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Structures and Materials Bridge Design Report: The Design Procedure of Concepts I and II*

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CIV102: Structures and Materials- An Introduction to Engineering Design

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*Please consider design II for bonus

1.1 - Description of Concept I Bridge Design

The bridge design that has been chosen was inspired by a simple Pi beam. The beam bridge is the foundational concept of the bridge, made up of multiple layers resembling a Pi cross section. The bridge is constructed by having 2 flange top section panels with the dimensions 1000x100x1.27mm, these would be glued together to strengthen the friction between both panels to avoid sliding between the flange sheets. The flanges would be aligned in parallel where the 1000mm becomes the span of the bridge connecting both ends and serving as the top flat platform of the bridge to allow loads. On this platform the 30x100mm loading plates are added 280mm from the supports. The bottom legs are constructed out of 4 1000x122.46x1.27mm web wall panels, these are cut and glued together where the glue allows for a more rigid structure preventing the sliding between both plates, allowing them to behave as a single wall of double thickness. These cross section legs are then glued on the bottom section of the top flanges vertically having a gap of 90mm between them centered along the central axis parallel to the span of the bridge. In this manner a Pi cross section is formed, diaphragms are added periodically, at sections of highest forces applied on the bridge to build up its structural integrity as well as increasing the resistance to thin wall shear forces. These are placed specifically in alignment with the loading plates on top and below the bridge. In this manner the bridge is within the size dimensions whilst passing the failure stress requirement and being efficient in the use of matboard. Since our design is very strong in the glue stress failure department, we decided to not use top tabs to increase glue strength like in classic pi beam design, with the intention of minimizing material use. Our bridge is designed for a failure load of **1386N**, and the mode of failure will be due to flexural compression forces. The strength-to-weight ratio is calculated to be 1.938N/g.

1.2 Process of the Bridge Design

Our initial concepts considered all forms of bridges that we had studied throughout CIV102. We eventually converged to a beam bridge due to its simplicity and its high strength to weight ratio. We went on to determine the design of the cross-section for the bridge, for which we had two initial ideas: the I beam and the pi beam. The calculations for both cross-sections were done in between meetings.

After the calculations were finished, we discussed and compiled our results of the varying failure stresses for the I and pi simple cross sections. The base case had a height of 200mm, with one single layer flange and one and two 198.73mm web members respectively. We have found that a pi beam is highly favourable over an I beam due to the I beam's wide range of member strengths. Specifically we had found that the I beam has a very weak top flange as it is only supported by a thin pillar in the middle. To increase the top flange strength, either the web member's thickness or the flange's thickness must be increased by a factor of approximately 3. This means that we would need to triple the thickness of the beam or the thickness of the flange. In either situation, this would result too many undesired changes on safe parameters that were calculated. The I beam bridge seemed to fail by 50.5N at unrestrained flange buckling while the pi beam bridge failed at 369N by tensile flexural failure of the webs. We had then decided to build upon the Pi beam concept as it possessed greater potential to become our design.

To verify our initial calculations, we decided to build an excel program which calculates the different modes of failure when given the initial parameters of the bridge. We used this to verify our calculations for the initial design, as well as for every iteration that we would do later on. Then, we selected the top modes of failure for each cross section design, and tried to fix them one by one.

We found that the initial design for the Pi beam bridge failed on tensile flexural strength of the webs at 366N, web shear buckling at 518N, and restrained flange buckling at 547N. We would change specific dimensions of the bridge until the force needed for the bridge to fail would exceed 1000N for each mode of failure.

For our second iteration, we tried to eliminate the restrained flange buckling by doubling the thickness of the top flange from 1.27mm to 2.54mm, as well as moving the web members closer, from 100mm apart to 90mm apart. This effectively amplified the failing load from 549N to 4042N. This gives us lots of leeway for future iterations.

For our third iteration, we decided to double the web member's thickness and minimize its height. In theory, this should increase the second moment of area, thereby increasing the tensile flexural strength of the webs. We changed the height from 198.73mm to 122.46mm for the web members, and changed the width from 1.27mm to 2.54mm. This effectively increased the tensile flexural strength from 333N to 2805N, and it also changed the shear web buckling of the web members from 523N to 6661N.

For our last iteration, we decided to add diaphragms at the location of the loads as well at the location of the supports. This was not a crucial component of our design, as we already have more than enough shear web buckling strength at 6661N, however, minimal diaphragms were added to satisfy the requirements of the bridge design. This changed the distance between diaphragms to 360mm, which changed the failing load due to shear buckling from 6661N to 7464N.

Our final design for the bridge design concept 1 is now complete. It involves a simple pi beam with a flange member of 1000mm x 100mm x 1.27mm, and two web members of dimensions 1000mm x 122.46mm x 2.54mm. It also involves 8 diaphragms of dimensions 100mm x 122.46mm x 1.27mm, installed at the supports and at the loading points as shown in the diagram below.

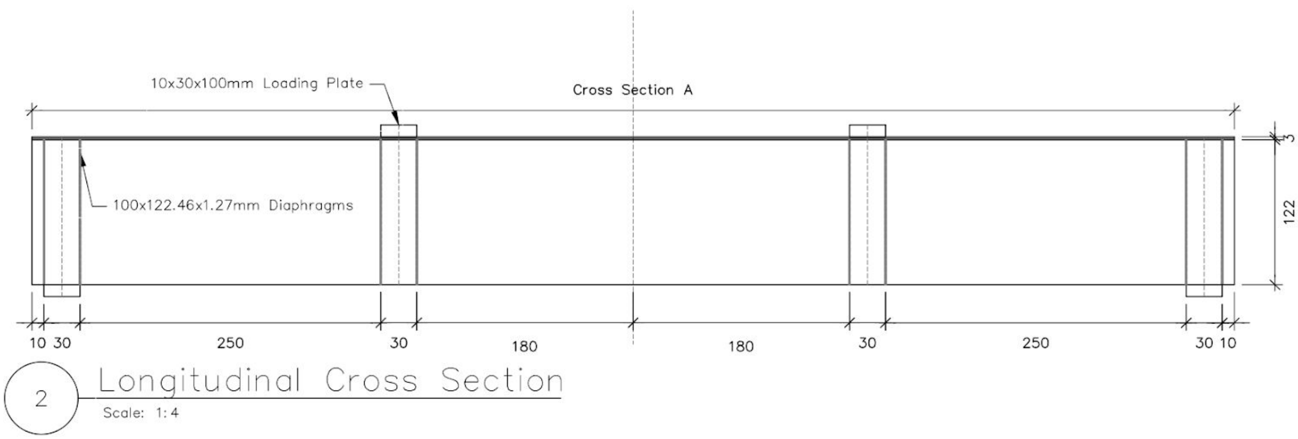

Figure 1: The Longitudinal Cross Section of the Concept 1 Bridge

1.3 Building of Bridge I

To construct our bridge design #1, we first need to cut the Matboard into pieces of appropriate size as described in the Matboard diagram. Then, we would use contact cement to glue everything into place. The flange and web members will first need to be glued to become double-layered. Then, we will construct the general shape of the bridge. We would make sure the distance between the web members is 84.92mm measuring from the inner sides, and 90mm measuring from their outer sides. Lastly, we would install the diaphragm members by cutting out spaces for the diaphragm in the web members at each location. We will, once again, apply contact cement as adhesive to install the diaphragms, and the bridge construction is complete.

2.1 Description of Concept II Bridge Design -- <u>Please consider for bonus</u>

This bridge design was divided into three different components: positive moment section, negative moment section, and middle support beam. For the positive moment section, the bridge is built with a modified pi beam cross section. A top tab and a bottom tab was added to each web member, the prior for increasing glue strength, and the latter for increasing the second moment of area, which in turn increases the shear stress failure allowance. The flange would be 100mm wide, and the web members would be 69mm high, 1mm would be used for the top tab and 16mm would be used for the bottom tab by bending the web members. For the negative moment section, the bridge was built with a simple pi beam cross section. This is because the top half the cross section would be subject to tension instead of compression due to the negative total moment, meaning the top flange would not be under any form of buckling. A different cross section was used because it was found to be more efficient at maximizing loads whilst minimizing the material used, as the bottom tabs and glue tabs were found unnecessary with the negative moment. This resulted in us having the bridge be varying in height and allowing it to adapt its height with the moment applied maximizing its efficiency. The middle cross section for the negative moment was found to be considerably taller at 115mm, this The middle support was designed by applying the maximum force on the bridge and evaluating the necessary material needed to support the force, the force was found to be 1201N and the resulting design was found to be a hollow square cross section being a 167x167mm with the matboard used being 1.27mm thick. Due to the increased height of the bridge the support middle beam will be reduced in height to only being 554mm reducing the necessary materials needed for the support beam, further minimizing the amount of sheets used. Due to the high optimization and multiple iterations of design, through the use of varying height and changing cross section we were able to maximize the strength to weight ratio to 1.994N/g making it significantly more efficient than concept 1 and allowing it to be efficient enough and impressive to be eligible for a bonus.

2.2 Process of Bridge Design

Since a middle-supported structure is considered an indeterminate structure, we first needed to figure out the load distribution from the three supports. We used the same method as in assignment 8, first ignoring the support at the middle, we calculated the deflection of the beam in terms of P. Then we calculated for the force at the middle which would result in the same deflection upwards, while ignoring the two point loads coming down. With the upwards force at the middle, we are able to draw a new set of SFD and BMD, which describes the actual behaviour of the indeterminate structure. We found a positive max moment and a negative max moment from the BMD, the prior on both sides of the middle support, and the latter at the middle of the support. This meant that we had to account for two types of moments at different regions of the bridge, negative moment at the middle and positive moment on the two sides.

We decided to design the positive moment parts first. The first thing we did was calculate the failure load of a simple pi beam with a total height 200mm. This only gave us a failure load of 518N due to shear buckling, and all the other modes of failures passed. However, this design took way too much material, so we decided to decrease the height of the web members from 198.73mm to 69mm, which is our second iteration. This gave us multiple failure modes, including glue and Matboard shear failure and restrained flange failure.

For our third iteration, we decided to tackle the restrained flange failure by decreasing the distance between the webs to 63mm, which results in the optimal distribution for flange restrained and flange unrestrained thin wall buckling failure load. This increased our flange failure load from 480N to 1252N, which satisfies the applied load of 1200N for a bonus going beyond the necessary 1000N.

For our fourth iteration, we decided to add top tabs to increase the glue strength between the top flange and the web members. We found that by adding 1mm of top tab, the glue shear surpasses the required load of 1200N from the original 630N.

For our fifth and last iteration, we decided to add bottom tabs to account for the Matboard shear failure. This is our "own touch" to the bridge, as the bottom tabs in theory should only affect the "I" value and the location of the center of mass of the cross section, as well as the Q values used to calculate shear failure. **In order to obtain the maximal force with the minimal amount of material used, we built an optimization program and ran the program through varying heights ranging from 10mm to 150mm to obtain the option that is just over 1200N**. This program gave us a total height of 76mm for each web, of which 1mm is used for the top tab, and 16 is used for the bottom tab. This was done to minimize the material used for the bridge component, effectively leaving more material for the middle beam, whose size is currently undetermined. We then double checked this result with our own calculations, which can be found in the calculation section of the submission.

For the negative moment component, we started with a similar starting point as the positive moment. We first calculated the failure modes of a 200mm height pi beam, and then, to minimize the material used, **we modified the optimization program to fit with a simple pi beam, and found the optimal height for the web members of the pi beam to be 115mm.** This was our second iteration, the height was decreased from 198.73mm to 115mm.

For our third iteration, we found that the shear buckling of the webs is a mode of failure as it currently stood at 900N. We decided to implement diaphragms. However, since we plan on implementing the diaphragms at the edges of the middle support, we were not sure what the maximum distance between the diaphragms were. To be safe, we took the distance from the point load to the middle of the support, which is the maximum possible distance between the two diaphragms. To make sure that the bridge would still hold up after implementing the middle support diaphragms, we performed a calculation with the final design of the bridge and confirmed its shear strength. This can be found at the last part of the calculations.

Given our final iterations, we utilized the final maximum forces values to determine the necessary design for the support, following the optimized varying cross sections, we found that globally the minimum failure force was 1201N, this was minimal to allow for minimization of the material used, however could be increased significantly if necessary given the excess material available. With a force of 1201 N the force on the support was found to be 889N through the ratio of the support force to force applied calculated using the method of deflection. A hollow square cross section was preferred to stay within the size constraints for the bridge, as a rectangular cross section would exceed the 200mm allowable length for the support. The minimum cross section area was then found to be 148.21mm^2 whilst the second moment of inertia was 3830007mm^4 . Through these values the necessary base of the support was found to be 167mm with a thickness of 1.27mm, this was adequate as it was found to be within the size and material restriction whilst still providing the necessary reaction force. With the support found the components of the bridge were complete.

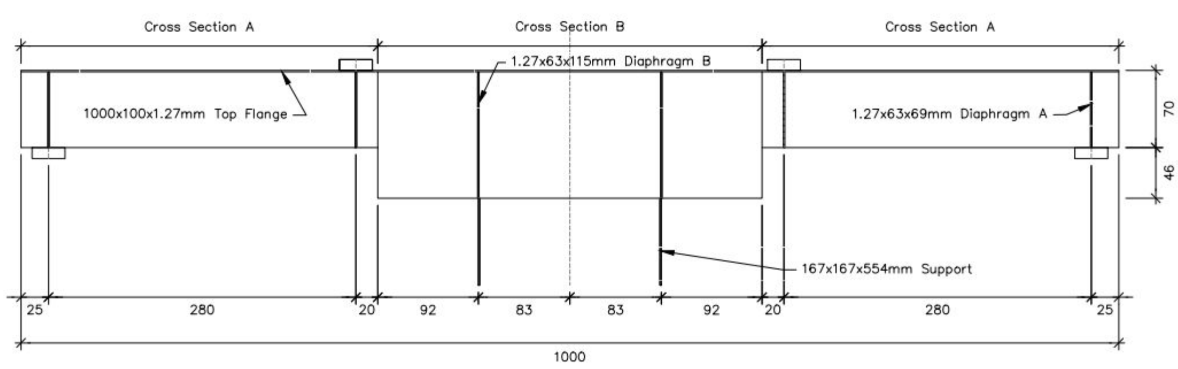

Figure 2: The Longitudinal Cross Section of the Concept 1 Bridge

2.3 Building of Bridge II

First, we will cut out each member of the bridge as shown in the Matboard diagram for Bridge 2. Then, we will proceed to bend out the top and bottom tabs for the positive moment parts of the bridge, and using the contact cement, we will glue the webs to the top flange. Then, we will glue together the middle support component, as well as the negative moment part of the web members to the top flange. Lastly, we would assemble the diaphragms using contact cement onto the top flange, and then bridge design is complete

Figure 3: The table of final maximum forces of failure

Cross Section		**Pi Beam (Bridge 1)**	**Pi Beam (+ve moment Bridge 2)**	**Pi Beam (-ve moment Bridge 2)**
flexural stress	tension	3997N	4597N	12934N
	compression	1386N	1509N	1412N
shear stress	Matboard-shear	3766N	1201N	1761N
glue failure	shear	2672N	1509N	1226N
thin wall buckling	Flange - Restrained	2838N	1521N	N/A
	Flange - Unrestrained	38323N	1512N	N/A
	Webs - Flexural - Tensile	2805N	2662N	1383N
	Webs - Flexural - Compressive	16547N	13028N	8987N
Shear buckling	Webs - Shear	7464N	1787N	1276N

3 The comparison of Concepts

The first concept designed was found to be strong whilst being very simple to construct, this allowed it to be an overall flexible option. However, the concept 2 bridge with its extreme optimization through multiple design iterations of its respective varying height and cross sections, was found to be the favourable option as it overall, it had a greater potential of being a greater potential of being a stronger bridge as it possess a greater failure force whilst minimizing the amount of material used to the lowest possible amount. Furthermore, concept two was overall found to be a more innovative bridge covering a greater range of engineering concepts whilst the multiple revisions over each section allows it to be a safer bridge. The minimal use of materials can be converted into a greater factor of safety for the bridge allowing it to be an overall safer bridge.