in millimetres) and an illustration of the train movement are shown in Figure 4 and Figure 5. Note the train may also traverse the bridge in reverse, meaning it can also move from right to left.

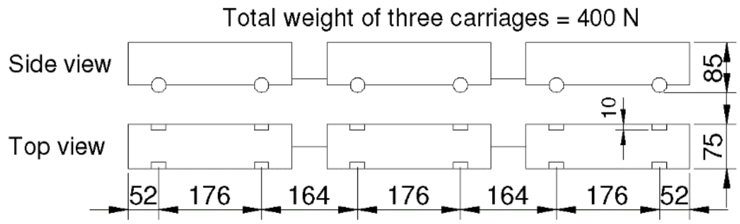


Figure 4. Train dimensions.

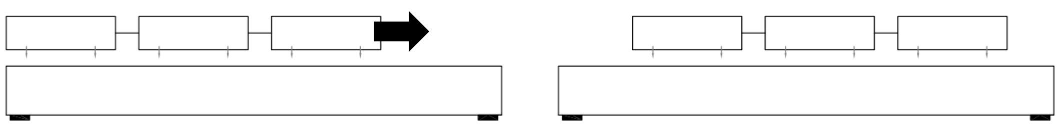


Figure 5. Loading schematic showing the movement of the train from left to right.

1.6.1. Load Case 1

Initially, the train will not be loaded with any additional weight. Therefore, the total train weight will be 400 N. This total weight will be evenly divided across the six (6) train axles.

1.6.2. Load Case 2

If your bridge withstands the load applied by the first pass of the train, **congratulations!** Your team will advance towards the next phase of the test. During this phase, the weight carried by the train will progressively increase according to a prescribed, monotonically increasing load protocol.

1. The **first or last car** is designated the **"locomotive"** and the remaining cars are "freight cars".

2. For the first pass across the bridge in Load Case 2, all freight cars will have identical weights, and the locomotive will be approximately **1.35 times heavier** than a freight car.

3. Proceed to the next page...

4. **(Load Case 2, continued):** For subsequent passes until eventual failure, the freight car **furthest away** from the locomotive will have a **heavier** weight than the other freight car.

5. The weight of this heavier freight car will be approximately **1.10 times** the weight of the lighter freight car for any given subsequent pass.

6. The locomotive weight will remain approximately **1.38 times heavier** than the weight of the heaviest freight car for any given subsequent pass.

For example, in the first pass of Load Case 2, if both freight cars weigh 135 N, then the locomotive weight will be 182 N. This train with a total weight of 452 N will act as the **"base case"** train loading for Load Case 2. Please note the locomotive may be at the front or end of the train during each pass but will **never** be in the middle.

1.6.3. Load Protocol Comments

Exact details of the train loads after the first pass of Load Case 2 remain a **closely guarded secret** among the CIV102 teaching staff (even the professor is not privy to this information! 😮). However, the teaching staff can confirm that teams from previous years have managed to design and construct matboard bridges that can withstand **beyond 1,000 N (1 kN)** of train load, which is impressive! If your team manages to surpass this 1 kN threshold, then all team members will be "low-key" inaugurated into the legendary **"Kilonewton Klub"** 🐉**.** However, your team can **still do well** on the bridge performance component (and the project as a whole) even if your bridge does not reach that high of a load, so please do not stress too much about this!

1.7. Construction Materials

The following materials will be provided for each team. **Please take care to not lose these!**

1. **One (1)** rectangular sheet of **matboard.**
   a. Dimensions: 32” × 40” × 0.05” (813 mm × 1,016 mm × 1.27 mm).
   b. Approximate mass: 750 grams.

2. **Two (2)** tubes of **contact cement.**
   a. Approximate volume: 30 mL per tube.
   b. It has negligible mass when dry.
   c. Full strength will only be attained if the contact cement is properly used and left to cure for at least 72 hours (3 days).
   d. All students **must** review the linked technical data sheet for contact cement in “Appendix III: Contact Cement Data Sheet” (and Section 1.8) to be informed about its safe use.

The material properties of the matboard and contact cement are shown in Table 2.

Table 2. Specified material properties for this bridge design project.

Material	Material Property	Specified Value(s)
Matboard	Specified dimensions	32” × 40” × 0.05” (813 mm × 1,016 mm × 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	4,000 MPa
	Poisson’s ratio, ν_m	0.2
Contact Cement	Shear strength, τ_g'	Up to 2 MPa if properly cured**

*** Full strength will only be attained if the contact cement is properly used and left to cure for at least 72 hours (3 days). Periods less than 3 days will result in a strength reduction.*

The pickup details for the materials will be announced via Quercus. Students may decorate their bridge with hand-drawn pencil, pen, and marker sketches. Students are also responsible for safely transporting their project materials/completed bridge to and from their practical. **Please note the CIV102 teaching staff are not responsible for storage. The use of any additional, unauthorized materials or extra contact cement tubes is strictly prohibited and will constitute a violation of academic integrity.** Prior to testing, your bridge will be weighed. Any suspiciously large weight warrants a bridge inspection and could lead to a potential disqualification from testing.

1.8. Construction Conduct and Location

Care **must** be taken when determining a suitable space for your team to build the bridge.

1. **The common spaces of Myhal are not permitted construction spaces. In previous years, the teaching staff received complaints from operations staff and/or caretaking. Teams that are found to have constructed their bridge in a common space of Myhal may be subject to marking penalties or disqualification.**

2. When working with contact cement, you will need to choose a sufficiently **open, room-temperature space.** Fumes from the contact cement can cause discomfort. **As such, avoid engineering common rooms (such as the EngSci common room) and residence common areas.**

3. **Regardless of the location, you must not damage any space and clean up after each working session. It is strongly recommended that you acquire and use tarps or garbage bags to make the disposal process smoother.**

4. Which using contact cement, please consider the following information:

    1. An older version of the **technical data sheet** for contact cement is available here.
    2. A recent version of the **safety data sheet** for contact cement is available here.

    As mentioned previously, working with contact cement requires an open space. This open space should also be **sufficiently ventilated.** To supply your own ventilation, you may purchase a small, portable electric fan (such as this one). When it is not too cold nor too wet outside, it is a great idea to **open windows or doors** to improve air circulation.

5. Teams may also elect to purchase **safety equipment** prior to working, such as face masks, disposable gloves, and/or a pair of flexible work gloves (such as this pair). Other construction tools can be purchased from a suitable store, such as Home Hardware, Canadian Tire, Staples, or Dollarama. Utility knives, scissors, cutting mats, straightedges, and clamps have also been beneficial to purchase from previous experience!

Some **possible or recommended places** to work are listed below:

Table 3. Possible team workspace locations.

Private	Public
Teammate's house, apartment, room, garage	Library group study room via bookings
Backyard	Outside at a not-too-busy public park**
Private workshop, design room, or warehouse	Front Campus*
A friend's studio apartment or other space	Empty storage room or parking garage
Pick-up truck or spacious van	Community centre multi-purpose room

*** Ensure the outside ambient temperature is between 15°C and 25°C. Good weather helps as well: no rain, no snow, and no strong wind. These conditions will help develop a good bond between the pieces you are attaching with the contact cement.*

When applying contact cement, remember to put it on both surfaces you would like to adhere together. Wait 15 minutes for the contact cement to stiffen (and be dry to the touch), and then press the surfaces firmly together. Clamp the surfaces together using small clamps for at least two to four hours (you can keep pieces and/or your bridge clamped overnight). For more details, visit this LePage website.

1.9. Permitted Software and Programming Languages

For your structural calculations, you can use any of the following to help:

1. Microsoft Excel, Microsoft Office...
2. Google Sheets, Google Drive...
3. Mathcad, or any other free spreadsheet software...
4. MATLAB, Python, Jupyter Notebook, GitHub...
5. AutoCAD, or any other free CAD software...

1.10. Use of Large Language Models (LLMs)

Humans have found great (and not-so-great) uses for large language models (LLMs) and this technology can evolve rapidly within our lifetime. When we say, "artificial intelligence" or "AI", we are referring to these LLMs. For this bridge design project, **LLMs can only be used (and hence, authorized) at the professor's discretion. If you use LLMs as an unauthorized aid for this project, this will constitute a violation of academic integrity outlined by the University of Toronto.**

1. Please read the scenario described in this University of Toronto Academic Integrity page concerning the use of AI (LLM) tools on marked assessments.

2. While one of the primary objectives of this project is to build the strongest bridge possible from the given materials, **we are not asking students to obsessively optimize every facet of the process.**

3. We intend for students to **appreciate the structural analysis and design processes** and not solely focus on getting big numbers at the end.

4. If your team is struggling with writing code, **please talk to a teaching assistant first.** You **cannot use LLMs to blindly write code** for your team and blindly copy this into your submissions.

5. If your team is encountering difficulty with brainstorming design ideas, please talk to a teaching assistant, ask around for some suggestions, or **take a nice walk outside with friends** and **look at a built bridge in Toronto** for some inspiration (and fresh air).

2. Project Deliverable Details

This project is worth **17%** of your final CIV102 grade. Table 4 summarizes the breakdown of marks and reveals information about deadlines.

Table 4: Breakdown of weights and deadlines for this Bridge Design Project.

Category	What to Submit?	Weight	Deadline
Structural Calculations (45%)	Deliverable 1	7%	Nov. 11th (11:59 pm) via Quercus
	Design Calculations	38%	Nov. 23rd (11:59 pm) via Quercus
Writing Components (20%)	Design Report	12%	Nov. 23rd (11:59 pm) via Quercus
	Engineering Drawings, Construction Process, and Time Log	8%	Nov. 23rd (11:59 pm) via Quercus
Bridge Performance (35%)	Physical Build	35%	Nov. 24th – Nov. 28th in Tutorial

Your project submission should consist of **4 separate PDF files** described in the following sections. Documents can be prepared using any combination of popular word processors, collaborative platforms (such as Google Drive or GitHub), open-source software such as LaTeX, or note-taking applications with an electronic device (such as an iPad).

Submission details begin on Page 13.

2.1. Deliverable 1

Deliverable 1 is due by **Nov. 11th at 11:59 PM.** Please submit one PDF.

1. Name this PDF as "CIV102 Project Team XXX Deliverable 1.pdf". Please replace 'XXX' with your assigned team number.

Please complete the following:

1. Assume the train is centered on the bridge (see Section 1.5).
2. Suppose the train is loaded according to the "base case" of Load Case 2 (see Section 1.6.2).
3. Determine the shear force diagram $V(x)$ and the bending moment diagram $M(x)$.
   a. **Neglect the self-weight of the bridge.**
   b. Assume the contact area of each wheel on the bridge deck is very small, so you can treat applied loads as point loads.
4. Calculate the centroidal axis location, $\bar{y}$, and the second moment of area, I, for Design 0 (see Appendix II: Design 0 Details). Include the presence of the glue tabs!
5. Calculate and submit the **factor of safety (FOS)** against flexural tension failure and flexural compression failure of Design 0.
6. Complete the **team dynamics survey** on Quercus.

2.2. Design Report

1. Please submit the design report as **one PDF by Nov. 23rd at 11:59 PM.**
   - a. **Typical length of this report: 12 to 20 pages, in total.**
   - b. Name this PDF as "CIV102 Project Team XXX Design Report.pdf". Replace 'XXX' with your assigned team number.
   - c. Please write the **names** of your team members on the first page of this report.
   - d. Please write the name of your teaching assistant on the first page of this report.
   - e. Please remember to write in a **neat, clear,** and **professional** manner! Points will be awarded for **nice formatting** as well!

2. Include an **introduction** section.
   - a. Present a clear description of your bridge (write a couple of paragraphs).
   - b. List of the key design decisions your team made (can use bullet points, write in paragraphs, use a table, or any combination of the above).
   - c. You can include photographs or other visuals as well!

3. Include sections that discuss your **major design iterations.**
   - a. Present **three (3) to ten (10) major design iterations** that your team performed before converging upon your final bridge design.
   - b. The results of each iteration should be explained using CIV102 knowledge, or from additional research that your team found online, **with references.**
   - c. Describe the design parameters you changed and **justify** your reasons (bullet points, small sentences, small paragraphs, tables, mathematical equations, labelled diagrams, or any combination of the above).
   - d. Images can be added to the report, where appropriate. These images should include labels and/or captions. They also should not be too blurry.
   - e. You **may include snippets or small screenshots of code** you wrote to emphasize points. You can also include a link to an external website to showcase all of your code, if your team prefers to do that!

4. If you used online sources outside of what is available within the scope of CIV102 to research anything, please provide in-text citations using a **consistent citation format.**
   - a. For this project, let's use the **IEEE** format.
   - b. A **bibliography** will be placed at the end of this design report.
   - c. **Citation managers,** such as RefWorks or Mendeley, can be used.

2.3. Engineering Drawings, Construction Section, and Time Log

1. Please submit this component as **one PDF by Nov. 23rd at 11:59 PM.**
    a. Name this PDF as "CIV102 Project Team XXX Engineering Assembly.pdf".
    b. The goal of the drawings is to convey your final bridge design and construction process to others. Think of these drawings as good drafts of your sketches.

2. The **first portion** of this PDF consists of your **(2D) engineering drawings.**
    a. Please provide the following:
        i. A 2D drawing showing how you plan to cut the matboard.
        ii. Bridge elevation, top, bottom, and cross-section views at important locations.
        iii. Splice, diaphragm, and any other connection details.
        iv. In addition to the 2D drawings, your team has the option of including a 3D rendering or 3D pencil/pen sketch of the entire bridge, if you have time.

    b. Drawings can be done **by hand via pencil** or **digitally via software.**
    c. An effort shall be made to make drawings that are **to scale.**
    d. AutoCAD can be used to make these drawings, if you know how to use it.
    e. Drawings may be spread across multiple pages. The minimum allowable page size is letter size (8.5" × 11") and the maximum is tabloid size (11" × 17").
    f. Dimensions for drawings shall be in **millimetres (mm)!**
    g. All drawings must be **neatly** drawn and **legible.**
    h. **Labels** may be included in drawings to enhance communication but avoid clutter.
    i. **Colours** may be used in drawings to add some vibrancy!

3. The **second portion** of this PDF details your team's **construction process.**
    a. **Photos that show bridge construction taking in a common space in Myhal may be subject to marking penalties or disqualification.**
    b. Please provide **timestamped, non-blurry** photo evidence of work.
    c. Add a **caption or label** for each photo to communicate what is happening.
    d. You **must** include a picture showing all the **precautions** your team took to **keep your building space clean.**
    e. You **must** also include a picture showing what your building space looked like when you **finished** a construction session. Include photos for all such sessions.

4. The **third portion** of this PDF is a **time log.**
    a. Please attach a detailed **time log** for all work on this project.
    b. Tasks and time spent on these tasks should be **recorded** for each team member.
    c. Each team member **must sign** this time log to signify they agree with the reported breakdown of project work.
    d. A **time log template** will be available on Quercus.

2.4. Design Calculations

1. Please submit the design calculations as **one PDF by Nov. 23rd at 11:59 PM.**
    a. Name this PDF as "CIV102 Project Team XXX Design Calculations.pdf".

2. This **first portion** of this PDF includes **hand calculations:**
    a. Hand calculations to determine the **FOS against failure** and **failure mode** for Design 0 under a moving 400 N train loaded according to Load Case 1 (see Section 1.6.1).
    b. Any other 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 (see Section 1.6.2).
    c. Presentation of hand calculations can include **non-blurry** photographs of calculations done on physical sheets of paper or electronic ink written using a tablet.
    d. Hand calculations deemed illegible or messy will receive mark deductions.

3. This **second portion** of this PDF includes **evidence of programming:**
    a. Code output for **all intermediate calculations** (such as centroidal axis location, moment of area, etc.) performed in the hand calculations of Design 0 under a moving 400 N train loaded according to Load Case 1.
    b. A graphical presentation of all **shear force capacities** (i.e., an SFE) of Design 0 for Load Case 1 and for your final design under Load Case 2.
    c. A graphical presentation of all **bending moment capacities** (i.e., a BME) of Design 0 for Load Case 1 and for your final design under Load Case 2.
    d. Code output of all **FOS values** along the bridge for Load Case 1 and for your final design under Load Case 2.
    e. Include the **entire script,** showing comments, formatting, and user-defined functions. Also indicate the **packages** you installed as well, such as "NumPy".
    f. Code deemed illegible or messy will receive mark deductions.

2.5. Bridge Performance

During your bridge testing session, you will observe, in real-time, how your bridge's design will fare (or buckle) under the train loads!

1. Marks will be allotted for:

   a. **Construction Quality (10 marks).**
      - This is a subjective assessment by Professor Bentz and is scored out of 10 points.
      - To obtain a high score, ensure your contact cement is applied cleanly and there are no frayed edges and/or creases on the matboard.
      - Teams that make an aesthetically pleasing bridge (i.e., with cool drawings, sketches, and colours) can sometimes get high scores as well.

   b. **Bridge Performance (20 marks).**
      - This is the value of the test failure load, which is a rough measure of **strength**.
      - The score is determined using a set of calculations that involves a cumulative density function (CDF) and the bridge's **strength-to-weight ratio.**

   c. **Accuracy in Estimation of the Total Failure Weight (5 marks).**
      - The score is determined using a set of calculations that involves a cumulative density function (CDF), similar to the previous bullet point.

2. Prior to testing, your bridge **must be clearly marked** with the following:
   - Your **team number!**
   - Your **team member names!**
   - Your **team's name,** if you have one!
   - Your **bridge's name** (can be creative)!
   - Your **teaching assistant's name!**
   - The **predicted total failure weight,** in newtons (N)!

2.6. Analysis Methods

Analysis of your own bridge design can be performed using either a **MATLAB** script or a **Python** script. For engineering students, the University of Toronto has an academic license for MATLAB available here, which you may activate in order to install MATLAB onto your local device, such as a laptop. Regardless of the method you choose, you should **ensure the code returns the same result as what the rest of your team obtains and ensure it runs smoothly.**

1. All results must be presented **neatly** and **concisely.**

2. **The output of your script should match the hand calculations for Design 0.**

3. "Appendix I: MATLAB Pseudo-Code" contains example code which can be used as a starting point for developing a MATLAB script.
    a. This method may be helpful for teams interested in building a **variable-depth** box girder, where different-sized cross-sections exist along the length of the bridge.
    b. This example shows a train loaded to 400 N according to Load Stage 1 (see Section 1.6.1).

3. Project Design Details

3.1. A Possible Calculation Procedure

Your team may 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 **reaction forces, internal forces,** the **shear force diagram (SFD),** and the **bending moment diagram (BMD).**
   a. Denote the SFD as $V(x)$ and the BMD as $M(x)$.
   b. Each of these diagrams will be calculated 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.** This is crucial because the train will move across the bridge and thus the load will also move. As such, you will have multiple SFDs and BMDs.

3. Using these SFDs and BMDs, you will then construct a **shear force envelope (SFE)** and a **bending moment envelope (BME).**
   a. Denote the SFE as $V_{\text{env.}}(x)$ and the BME as $M_{\text{env.}}(x)$.
   b. Each respective envelope reflects the maximum values of shear force and bending moment at every location along the bridge, corresponding to all possible train locations.
   c. Given the nature of this task, it is advantageous to write code to accomplish this.

4. Define bridge **geometry (design parameters).**
    a. Define bridge cross-section shape and parameterize dimensions. Some possible parameters include widths (b), height (h), thickness (t), etc.
    b. For variable-depth cross-sections, define changes to cross-sectional dimensions along the length of the bridge.
    c. Choose geometry $\{b(x), h(x), t(x), \ldots\}$.

5. Calculate cross-sectional **geometric properties.**
    a. $[\bar{y}(x), Q(x), I(x)] = f(\text{geometry})$.

6. Calculate applied **stresses.**
    a. $[\sigma_{\text{top}}(x), \sigma_{\text{bot.}}(x), \tau_{\text{cent.}}(x), \tau_{\text{g}}(x)] = f\left(V_{\text{env.}}(x), M_{\text{env.}}(x), \bar{y}(x), Q(x), I(x)\right)$

7. Calculate material/thin plate buckling **capacities.**
    a. $\left[\sigma_{\text{tens.}}(x), \sigma_{\text{comp.}}(x), \sigma_{\text{buck.}}(x)\ \tau_{\text{max.}}(x), \tau_{\text{glue}}(x), \tau_{\text{buck.}}(x)\right] = f(\text{geometry}, \text{material properties})$

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

$$\text{FOS}_{\text{tens.}}(x) = \sigma_{\text{tens.}}(x)/\sigma_{\text{bot.}}(x)$$

$$\text{FOS}_{\text{comp.}}(x) = \sigma_{\text{comp.}}(x)/\sigma_{\text{top}}(x)$$

$$\text{FOS}_{\text{flex\_buck\_1,2,3}}(x) = \sigma_{\text{buck\_1,2,3}}(x)/\sigma_{\text{top}}(x)$$

$$\text{FOS}_{\text{shear}}(x) = \tau_{\text{max.}}(x)/\tau_{\text{cent.}}(x)$$

$$\text{FOS}_{\text{glue}}(x) = \tau_{\text{glue}}(x)/\tau_{\text{g}}(x)$$

$$\text{FOS}_{\text{shear\_buck.}}(x) = \tau_{\text{buck.}}(x)/\tau_{\text{cent.}}(x)$$

9. Find the **minimum FOS**.
    a. This value represents "how many" trains would fail the current design.
    b. FOS values are computed as the **capacity-to-demand** ratio.
    c. If minimum FOS <1, the current design will not support the given train.
    d. If minimum FOS >1, the current design will be able to carry a heavier train. Calculate maximum train weight the current design can hold.

10. For **visualization purposes,** plot the shear force capacities $V_{\text{fail}}(x)$ and bending moment capacities, $M_{\text{fail}}(x)$.

$M_{\text{fail\_tens.}}(x) = \text{FOS}_{\text{tens.}}(x) \cdot M(x)$

$M_{\text{fail\_comp.}}(x) = \text{FOS}_{\text{comp.}}(x) \cdot M(x)$

$M_{\text{fail\_buck\_1,2,3}}(x) = \text{FOS}_{\text{flex\_buck\_1,2,3}}(x) \cdot M(x)$

$V_{\text{fail\_shear}}(x) = \text{FOS}_{\text{shear}}(x) \cdot V(x)$

$V_{\text{fail\_glue}}(x) = \text{FOS}_{\text{glue}}(x) \cdot V(x)$

$V_{\text{fail\_buck}}(x) = \text{FOS}_{\text{shear\_buck.}}(x) \cdot V(x)$

11. **Repeat starting from step 4.** Choose new **geometry** to **increase the minimum FOS** and thus maximum train weight. This new maximum train weight represents your new failure load estimate.

3.2. A Possible Design Procedure

To begin the iterative design process, there must be an **initial design** either chosen arbitrarily or based on prior experience. For this project, the initial design (**Design 0**) has been chosen for you. The details of Design 0 are provided in "Appendix II: Design 0 Details".

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

Once these calculations are complete, commence the design of your own bridge by changing the geometric parameters (Step 4 in Section 3.1). For every major design iteration, record the...

1. **Design decisions** you made as a team.
   a. Examples include changes to geometric parameters or how to fold the matboard.

2. **Justification** for each decision made.
   a. This may come from hypothesis, calculations, or experience.

3. **Results** to provide evidence for each justification.
   a. This includes important output parameters and the failure load.

At the same time, you will have to balance...

1. **Material constraints,** such as the available matboard area.
2. **Feasibility constraints,** such as construction difficulty.

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

3.3. 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.

1. **Splice connections.**
   - The maximum dimension of the provided matboard is shorter than the required span.
   - Therefore, a **splice connection** in the bridge is required at some point.
   - Failure across this location will not be reflected in the calculations suggested in Section 3.1.

2. **Rigid cross-sections.**
   - The concepts discussed in CIV102 assume the cross-section **remains rigid** under loading.
   - This assumption may not remain true, which could void the calculations discussed in Section 3.1.

3. **Rigid support sections.**
   - Areas near supports will be subjected to **direct vertical compression.**
   - This is not considered in the calculations described in Section 3.1.

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.

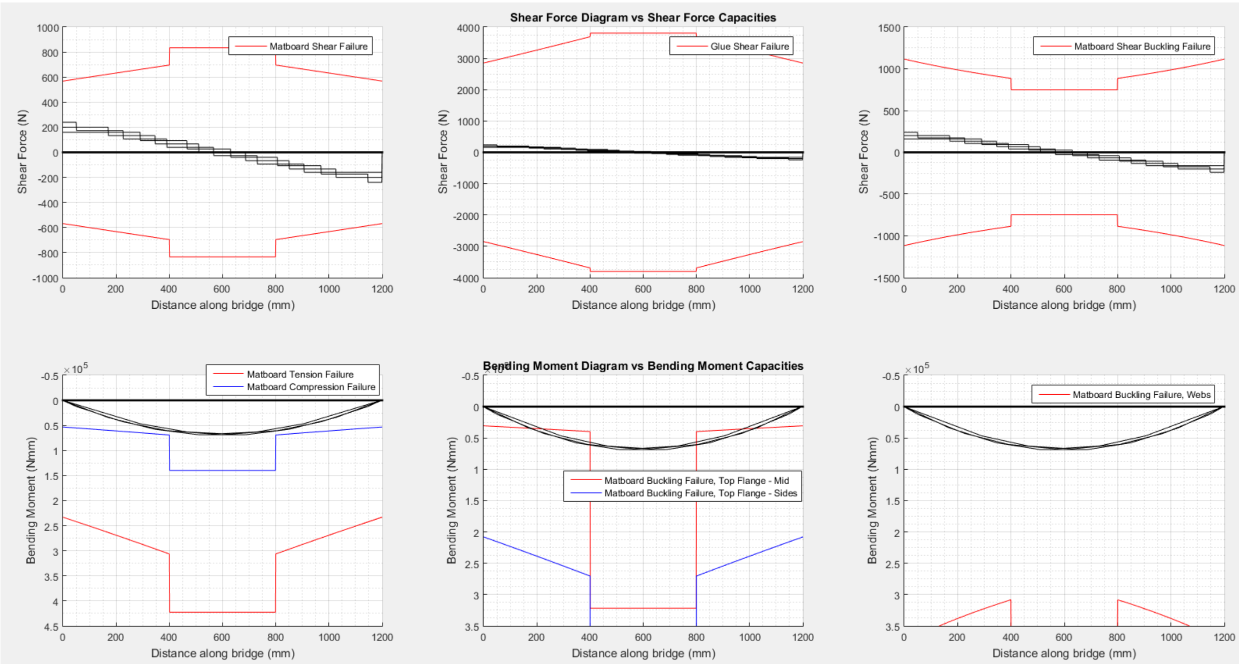
4. Appendix I: MATLAB Pseudo-Code

The following MATLAB code is meant as a guide only. It was written by a famous and esteemed previous head TA of CIV102, Raymond 💯🔥. You are not required to follow any of its given methods or format. As a reminder, you may also use Python to write code if that is your team's preference.

```
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:

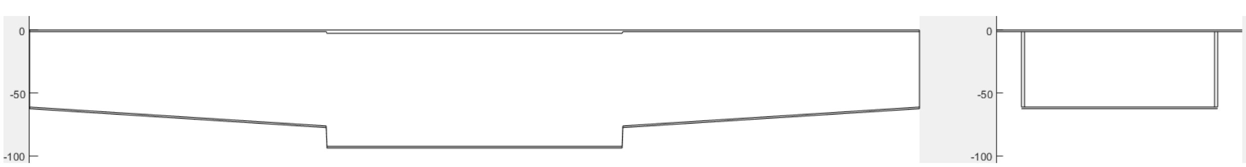


In the above analysis, the proposed bridge is:

- Far from failing due to glue failure (FOS = 11.87).
- Far from failing due to buckling in the webs (5.03).
- Far from failing due to tension (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 (FOS = 0.649).**

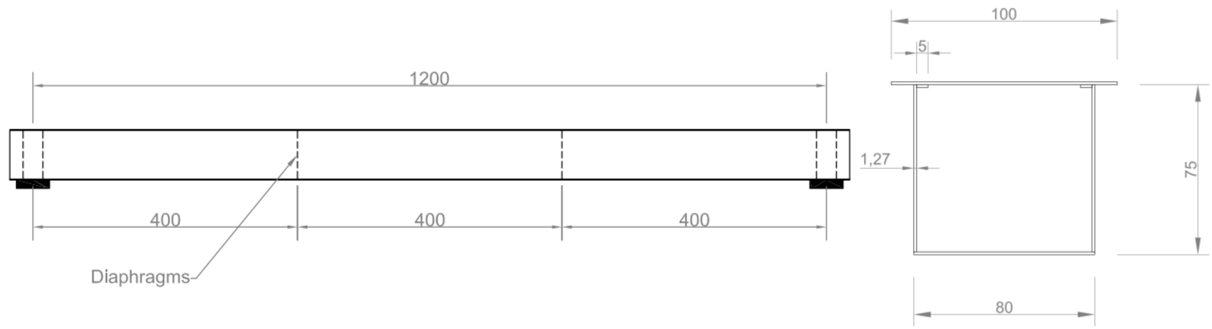
Thus, the maximum train load this bridge can support is 0.649 × 400 N = **260 N.**

The bridge had the following geometry (notice the variable depth of the web from left to right). This output is not required from your code.

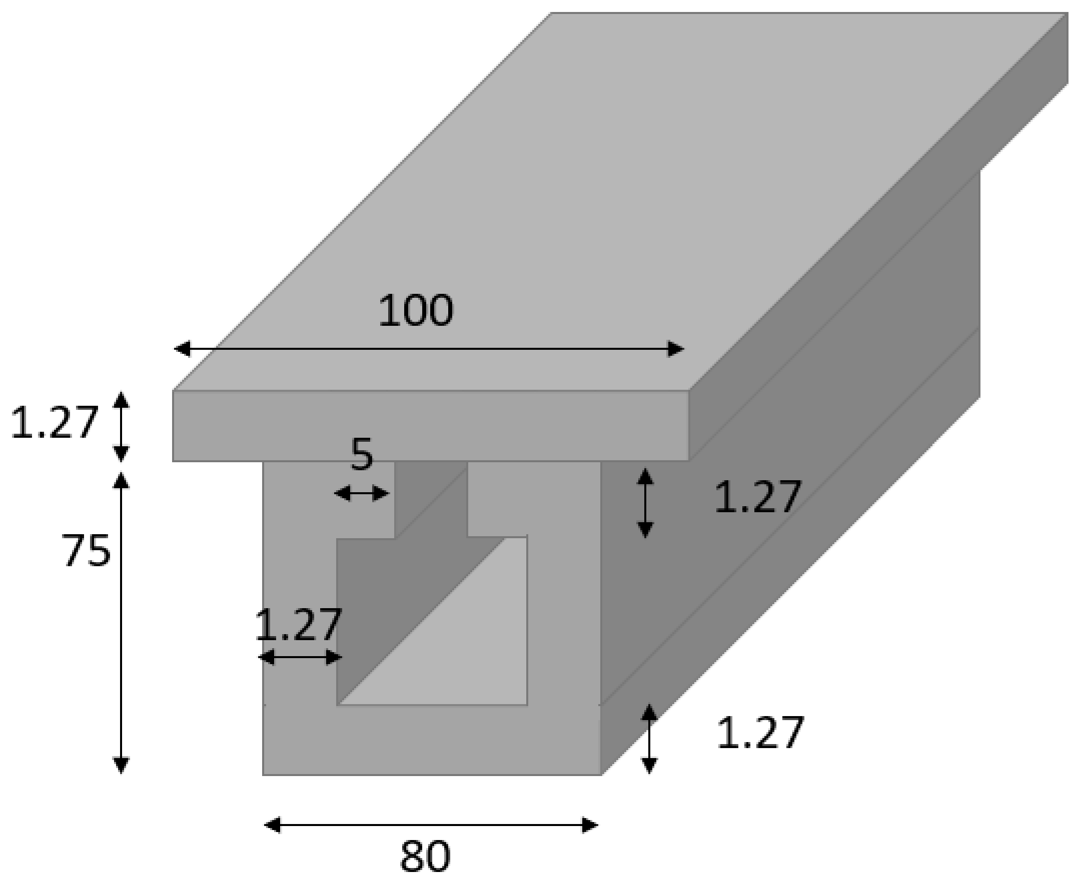


5. Appendix II: Design 0 Details

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



Cross-sectional shape and dimensions (in millimetres) of Design 0:



This is a **not-to-scale sketch.** The 5-mm wide piece has a surface for which glue on be applied to attach the bottom "U" piece to the top. There are other ways to glue your bridge together—this example is only showing one out of many possible approaches.

6. Appendix III: Contact Cement Data Sheets

An older version of the **technical data sheet** for contact cement is available here.

A recent version of the **safety data sheet** for contact cement is available here.

Please note that the ***contact cement is volatile*** and prolonged exposure to its smell is ***not*** healthy. ***Remember to take frequently breaks while working.***

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

Contact cement is difficult to clean, so please do not leave it everywhere...