Design, Construction and Testing of a Pasta Bridge

Final Report

Group 12 – Team name

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7/02/2014

Engineering Design (EI150)

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1 Introduction

The following is a detailed report outlining the methods used by our team to create a pasta bridge which had to meet certain criteria:
We were tasked with designing and building a bridge made entirely from spaghetti. This bridge had to be able to carry a minimum load of twenty kilograms acting through the centre of the bridge. It also had to be of certain dimensions (0.6mx0.25mx0.1m). The design and building of the bridge was split equally between all members of the team. The following is a guide of how our time was split up between the four weeks:

1.1 Week One

During the first week, we met up as a team in the design and build lab to discuss possible designs and strategies for building the bridge. Certain strong designs were made clear from our match stick models which we each presented. We decided on the design which we believed was the strongest, and simplest to make within the time constraints given.

1.2 Week Two

In our second week we again met up to discuss trusses, members and the forces acting on them. We had used the John Hopkins bridge designer tool to find all the forces acting on the members. This also allowed us to see which members were in compression and which were in tension. Using this as a guideline, we were able to decide on how many strands of pasta were required to build the member of the bridge.

1.3 Week three

During week three, we started building both in the labs and in our free time. We used a hot glue gun to join all the pieces of the bridge together. This turned out to be very time consuming and we needed to use our time as efficiently as possible. The four of us were very motivated and met up regularly outside of lectures to finish the project in time for testing. We also carried out simple prototype tests to aid us in constructing the final design.

1.4 Week four

In our final week we had a very limited amount of time to finish the bridge. We managed to finish the bridge with time to spare, which allowed for testing of the bridge and analysis.

2 Design Overview

As a group we decided on the Baltimore truss design for the project. When each member presented their matchstick prototype in week one, we decided that the Baltimore design was the most structurally sound design largely based on its properties including numerous trusses and 45° nodes .

2.1 Chosen Design: Baltimore Truss

A key area for us in designing this bridge was to incorporate as much triangulation as possible. We learned from our research, that this would be the most efficient way of carrying the load throughout the bridge from member to member, hence strengthening the bridge hugely. The Baltimore design clearly implements the use of many trusses angled at both 45° and 90°, clearly seen in figures 1 and 2.

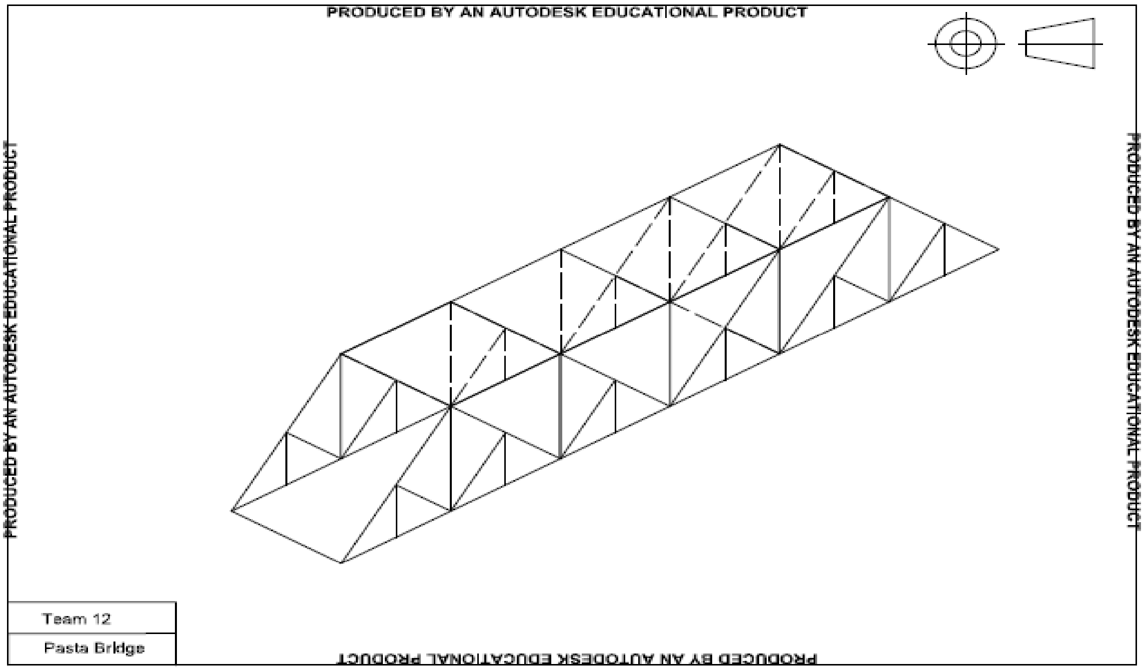


Figure 1: Isometric view of the Baltimore truss design

We used the John Hopkins bridge designer tool to analyse how the load would be distributed between the trusses (see figure 3). From our analysis of triangulation in bridges, it became very clear that this was the best structure to go with because of the properties of the triangle: It cannot be deformed easily and it can also take large loads without pivoting.

It was clear from our testing of individual trusses that the bridge would be able to hold 20+ times its own weight. As well as this, we had also seen similar bridges to ours used in real life as railway bridges which were obviously very effective at supporting loads. We debated leaving out the smaller struts as we saw from calculations that they didn't support any forces. Eventually, we agreed on using them to increase and improve the load distribution across the structure. Our understanding was that they would aid in supporting the tensile and compression loads carried in the larger members and help prevent them from failing.

We also felt that it was the simplest design for which to calculate the forces acting on each member and we believed that this design gave us the best possible opportunity to hold the twenty kilogram load.

3 Detailed design

Having finally selected the Baltimore truss design for the project, we proceeded to examine and discuss how we could create this design from the assigned materials of glue and spaghetti.

From our brainstorming we decided on 7 key areas which would have to be examined before commencement of the building stage. These areas will be developed in the following sections:

3.1 Overall dimensions of the truss design:

We decided that the dimensions of the bridge design were the best place to begin.

3.1.1 From our knowledge of civil engineering covered in semester 1 and from our individual research over Christmas, we chose to make use of the maximum width of 10 cm (see figure 2). With a larger surface area on the bottom surface, the overall rotating moments and the bridge's possible desire to rotate would be considerably reduced.

3.1.2 We also decided to utilise the maximum length of 60cm as it made our spaghetti production more accurate as we would be dealing with whole numbers but largely because the bridge would be well stabilised on the testing bench as it would have sufficient and equal coverage on both sides.

3.1.3 The height of the bridge was limited because of our chosen length. The truss system is largely composed of six equilateral triangles spanning a distance of 60cm as seen in figure 2. Therefore, the height was restricted to 10cm in keeping with the isosceles triangles. This suited us as we had learned in our lectures that truss systems have greater stability at reduced/low heights.

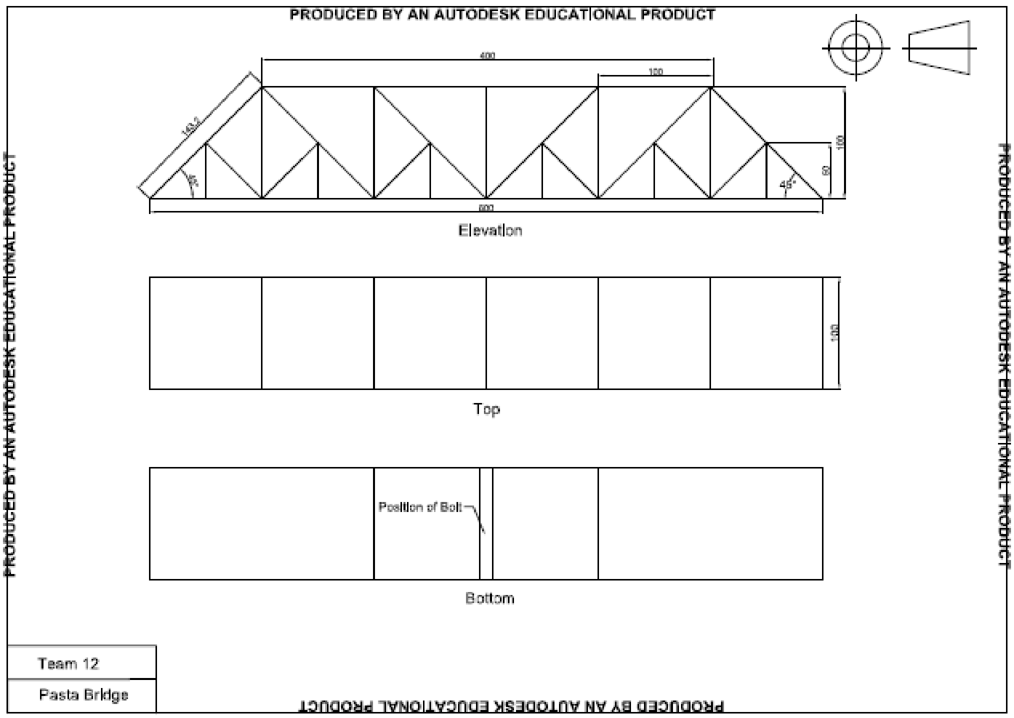


Figure 2: Orthographic view of Spaghetti Bridge.

3.2 How many spaghetti strands should be in each strand:

To aid us with these designs we used the John Hopkins Bridge Designer. Having entered in our design and loads of both 100N and 200N we examined the members in tension and compression. The following diagram (Figure 3) gave us a clear outline of what tensile and compressive stresses each member was under.

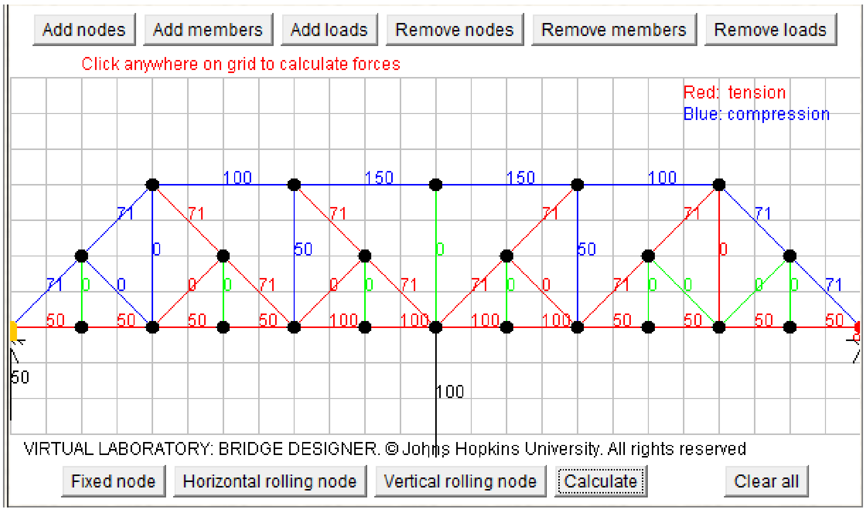


Figure 3: Analysis of final design using John Hopkins Bridge Designer, with a load at centre of 100N

From this we began our design calculations:

3.2.1 Members in tension (see appendix 4.):

From our research we discovered that spaghetti strands were strongest in tension. To calculate the amount of strands to be incorporated in each member we used the following equation:

$$F_m = UTS \times A \qquad (1)$$

Where (F_m) is the maximum force a beam can handle in tension found by multiplying its Ultimate Tensile Strength (*UTS*) by its cross-sectional area (*A*).

The value for (F_m) was taken from both the internal members calculations as well as the information provided by the John Hopkins bridge designer (see figure 3).

A value of 13.8 *N/mm2* was assumed for the UTS.

Therefore to calculate the necessary area the rearranged equation used was:

$$A = F_m / UTS \qquad (2)$$

The calculations for the prototype (see appendix 4) gave a value of 2.3077 pieces to support a tensile force of 100N (not including a factor of safety). We originally assumed a factor of safety (FoS) of 10. Based on our preliminary testing we decided that a greater factor of safety was necessary. For the final design we used a FoS of 25 giving us a total of 50 spaghetti strands per 100N of tension. This gave a stable and thick diameter for the base (2cm).

3.2.2 Members in Compression (see appendix 5):

Based on research on other spaghetti bridge competitions, we knew that spaghetti was weaker in compression than in tension. As a result we were most concerned with failure by buckling. The equation for calculating the cross-sectional area and therefore the number of strands for each member was:

$$I = P_c L^2 / E \pi^2 \qquad (3)$$

Where I is the second moment of area and is calculated using the buckling force (P_c), the length of the member (L), a function of Young's modulus (E) and π = 3.14159. Due to time constraints, we were unable to establish a specific (E) value for our brand of spaghetti but we compared the other results found and utilised the lowest value recorded by Rowan University students (6,895 N/mm^2).

With a value of I for each member in compression, we were able to calculate the number of strands needed for each member using common second moments of area for spaghetti beams: For example, a member with 9 elements arranged in a square shape, used in our initial design:

$$I = \frac{105\pi^4}{64} \qquad (4)$$

Where d is the diameter of the spaghetti. From equations (3) and (4) along with our initial testing stage we noticed that by making the beam wider or by replacing a long beam with a series of shorter ones, it would be able to withstand a greater buckling force.

3.3 Shape of the members:

Based on our compression and tension analysis we decided that members with a circular cross-section would be best. These column shaped members were easy to construct and once the factor of safety was applied to our final calculations, members with circular cross-sections fitted our results. Furthermore, their shape provided the necessary width for the members in compression to withstand the applied buckling forces. Figure 4 provides an example of a 19 strand member used in compression:

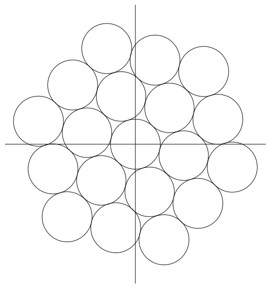


Figure 4: A cross-sectional view of a member with 19 strands of spaghetti.

3.4 Construction of the members:

Due to the relative short construction period for this project we knew a systematic approach was necessary for the construction of our members. Following the failure of our preliminary design at a load of 7kg , we learned that the individual spaghetti pieces in the beams were not perfectly attached to one another. Following this we designed a more efficient method of constructing the members. Each team member was assigned a specific task which they would carry out throughout the production stage. The tasks were; measuring and preparing the spaghetti, cutting the spaghetti, bunching the necessary number of strands and preparing them for the gluing stage and finally the gluing process itself.

We knew that our calculations would go to waste unless the members were constructed properly so, this was done with utmost accuracy and care. The spaghetti strands were laid out in a fan shape whilst glue was spread on both sides of one end. Then, the members were quickly arranged in the agreed shape before finally fixing them within a tight rubber band to ensure they set in the correct shape. The same process was repeated on the other end of the members before setting them to one side.

3.5 The method of connecting the built spaghetti members:

Having done research on other spaghetti bridges in other competitions, we agreed that a combination of glue-joined members and overlapping spaghetti strands at specific nodes would be best.

3.6 How the steel member would be incorporated in the design:

One of the most difficult challenges we faced was working out the best method of incorporating the steel member. We reasoned that the member needed to be completely stable for testing to avoid any ill distributed forces on one truss over another. Therefore we decided to build it into the centre of our design and have it supported and stabilised by four of the key members of the truss design; the middle vertical and two 45° members, as well as the bottom member

3.7 The addition of the underlying spaghetti strands

Based on our early testing and reasoning, we understood that the bottom member was under a lot of tension and based on the way we had connected the members we saw that some support was needed. This was most evident in our preliminary test when the bottom members were first to fail. Having carried out further tests, we concluded that the addition of an underlying member would stabilise and strengthen the base.

4 Testing

4.1 Strength of pasta

4.1.1 Objectives

The objective of this experiment was to determine the load that the spaghetti strands could support in tension.

4.1.2 Methods

1. A group of spaghetti strands were taped to two opposite chairs and a cup was hung the middle of the spaghetti. See figure 5.
2. A number of marbles were placed in the cup one by one.
3. Step 2 was repeated until the spaghetti strands broke.
4. The number of marbles it supported was recorded.
5. Steps 1-4 were repeated adding extra strands of spaghetti each time.

Figure 5: Set up of apparatus

4.1.3 Analysis

The weight of 1 marble is 5 grams. Therefore, to calculate the total load suspended form the spaghetti we used:

*Mass of load = Number of marbles * 5* (5)

Where the mass of the load is measured in grams.

4.1.4 Results

Number of spaghetti strands	Load (Grams)
10	50
15	80
20	115
25	125

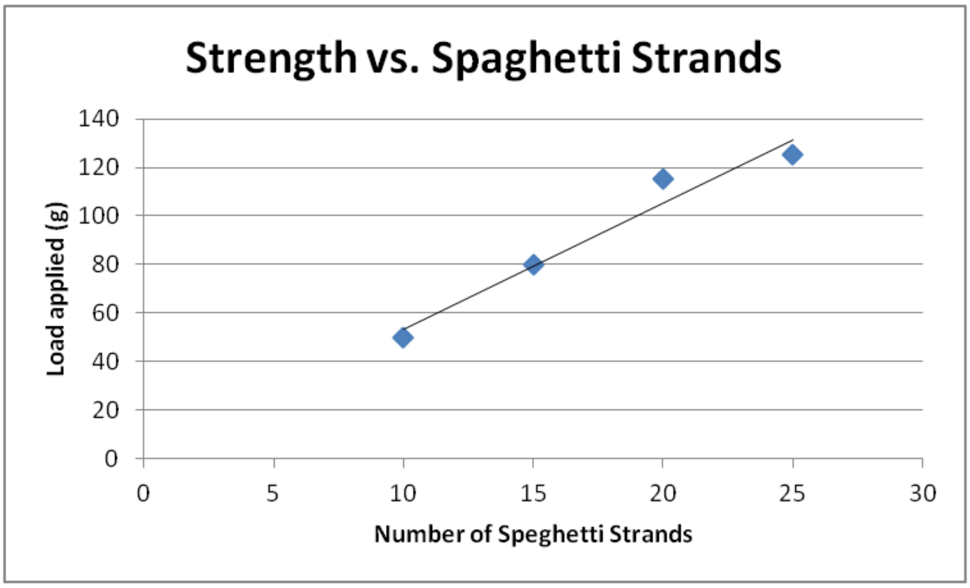


Figure 6: Strength of spaghetti against number of strands graph

4.1.5 Discussion

As the number of spaghetti strands increases, the strength of the bridge increases proportionally. Every one strand of spaghetti carried approximately 5 marbles corresponding to a mass of 25g/strand . There was however some experimental error in this experiment including movement of the cup, time allotted to drop the marbles, and the length of each spaghetti strand.

4.1.6 Conclusion

As the number of spaghetti strands increases, so does the tensile strength of the beam.

4.2 Testing 10 kg on one side of the bridge.

4.2.1 Objectives

The aim was to measure the strength of one side of the pasta bridge. Our objective was for the bridge to carry a load of 10kg and to use the experiment discover any flaws in the bridge.

4.2.2 Methods

1. The sides of the bridge were supported by two metal beams (see figure 7).
2. The bridge was supported vertically by hand, to prevent a turning moment, and a hook was attached to the middle of the bridge.
3. While the bridge was still being held up, 4 kg weights were attached.
4. Step 3 was repeated adding 1kg every time until 10 kg was reached.

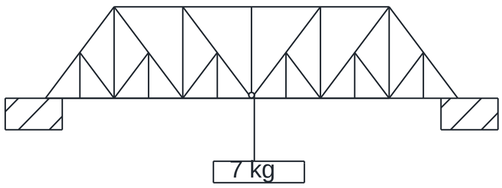


Figure 7: Set up of apparatus for preliminary test

4.2.3 Results

The bridge failed in the middle at a load 7 kg

4.2.4 Discussion

We observed that the bridge was very weak at the point where the load was applied. The weights ripped right though the pasta strands and the bottom nodes were observed to be under a severe stress.

4.2.5 Conclusion

The bridge design appeared to be successful. However an underestimate of spaghetti strands was spotted at the middle of the bridge where it failed. From this, we agreed, extra spaghetti strands had to be added to the middle as well as creating a new method of incorporating the steel. We also decided on adding an underlying member to the bottom beam to give it extra stability.

4.3 Final lab testing of the bridge

4.3.1 Objectives

The aim was to determine whether the bridge could support a minimum load of 20 kg.

4.3.2 Methods

1. The bridge was supported on both sides by a metal beam.
2. A hook was attached to the middle of the bridge around the mental bolt.
3. 5 kg weights were attached to the bridge using the mental hook.
4. Step 3 was repeated adding 5 kg every time until 15 kg was reached
5. Finally, the 20kg limit was reached by adding smaller weights of 2kgs and 1kg.

4.3.3 Results

The bridge carried the 20 kg and passed the testing process.

4.3.4 Discussion

The bridge was very steady and firm during the final test. It didn't show any signs of excessive stresses or evidence of weakness at any point. It carried the load of 20 kg very easily and would certainly support a larger load. In addition, the glue kept the nodes fixed during the testing.

4.3.5 Conclusion

The bridge could indeed support a minimum weight of 20 kg. Our bridge design was successful and our calculations were correct. The underlying spaghetti strands also proved to be successful. Moreover, our improved method of making the members also proved to be a lesson well learned from the preliminary test.

5 Conclusions

Overall, the bridge performed as expected, and held the 20kg load with little difficulty. We, as a team, feel that we chose the right truss design.

It is visible from the John Hopkins diagram (figure 3), that the short vertical and 45° members are not in tension or in compression, however we felt that these members still needed to be included as they prevented some of the larger 45° members from buckling under compression.

We used an overlapping technique, which was added following our preliminary testing, on the bottom member of our bridge and from the video we can see it was very effective in stopping the bridge from failing when it was under the 17kg load.

Our method of joining the members to one another proved to be a success both in the preliminary and final tests. In both tests, the nodes remained intact and held firm. Moreover, the method by which the members were created from the individual strands was improved on following our first test and proved to be successful in the final test.

6 Recommendations for Future Work

There are many things we could have done to improve our design and make a much more efficient bridge.

- Use less strands of spaghetti: Although our bridge held the 20kg load, we would have been in with a better chance of winning the competition if we used less strands of spaghetti in the members. Our members were capable of holding much more mass than 20kg and therefore, the bridge carried some unnecessary weight.
- Neater with glue: The group was inexperienced in using the glue gun and as a result, our nodes were very messy and contained a lot of unnecessary glue. Our glue gun was a heavy duty gun which released a lot of glue from the nozzle when the trigger was pulled. If we had used a smaller glue gun and if we were more experienced in using it, we could have reduced the weight of the bridge by 5-10% .
- Time management: Our time management was quite good during the four weeks of this project. I feel that this is one of the most important factors in building the bridge. Allowing sufficient time for each of the members to dry before constructing the trusses is a key element to a successful bridge. Furthermore, our bridge was well settled and the glue had fully set and dried by the time of the final test.
- Strengthening of nodes: We could have increased the strength of our nodes by filing down and angling the ends of the members before gluing them, rather than just sticking them together with a ball of glue. We did not do this to the greatest of accuracy because, it would have been very time consuming and we did not have the proper equipment to do so

7 References

1. John Hopkins Bridge Designer- http://www.jhu.edu/virtlab/bridge/bridge.htm.
2. Rowan University - http://users.rowan.edu/~everett/courses/frcli/spagBrdge.htm, accessed 22/01/2014.
3. Anonymous, “Warren Truss Bridge Designs”, http://www.toothpickdesign.com/trusstoothpickbridges.htm.
4. Anonymous, “Forces That Act On Bridges”, http://www.garrettsbridges.com/design/theforces/
5. Autodesk, “AutoCAD”.

Appendix 1 Individual Contributions

A1.1 Eoin Clancy

I proposed the idea of the Baltimore truss design in week one, based on the stability of my matchstick bridge. I was assigned the job of calculating the member forces, along with the analysis of the tensile and compression forces. Also, I contributed more than seven hours directly to the building of the bridge, including 2-3 hours at the weekend with Cian. Moreover, I proposed the idea of the underlying beam at the bottom of the bridge based on what I observed during the preliminary test. Finally for my contribution to the report, I completed the detailed design and typed out all of the calculations. I also organised for the other members to email their completed report pieces to me so that I could compile the report in an organised and free-flowing manner.

A1.2 James Clifford

I supplied the glue sticks and glue gun that I had at home, which helped us save on the cost of the project and also allowed us to start building our bridge as soon as possible. Cian and I both live on the on campus accommodation and our houses were very useful for building the bridge in out of Lab time. I completed the conclusions, recommendations and references for the report and drew the isometric and orthographic AutoCAD drawings. I also help design the method of incorporating the steel bolt and was the primary user of the glue gun. I thought that it would be a good idea to lay it on top of the two descending members at the centre of the bridge

A1.3 Cian Costolloe

I researched different types of bridge designs over the Christmas holidays. As well as the design and build lab , my house was used to meet up and work on the bridge with the team. Myself and Eoin worked on the bridge during a weekend in order to use our time efficiently and get a good head start on the bridge building. I also went out and bought the pasta for the team. While building with the team, I was mostly in charge of cutting the pasta to specific lengths or helping with the gluing by holding the members in place. I was also in charge of the introduction and design overview of this document.

A1.4 Ahmed Wanas

I supplied the rubber bands, scissors and a few different brands of pasta that we could test and choose from. Also I helped my teammates to cut the pasta strands, stick the strands together, take measurements and attach the different trusses of the bridge together and I was in charge of operating it and spreading the glue on the pasta. I believe we worked great as a team each knowing their task and getting it done on time. Furthermore we also divided the report in to four equal sections assigning one section to each of us. I contributed to the report by completing the testing and materials cost section. During the project, I was in charge of conducting the preliminary test and for taking all of the results as well as creating the graphs.

Appendix 2 Parts, materials and costs

Part	Material	Source	Cost (€)
2kg of pasta	Spaghetti	Dunnes	€ 2.99
5 Parkside Glue Sticks	Glue	LIDL	€6.0
1 Scissors	Metal	Home	€ -
1 Box of match sticks	Wooden sticks	Shop	€ 1.0
1 Glue gun	Plastic and metal	ALDI	€ 20.0
40 Rubber elastic bands	Rubber	Shop	€1.99

Appendix 3 Reflection

A3.1 Eoin Clancy:

Looking back, if I were to complete this project again I would most certainly start the report much earlier. In doing this, it would provide the reader with a deeper insight as to how our designed varied and progressed over time, as some information is understandably forgotten come the time to write it.

Moreover, I believe more testing should definitely be done in the lead up to the final design. Based on the testing we actually did, we gained many important insights which led us to changing the design subtly which made all the difference in the final test.

Having completed this project, my knowledge of calculating member forces and turning effects has been greatly enhanced. I also discovered some important engineering properties including stress-strain graphs, Young's modulus and the importance of the factor of safety.

A3.2 James Clifford:

Our project was planned very well and our time management was very good. We decided very early in the project what design we would use so that we could calculate member forces and how we would go about constructing it.

If I could change anything about our project, I would suggest that we start the report a bit earlier rather than spending all our time on constructing the bridge. Since the report is worth 50% of the overall mark I feel it is necessary to have it at the same high standard as the bridge itself.

A3.3 Cian Costelloe:

If I were to do this project again there would be a number of things that I would repeat and a number of things that I would change:

I would definitely repeat meeting up regularly as a group and discussing and sharing ideas. I would repeat how we split up and managed the project together and the way we built the bridge and divided up our individual time to it in order to finish it before schedule.

What I would do differently:

At the beginning of the project I would start straight into it and do not waste the first week. I would swap certain roles within the group to ensure that all members of the team try a new part of the next project e.g.(Swap which members write which part of the report as the calculations are more difficult than the introduction to write). As well as working on the building, also work on the report as you go along because it is very time consuming also and it can be difficult to remember what work was done on certain weeks without a log kept.

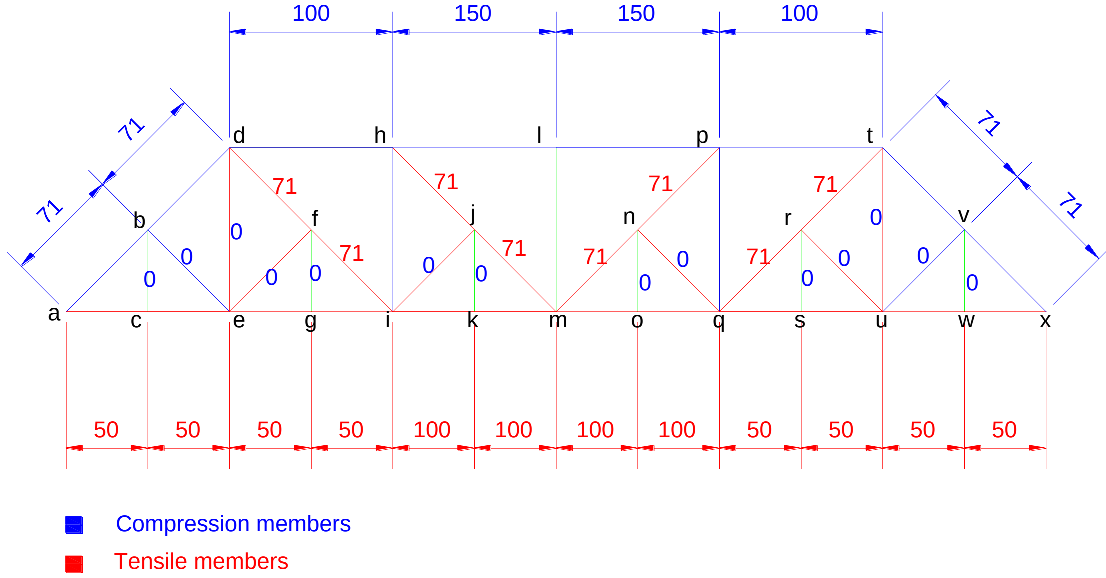
A3.4 Ahmed Wanas:

Overall I believe the pasta bridge project was a great success.

If I was to do the project again I would have started building the bridge a little bit earlier as to not be panicking close to the deadline. I would also have bought extra small rubber bands as the ones available were too large and an extra glue gun would have also come in handy.

I also believe that more testing should have been done to improve our design.

Appendix 3 Calculation of Member Forces:



Node A:

Figure 8: Identification of Nodes on Final Design

Node A:	**Node B:**
ΣFy: $T_{ab}Sin45^{\circ} + 50 = 0$ $\frac{1}{\sqrt{2}}T_{ab} = -50$ $T_{ab} = -\frac{50}{\frac{1}{\sqrt{2}}}$	ΣFy: $T_{bc} = 0$ ΣFx: $50 + T_{ce} = 0$ $50 = T_{ce}$

$T_{ab} = -70.71$ ΣFx: $T_{ac} + T_{ab}Cos45^\circ = 0$ $-70.71*Cos45^\circ = T_{ac}$	
Node C: ΣFy: $T_{bd}\,Sin45^\circ + T_{be}Sin45^\circ - T_{ba}Sin45° = 0$ $\frac{1}{\sqrt{2}}T_{bd} - \frac{1}{\sqrt{2}}T_{be} - 50 = 0$ $\frac{1}{\sqrt{2}}T_{bd} - \frac{1}{\sqrt{2}}T_{be} = 50$ ΣFx: $-T_{bd}\,Cos45^\circ + T_{bd}Cos45^\circ - T_{be}Cos45° = 0$ $-50 + \frac{1}{\sqrt{2}}T_{bd} + \frac{1}{\sqrt{2}}T_{be} = 0$ $\frac{1}{\sqrt{2}}T_{bd} + \frac{1}{\sqrt{2}}T_{be} = 50$ $\frac{1}{\sqrt{2}}T_{bd} - \frac{1}{\sqrt{2}}T_{be} = 50$ $\frac{1}{\sqrt{2}}T_{bd} + \frac{1}{\sqrt{2}}T_{be} = 50$ ——————— $\sqrt{2}\,T_{bd} = 100$ $100/\sqrt{2} = T_{bd}$ $C_{bd} = 70.71$ $\frac{1}{\sqrt{2}}(70.71) - \frac{1}{\sqrt{2}}T_{be} = 50$	**Node D:** ΣFy: $T_{bd}\,Sin45^\circ - T_{df}Sin45^\circ = 0$ $\frac{1}{\sqrt{2}}T_{bd} - \frac{1}{\sqrt{2}}T_{df} = 0$ $T_{bd} = T_{df}$ $T_{bd} = 70.71$ ΣFx: $T_{dh} + T_{df}Cos45^\circ + T_{db}Cos45° = 0$ $T_{dh} + 70.71\frac{1}{\sqrt{2}} + 70.71\frac{1}{\sqrt{2}} = 0$ $T_{dh} = -100$
Node E: ΣFy: $T_{ef}\,Sin45^\circ = 0$ $T_{ef} = 0$ ΣFx: $T_{eg} - 50 = 0$ $T_{eg} = 50$	**Node G:** ΣFy: $T_{fg} = 0$ ΣFx: $50 - T_{gi} = 0$
Node F: ΣFy: $T_{df}\,Sin45^\circ + C_{fi}Sin45^\circ = 0$ $C_{fi} = 70.71$ ΣFx: $T_{df}Cos45^\circ - C_{fi}Cos45° = 0$	**Node I:** ΣFy: $T_{fi}\,Sin45^\circ + T_{hi} = 0$ $T_{hi} = -50$ $C_{hi} = 50$ ΣFx: $T_{ig} - T_{ik} + T_{if}\,Sin45^\circ = 0$ $50 - T_{ik} + 50 = 0$ $T_{ik} = 100$
Node H: ΣFy: $-50 - T_{hj}\,Cos45^\circ = 0$ $-50 = \frac{1}{\sqrt{2}}T_{hj}$	**Node J:** ΣFy: $C_{jh}\,Sin45^\circ + C_{jm}Sin45^\circ = 0$ $70.71(\frac{1}{\sqrt{2}}) + (\frac{1}{\sqrt{2}})T_{jm} = 0$

$-\frac{50}{\frac{1}{\sqrt{2}}}$ = T_{hj} -70.71 = T_{hj} 70.71 = C_{hj} ΣFx: -100 + C_{hl} - C_{hj} Sin45° = 0 C_{hl} = 100 + 70.71($\frac{1}{\sqrt{2}}$) C_{hl} = 150	($\frac{1}{\sqrt{2}}$)T_{jm} = 50 T_{jm} = 70.71

Appendix 4 Calculation of Tensile Forces:

Using equation (2) above to calculate the number of spaghetti strands in each member:

Area of 1 piece of spaghetti (Ø = 2mm)

$A = \pi r^2$

$= \pi\ (1\text{mm})^2$

$= 3.14\ \text{mm}^2$

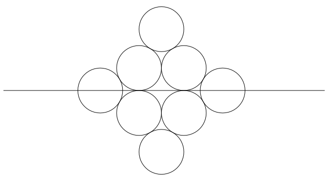
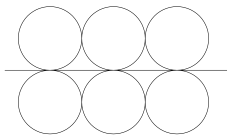
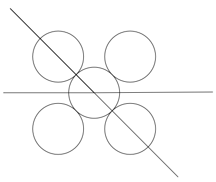
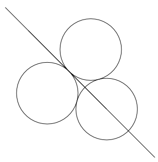
Tensile force of 100N $A = F_m / UTS$ $A = \frac{100N}{13.8N/mm^2}$ $A = 7.24637\ mm^2$ No.pcs = 7.24637/3.14 = 2.3077 pcs Factor of safety 2.3077*22 = 50.7694 pcs	**Tensile force of 50N** $A = F_m / UTS$ $A = \frac{50N}{13.8N/mm^2}$ $A = 3.6232mm^2$ No.pcs = 3.6232/3.14 = 1.15388 pcs Factor of safety 1.15388*22 = 25.385 pcs
Tensile force of 71N $A = F_m / UTS$ $A = \frac{71N}{13.8N/mm^2}$ $A = 5.1449\ mm^2$ No.pcs = 5.1449/3.14 = 1.6385 pcs	

Factor of safety 1.6385*22 = 36.047 pcs	

Appendix 5 Calculation of Compression Forces:

Beams in compression :

Using equation (3) above to calculate the second moment of area (I) for all members 0.1m:

Compression force of 150N: $I = P_c L^2 / E \boldsymbol{\pi}^2$ $I = \frac{150(100mm)^2}{\pi^2 (6895N/mm^2)}$ $I = 22.0423 \ mm^4$  $I = \frac{83.8\pi d^4}{64}$	**Compression force of 100N:** $I = P_c L^2 / E \boldsymbol{\pi}^2$ $I = \frac{100(100mm)^2}{\pi^2 (6895N/mm^2)}$ $I = 14.694877 \ mm^4$  $I = \frac{15\pi d^4}{32}$
Compression force of 71N: $I = P_c L^2 / E \boldsymbol{\pi}^2$ $I = \frac{71(100mm)^2}{\pi^2 (6895N/mm^2)}$ $I = 10.433 \ mm^4$  $I = \frac{37\pi d^4}{64}$	**Compression force of 50N:** $I = P_c L^2 / E \boldsymbol{\pi}^2$ $I = \frac{50(100mm)^2}{\pi^2 (6895N/mm^2)}$ $I = 7.347 \ mm^4$  $I = \frac{11\pi d^4}{64}$