# CAMBRIDGE UNIVERSITY ENGINEERING

## STRUCTURAL DESIGN PROJECT

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Group : 170

Project : Bridge Design (Problem 2A)

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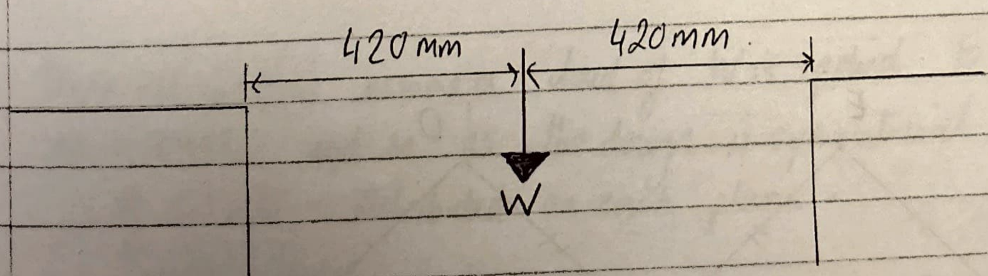
Project Report.

## Report Summary

This report outlines the problem definition, which establishes the fundamental requirements and constraints from the structural design project. Based on these, several models of bridges were evaluated, taking into account factors such as material cost, ease of manufacture, and intended functionality. A quantitative analysis is also conducted in this report, enabling a design suited for the project requirements. Key considerations included: optimising the length of compressive members to prevent various buckling modes; assessing tensile forces in bar members; designing and analysing the loading plate etc.

Following the manufacturing process, the structure was costed, and this report details the deviations made from the original design. The cost is also evaluated, as sustainable engineering is crucial in the current world. Further discussions include reviewing the mode of failure and reflecting upon the design and suggesting possible improvements.

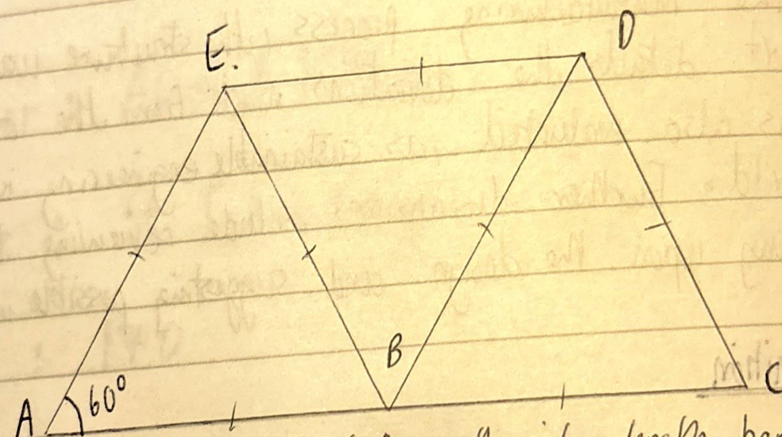
## Problem Definition



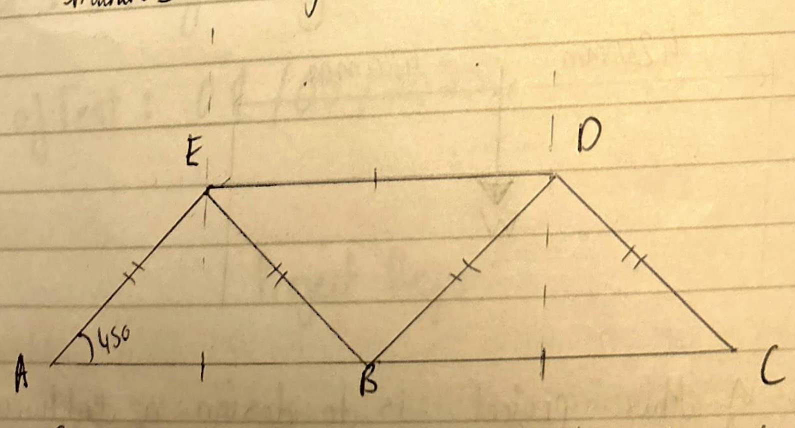

The aim of this project is to design a lightweight, easy-to-build truss bridge that spans a clear gap of 840 mm between 300 mm wide supports. It must carry a working load of at least 3.5 kN ~~and~~ without showing significant visible deformation. The load is applied through a 13 mm diameter hole in a vertical plate, which must sit somewhere between 5 mm and 75 mm above the level.

of the supports. The plate also must be thick and strong enough to avoid tearing under the load. The bridge will rest freely on the supports, and there must be a way to position the structure on the test rig as shown in the figure. Ideally the structure must fail at as close to 7.0kN as possible to meet the required load factor of 2. This needs to be carefully considered in the design process, as to design the most efficient bridge which will fail as close to 7kN as possible to avoid overengineering / underengineering the structure.

## Alternative Designs and Evaluation




Structure 1: All angles 60°, with uniform length bar members.




Structure 2: Structure consists of isoceles triangles with 45° angles.

The main two trusses considered were both a variation of the Pratt Truss, but one with angles of 45° and one with uniform length bar members with angles of 60°. From a qualitative perspective, Structure 1 has an ease of manufacturing advantage, due to having uniform bar members and symmetry additionally as will be shown in the next section it has shorter compression members and carrys less tensile force. However it is quite tall and so it uses more material which may not be the most economically viable.

## Calculations

| Bar Member | Force in Structure 1 (W) | F in S2 (W) | Force Structure 1 (KN) |
|---|---|---|---|
| AB | $+1/4\sqrt{3}$ | $1/4$ | 1.01 |
| AE | $-1/2\sqrt{3}$ | $-\sqrt{2}/4$ | -2.02 |
| BE | $1/2\sqrt{3}$ | $\sqrt{2}/4$ | 2.02 |
| BC | $1/4\sqrt{3}$ | $1/4$ | 1.01 |
| BD | $1/2\sqrt{3}$ | $\sqrt{2}/4$ | 2.02 |
| CD | $-1/2\sqrt{3}$ | $-\sqrt{2}/4$ | -2.02 |
| DE | $-1/2\sqrt{3}$ | $-1/2$ | -2.02 |

These calculations assume a load of W is applied to the Structure (where W = 7KN) and so as the design is symmetrical, a central point load of 3.5 kN distributed on each plane.

Therefore as can be clearly seen by the calculation table, structure 1 carries significantly less load accross it's members, and this is specifically significant regarding the compressive members. Hence due to a combination of these factors structure 1 was chosen as the starting point, and this design process involved further analysis to prevent different modes of failure as will be shown in the next few pages.

## Analysis of Tensile members.

$\sigma_Y$ of Aluminium Alloy $= 255 N/mm^2$

Therefore to choose the right angle (bar), it must ~~be able to sustain~~ ~~a yield (maximum~~ ~~be able~~ carry a stress, less than the yield stress. So choosing the lightest angle first:

Angle dimensions : $(9.5 \times 9.5 \times 1.60)$ mm

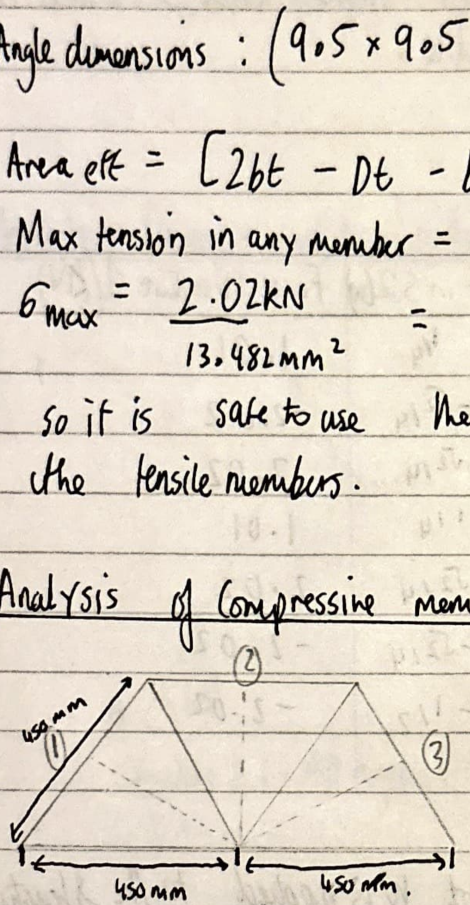
Area eff $= [2bt - Dt - b/_2 \times t] \times 0.9 = 13.482 mm^2$.

Max tension in any member $= 2.02$ kN

$$\sigma_{max} = \frac{2.02kN}{13.482mm^2} = \underline{\underline{149.9 N/mm^2}} \quad \text{which is} \le \sigma_Y$$

so it is safe to use the $(9.5 \times 9.5 \times 1.60)$ angle for all of the tensile members.

## Analysis of Compressive members.




The compressive members are members 1 2 and 3.

Therefore to avoid buckling bracing must be added to them as currently: (even using the biggest angle):

$$\frac{L}{b} = \frac{450}{16.0} = 28.125 \quad \text{which gives } \sigma_{crit} \approx 40 N/mm^2$$

but $\sigma_{Actual} > \sigma_{crit}$ as $\sigma_{actual} = 61.8$ so it buckles

Therefore applying bracing to the centre of the compressive members is necessary, and ~~hoping~~ as it reduces their effective length by half. So trying different angles to get a safe $\sigma_{actual}$ below $\sigma$ critical was necessary. Shown below are a couple of attempts:

Trying $(16.0 \times 16.0)$ gives $\frac{L}{b} = \frac{225}{16.0} = 14.1 \Rightarrow \sigma_{cr} = 125\ N/mm^2$

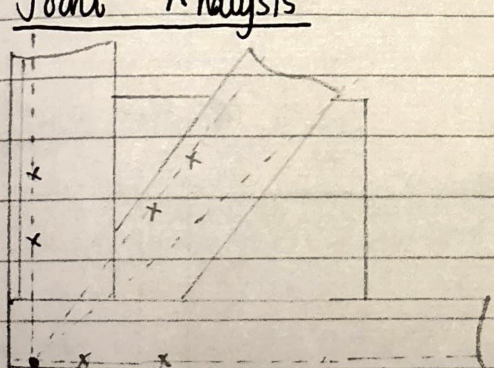
and $\sigma_{actual} = 61.8\ N/mm^2$ so this works.

$(15.9 \times 15.9)$ gives $\frac{L}{b} = \frac{225}{15.9} = 14.2 \Rightarrow \sigma_{cr} \approx 130\ N/mm^2$

And $\sigma_{actual} = 77.2\ N/mm^2$ so this also work.

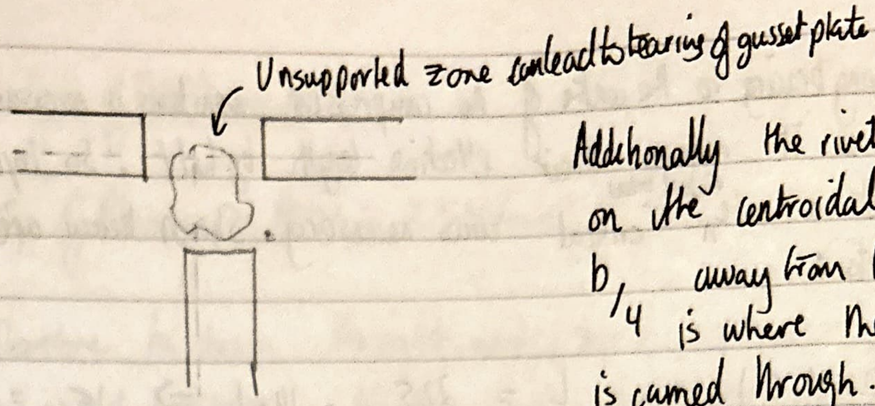
These calculations were repeated for other members however they all failed therefore the $15.9 \times 15.9 \times 1.60$ angle was chosen, as it doesn't buckle and is the most cost and ~~weight~~ mass effective.

## Joint Analysis

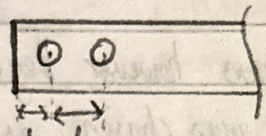


Shown on the left is an example of a joint designed for the bridge. The main considerations were the placement of the rivets ~~and~~, the number of rivets and the layout of the angles on the gusset plate.

The idea behind "butting" the angles together is to avoid an uneven distribution of shear stress on the gusset plate, which may cause it to tear. This is because if there is a gap between one ~~gus~~ angle and another angle, the force will be transmitted through the gusset plate which can cause failure at high loads.

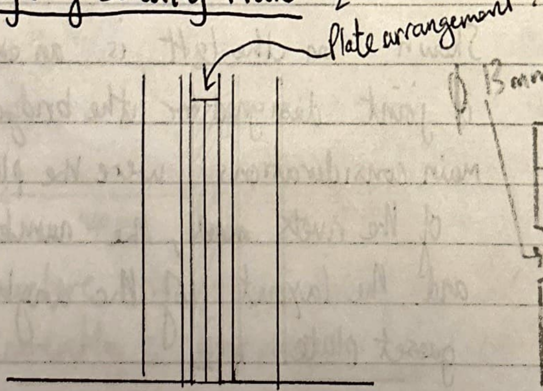


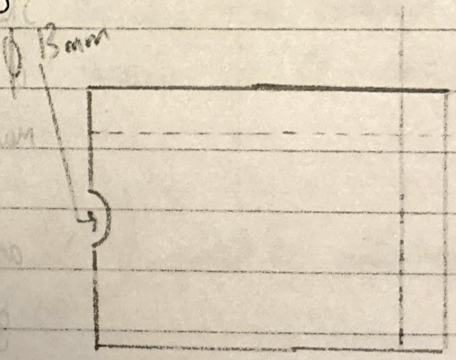

Additionally the rivets should lie on the centroidal line which is $b/4$ away from the edge, as this is where the shear force is carried through. ~~Also~~ This was considered in our design, and included within the drawings. Also 2 rivets were enough everywhere as they carry a load of 2.54 kN which was more than required. Additionally the rivets were positioned 10mm apart, and 10mm from the bar end because $L > 2.5D$ where $D$ is the hole diameter and $L < 32t$ where $t$ is thickness of either plane to allow even distribution of Tension across connections.




→ both L must be : $2.5D < L < 32t$ and choosing a value of 10mm is ideal as $2.5D = 6.40$mm and $32t = 32$mm.

## Design of Loading Plate .2




The loading plate is connected between the two planes of the bridge, and the design of it had to be considered quite carefully, as this is where the load acts. Therefore if the loading plate itself wasn't strong enough it could lead to immediate failure of the structure → as was observed in some other structures.

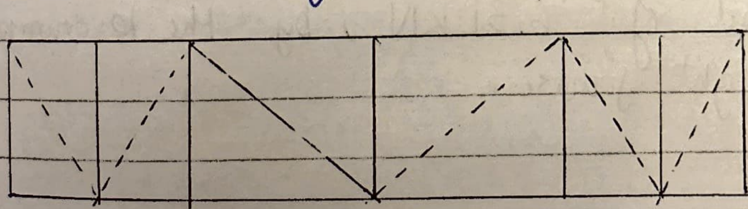
Linearly.

Extrapolating from the maximum loads that could be carried by the M4, M5 and M6 bolts, on different steel plates, ~~the~~ we found the materials to use for the plate.

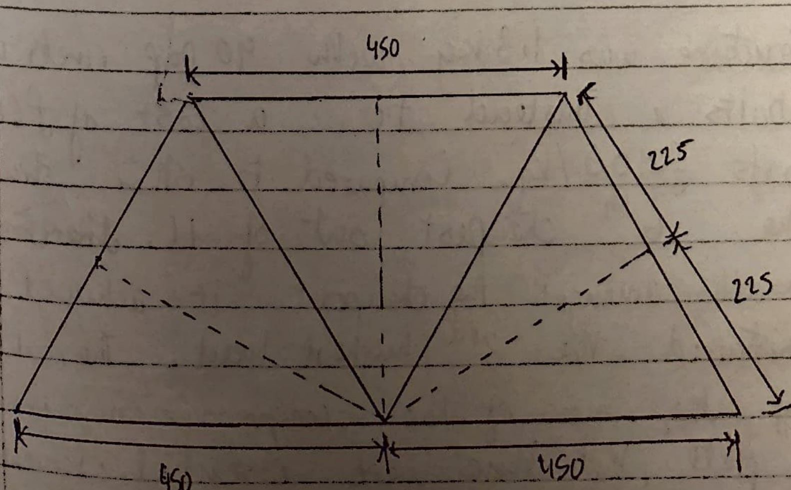
| Hole Diameter (mm) | Sheet Thickness (mm) and Load carried for that one (kN) | | | |
|---|---|---|---|---|
| | 1.00 | 1.22 | 1.50 | 2.00 |
| 4 | 0.88 | 1.06 | 1.32 | 1.76 |
| 5 | 1.10 | 1.32 | 1.65 | 2.20 |
| 6 | 1.32 | 1.58 | 1.98 | 2.64 |
| 7 | 1.54 | 1.84 | 2.31 | 3.08 |
| ↓ Extrapolate | | | | |
| 13 | 2.86 | 3.4 | 4.29 | 5.72. |

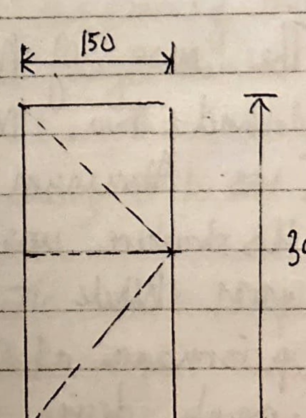
Therefore for a 13 mm hole, a single plate cannot sustain a load of 7 kN. Therefore we chose to use two ~~loading plates~~ 1.50 mm plates (riveted together) as they are the lightest plates that can sustain a load of > 7 kN as 2 × 4.29 = 8.58 kN

## Final Overall Design



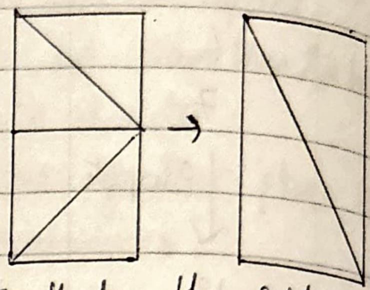
This was the final design chosen, with cross bracing included:



## Resuts and Deviations

The test was conducted by connecting a test rig to the loading hole, and an ~~a~~ increasing load was applied using the machine. Initially the expected failure was through buckling of the compressive members, however due to some errors in manufacturing there were some deviations from the planned design.



The main deviations were the side bracing due to time constraints and the realisation that this direction of buckling was quite unlikely to happen anyways. Additionally the loading plate was increased in height by 10 cm so that the fold wasn't too close to the loading hole. The fold in the loading plate was to stop the plate from crumpling near the top, as this is where the bending stress is greatest.

~~Or~~ The structure passed the working load of 3.5 kN without any visible deformation, and first started to show signs of deformation at around 4.5 kN, where the top right joint started to bend. It failed completely at a maximum load of 6.31 kN, by the ~~k~~ crumple of 2 of the top right joints.

## Costing Analysis

The mass of the structure was 1.3 kg, with 90 pop rivets used and two M4 bolts. This lead to a cost of £663, as Aluminum costs £500/kg. Compared to other structures this structure was the 6$^{th}$ cheapest out of 11. ~~Therefore there was~~ While it wasn't amongst the cheapest it achieved a good performance as it sustained the 3$^{rd}$ highest load. The cost was mainly driven by the mass of the compressive members, and also the loading plate, but these were essential elements to avoid buckling and loadingplate tear failure.

The cheapest structure used an elegant design, as it optimised by making the bridge one triangular structure. To avoid failure by buckling the constructors cleverly used multiple bracing supports, and approached the project with a cost-effective dominated approach. The structure weighed 0.84kg and cost £430.30, passing both the ultimate, and ~~poor~~ working load.

## Modification and Analysis of Results and Failures

The structure failed at a maximum load of 6.31kN which is slightly below the intended and required failure point of 7kN, by 10%. The failure was mainly due to the failure of both of the top corner joints, where the gusset plate folded and separated the angles enough, so that the tensile force wasn't acting through the same point.

Upon closer inspection several factors likely contributed to this failure:

- The rivets in the affected joint were not perfectly alligned with the centroidal axis of the members, however this would be quite difficult to improve due to the small area of angle. This likely introduced bending moments at high enough loads, which eventually led to the plate crumpling.

- There was a degree of asymmetry between the two planes of truss, so to fix this on the last manufacturing day the diagonal angle member had to be readjusted, leading to a slight twist within it. This likely caused an additional force on the weaker gusset plate causing it to fold.

- The three bars connecting at the joints were not completely butted together potentially creating a small unsuported region within the plate. Under compression this may have crumpled and folded,

Minor bending observed at other top joints, and this was a common source of failure in other design, indicating its significance.
These issues are mainly due to flaws in the manufacturing process, rather than wrong design choices. This was most evident due to small tolerances leading to our structure not being long enough on the last day, leading to a partial rebuild.

For improvements:

- Tighter quality control, and following the drawings more precisely is extremely important as to avoid major deviations from the plan over time.
- Ensuring that all members are fully butted together at joints would eliminate unsupported zones and reduce bending locally in gusset plate.
- Since the sheet metal is relatively thin, all angles should be connected compactly to avoid to much stress on the gusset plate.

With regard to design choices, perhaps choosing a smaller structure with more supports and bracing to compensate for the higher compression load could be more cost effective → similar to the cheaper structures. Additionally some cross bracing and connecting members to the loading plate could be removed.

Conclusion

In conclusion, the project involved designing a bridge, through qualitative calculations and evaluation of different designs, whilst keeping it as cost effective as possible whilst satisfying the project requirements. The requirements were to reach a working load of 3.5 kN which our structure comfortably passed but it failed just below the ~~coste~~ ultimate load at 6.31 N (10% less than planned). Our structure failed due to ~~shearing~~ of the top joint folding, ~~as~~ likely due to the asymmetry of the two planes, and the angles not being butted together leading to bending moments. Reflecting upon this various improvements were possible & focusing more on flaws in manufacturing, and ~~shakaw~~ following the drawing more strictly by making more accurate measurements. Overall our structure was quite satisfactory as it sustained the third highest load whilst at median cost comparatively.